
**Petroleum and natural gas
industries — Arctic offshore
structures**

Industries du pétrole et du gaz naturel — Structures arctiques en mer

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Published in Switzerland

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 7, *Offshore structures*.

This second edition cancels and replaces the first edition (ISO 19906:2010), which has been technically revised. The main changes compared to the previous edition are as follows:

- revisions to definitions and provisions to reflect updates in the general requirements standard ISO 19900 since the publication of the first edition of ISO 19906;
- significant revisions to provisions related to operational and emergency response measures, see 5.5, 8.2.7, clauses 13, 17, and 18;
- significant changes throughout the document to reflect user input on the first edition of the standard, notably with respect to ice actions in A.8.2;
- reference to the new data requirements standard ISO 35106 and corresponding revisions to Clauses 6 and 14, including significant deletion of now redundant content in Clause 14;
- reference to the new ice management (IM) standard ISO 35104 and corresponding revisions to Clause 17, including significant deletion of now redundant content;
- reference to the new EER standard ISO 35102 and corresponding revisions to Clause 18, including significant deletion of now redundant content.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

ISO 19906 is one of the International Standards on offshore structures prepared by TC 67/SC 7 (i.e. ISO 19900, the ISO 19901 series, ISO 19902, ISO 19903, ISO 19904-1, the ISO 19905 series and ISO 19906).

NOTE These are sometimes referred to as the ISO 19900 series on offshore structures.

The International Standards on offshore structures prepared by TC 67/SC 7 addresses design requirements and assessments for all offshore structures used by the petroleum and natural gas industries worldwide. Through their application, the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures, regardless of the type of structure and the nature or combination of the materials used.

The International Standards on offshore structures prepared by TC 67/SC 7 consist of the following documents:

- ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*
- ISO 19901 (all parts), *Petroleum and natural gas industries — Specific requirements for offshore structures*
- ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*
- ISO 19903, *Petroleum and natural gas industries — Concrete offshore structures*
- ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*
- ISO 19905 (all parts), *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units*
- ISO 19906, *Petroleum and natural gas industries — Arctic offshore structures*

It is important to recognize that structural integrity is an overall concept comprising models for describing actions, structural analyses, design rules, safety elements, workmanship, quality control procedures and national requirements, all of which are mutually dependent. The modification of one aspect of design in isolation can disturb the balance of reliability inherent in the overall concept or structural system. The implications involved in modifications, therefore, need to be considered in relation to the overall reliability of all offshore structural systems.

These documents applicable to the various types of offshore structure are intended to provide wide latitude in the choice of structural configurations, materials and techniques without hindering innovation. Sound engineering judgment is, therefore, necessary in the use of these documents.

This document was developed in response to the offshore industry's demand for a coherent and consistent definition of methodologies to design, analyse and assess arctic and cold region offshore structures within the Scope.

Structures capable of resisting ice have been in use in temperate regions for well over a century. These include bridge piers and navigation aids in ice-covered rivers and estuaries. In fact, bridge codes in cold

countries have included methods for addressing ice actions dating back many decades. In more severe arctic and cold regions, ice-resistant structures are more recent. But much experience has been gained commencing in the 1960s, and this knowledge is incorporated into this document. Where uncertainties still exist, conservative approaches and methods have been recommended.

Annex A provides background to and guidance on the use of this document and it is intended that it be read in conjunction with the main body of this document. The clause numbering in Annex A follows the numbering in the normative text to facilitate cross-referencing.

Annex B provides regional information on the physical environment of specific offshore areas in arctic and cold regions.

Some symbols in this document are not in accordance with the system of quantities on which the International System of Units is based, due to the need to conform with current ice literature. This might change in future editions of this document.

To meet certain needs of industry for linking software to specific elements in this document, a special clause-based numbering system has been permitted for figures, tables and formulae.

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Petroleum and natural gas industries — Arctic offshore structures

1 Scope

This document specifies requirements and provides recommendations and guidance for the design, construction, transportation, installation and decommissioning of offshore structures related to the activities of the petroleum and natural gas industries in arctic and cold regions. Reference to arctic and cold regions in this document is deemed to include both the Arctic and other locations characterized by low ambient temperatures and the presence or possibility of sea ice, icebergs, icing conditions, persistent snow cover, and/or permafrost.

The objective of this document is to ensure that complete structures, including substructures, topsides structures, floating production vessel hulls, foundations and mooring systems, in arctic and cold regions provide an appropriate level of reliability with respect to personnel safety, environmental protection and asset value. Value includes value to the owner, to the industry and to society in general.

This document does not contain requirements for the operation, maintenance, service-life inspection or repair of arctic and cold region offshore structures, unless the design strategy imposes specific requirements such as ice management (IM) to reduce ice actions.

Provisions for the operation, maintenance, service-life inspection and repair of mobile units are given in ISO 19905-1 and ISO 19905-3, supplemented by the provisions relating to ice actions and IM in this document.

This document does not apply to mechanical, process and electrical equipment or any specialized process equipment associated with arctic and cold region offshore operations except in so far as it is necessary for the structure to sustain safely the actions imposed by the installation, housing and operation of such equipment. This document applies to equipment used for the positioning and disconnection of floating structures (see Clause 13).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 17776, *Petroleum and natural gas industries — Offshore production installations — Major accident hazard management during the design of new installations*

ISO 19900:2013, *Petroleum and natural gas industries — General requirements for offshore structures*

ISO 19901-1, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating considerations*

ISO 19901-2, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 2: Seismic design procedures and criteria*

ISO 19901-3, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 3: Topsides structure*

ISO 19901-4, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 4: Geotechnical and foundation design considerations*

ISO 19901-6, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 6: Marine operations*

ISO 19901-7, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units*

ISO 19901-8, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 8: Marine soil investigations*

ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*

ISO 19903, *Petroleum and natural gas industries — Concrete offshore structures*

ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*

ISO 35101, *Petroleum and natural gas industries — Arctic operations — Working environment*

ISO 35102, *Petroleum and natural gas industries — Arctic operations — Escape, evacuation and rescue from offshore installations¹*

ISO 35104, *Petroleum and natural gas industries — Arctic operations — Ice management*

ISO/TS 35105, *Petroleum and natural gas industries — Arctic operations — Material requirements for Arctic operations*

ISO 35106, *Petroleum and natural gas industries — Arctic operations — Metocean, ice, and seabed data*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 19900, ISO 19901-1, ISO 19901-2, ISO 19901-4, ISO 35102, ISO 35104, ISO 35106 and the following apply. ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <http://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1 abrasion

effect of ice grinding against the surface of a structure thus removing paint, surface protrusions and coatings, oxidized material, or concrete particles and aggregate

¹ Under preparation. Stage at the time of publication: ISO/DIS 35102:2019.

3.2**action combination**

expression in which values of individual simultaneous actions for a design situation are summed to obtain the total *design action* (3.10) for design verification of a structure for a specific limit state

3.3**action effect**

effect of actions on structural components

EXAMPLE Internal force, moment, stress or strain.

3.4**adfreeze**

freezing of ice or soil onto the surface of a structure

3.5**aspect ratio**

ratio of structure diameter or width to ice thickness

3.6**broken ice**

ice pieces of varying size, broken up as a result of natural processes, or active or passive intervention

Note 1 to entry: Active intervention includes IM resulting in managed ice; passive intervention includes the channel, or wake, caused by a stationary structure in moving ice cover.

3.7**companion environmental action**

environmental action applied simultaneously with the principal environmental action

3.8**consolidation**

process of freezing of pore water in voids within ice rubble or between floes

Note 1 to entry: For soils, consolidation involves drainage of pore fluid as a result of overburden pressures.

3.9**consolidated layer**

portion of an *ice ridge* (3.35) keel, *rubble pile* (3.58), *rubble field* (3.57) or *stamukha* (3.66) below the waterline formed by the ice freezing process

3.10**design action**

sum of design values of individual simultaneous actions for an *action combination* (3.2)

3.11**design resistance**

resistance limit calculated from factored representative values of basic variables, or from factored expressions based on unfactored representative values of basic variables

Note 1 to entry: Material properties are examples of basic variables relevant to resistance.

3.12

disconnection

planned separation of the risers (and mooring, if applicable) for a floating system

3.13

ductility

ability of a material to deform and absorb energy beyond its elastic limit or ability of a component to sustain *action effects* (3.3) beyond yield

Note 1 to entry: See also *system ductility* (3.69).

3.14

dynamic action

action that induces acceleration of a structure or a structural component of a magnitude sufficient to require specific consideration

3.15

dynamic positioning

stationkeeping technique consisting primarily of a system of automatically controlled on-board thrusters, which generate appropriate thrust vectors to counter the mean and slowly varying *dynamic actions* (3.14)

[SOURCE: ISO 19901-7:2013, 3.9]

3.16

emergency disconnection

procedure involving separation of the risers (and mooring, if applicable) for a floating system, without depressurization of the risers

3.17

first-year ice

FY ice

sea ice formed during the current or prior winter that has not survived one summer melt season

3.18

floe

relatively flat piece of sea ice greater than 20 m across

Note 1 to entry: There are typically sub-categories of floe: small (20 m to 100 m across), medium (100 m to 500 m across), big (500 m to 2 000 m across), vast (2 km to 10 km across) and giant (greater than 10 km across).

3.19

flowline

pipework on the *sea floor* (3.61) linking one or more subsea wells to the production system

Note 1 to entry: Flowline functions can include production, injection, subsea systems control and export of produced fluids.

3.20 Freeboard

3.20.1

freeboard

<ice> vertical distance from the water surface to the top of the ice

3.20.2**freeboard**

<floating structure> vertical distance from the mean water surface at a given draught to the deck level, measured at the lowest point where water can enter the structure or ship

3.20.3**freeboard**

<platform or island> vertical distance from the water surface to the surface of a platform or man-made island measured at the perimeter

3.21**freeze-thaw**

possible degradation effect of repeated freezing temperature cycles on the properties of concrete, soil, and porous materials with water-absorbing properties

3.22**ice alert**

prescribed reaction to a forecast hazardous *ice event* (3.28)

Note 1 to entry: Several different levels associated with the time proximity of the hazard are normally recognized.

Note 2 to entry: Focus in this document is on alerts related to ice hazards. Ice alerts are linked with other constraints on operating protocols, including those due to metocean, equipment or production considerations, see for example ISO 19905-3.

3.23**ice belt**

strengthened hull region around the waterline, as specified in ice class requirements

3.24**iceberg**

glacial or *shelf ice* (3.65) of greater than 5 m freeboard that has broken (calved) away from its source

Note 1 to entry: Icebergs can be freely floating or grounded, and are sometimes defined as tabular, dome, pinnacle, wedge or block-shaped.

3.25**ice concentration**

proportion of the water surface covered by ice

Note 1 to entry: The proportion of surface coverage is usually expressed in tenths.

3.26**ice detection**

identification of ice features or associated conditions within the surrounding environment

3.27**ice encroachment**

movement of sea ice onto the surface of a platform or man-made island

Note 1 to entry: Ice encroachment can result from ice ride-up, pile-up, and ride-down processes.

Note 2 to entry: The extent of ice encroachment is typically included in operational or design criteria.

3.28

ice event

occurrence of ice-structure interaction for which ice actions can be calculated

Note 1 to entry: Ice events can be occurrences of interactions with discrete ice features such as icebergs, ice islands, ice ridges, stamukhi and ice floes, or can be occurrences of peaks within a specified length or duration of the interaction process.

3.29

ice gouge

ice scour

incision in the *seabed* (3.62) or removal of seabed soils by an ice feature

Note 1 to entry: Incisions can have the form of either an areal incision (pit) or a linear incision (furrow).

3.30

ice island

large tabular-shaped ice feature that has calved from an ice shelf or glacier

3.31

ice management

IM

processes and activities whose objective is to reduce or avoid ice actions

Note 1 to entry: IM includes, but is not limited to, detection, tracking, ice forecasting, threat evaluation, alerting and physical management.

3.32

ice management plan

IM plan

plan detailing the objectives, measures involved and individual responsibilities for the implementation of an IM system

3.33

ice management system

IM system

IM and the tools used for its implementation

3.34

ice model test

scaled physical testing of a structure or a component under controlled conditions

Note 1 to entry: The structure, ice properties and test parameters are normally scaled according to some similitude principles (scaled model tests).

Note 2 to entry: Ice model tests are often carried out in special laboratories which are called ice tanks or ice basins.

3.35

ice ridge

linear feature formed of ice blocks created by the relative motion between ice sheets

Note 1 to entry: Ice pressure ridges are formed when ice sheets are pushed together, and a shear ice ridge is formed when ice sheets slide along a common boundary.

3.36**ice scenario**

combination of conditions involving the presence of ice, resulting in *ice events* (3.28)

3.37**infill**

material deposited in an *ice gouge* (3.29), excavation or trench through natural processes

3.38**landfast ice**

fast ice

ice that remains attached to a shoreline, island or grounded ice feature

3.39**level ice**

sheet ice

region of ice with relatively uniform thickness

3.40**local failure**

localized damage to the structure with the potential for escalating to partial or complete failure

3.41**lowest anticipated service temperature****LAST**

reference temperature for determining test temperatures of structural materials

Note 1 to entry: LAST is used for structural steels but can also be used for other structural materials.

Note 2 to entry: For the purposes of this document, the concept of LAST presented in ISO 19902 for in air and in water is extended to include enclosed and/or heated zones.

3.42**lowest operational service temperature****LOST**

reference temperature for winterization

Note 1 to entry: LOST is a reference temperature used as a criterion for winterization of non-structural, non-critical systems, equipment, and materials and can vary by zone and position.

3.43**mat**

man-made weighted sheet structure used for the stabilization of soils or subsea components

3.44**material factor**

partial factor applied to the characteristic value of a material property

3.45**mudline cellar**

man-made areal excavation in the seabed used to protect subsea structures or equipment from damage due to ice actions

3.46

multi-year ice

MY ice

sea ice that has survived at least two summer melt seasons

3.47

old ice

sea ice that has survived at least one summer melt season

Note 1 to entry: Old ice includes both *second-year ice* (3.64) and *multi-year ice* (3.46).

3.48

pack ice

sea ice consisting of discrete *floes* (3.18) that is not landfast

3.49

pack ice driving actions

actions exerted by the surrounding sea ice on the structure or to an ice feature in contact with it

3.50

permafrost

ground (soil or rock) remaining at or below 0 °C for a duration of two years or more

3.51

polynya

area of open water surrounded by sea ice, caused by persistent winds, currents or upwelling of warm water

3.52

rafted ice

ice feature formed from the superposition of two or more ice layers of ice

3.53

recognized classification society

RCS

member of the International Association of Classification Societies (IACS), with recognized and relevant competence and experience relating to arctic and cold region structures or ice class vessels used in petroleum and natural gas activities

3.54

reliability target

specified average annual reliability to be achieved for structural components or structures

3.55

ridge keel

portion of an *ice ridge* (3.35) that extends below the waterline

Note 1 to entry: A ridge keel can consist of a *consolidated layer* (3.9) and an *unconsolidated layer* (3.70).

3.56

ridge sail

portion of an *ice ridge* (3.35) that extends above the waterline

3.57**rubble field**

region of ice blocks floating together as a continuous body, generally frozen together

3.58**rubble pile**

ice feature of areal, rather than linear, extent, composed of blocks of ice generally frozen together

Note 1 to entry: See also *stamukha* (3.66), the term for a grounded rubble pile.

3.59**safety-critical element**

equipment and other systems determined to be essential in preventing the occurrence of or mitigating the consequences of a major accident

3.60**scour**

removal of *seabed* (3.62) soils by currents and waves

3.61**sea floor**

interface between the sea and the *seabed* (3.62)

3.62**seabed**

material below the elevation of the *sea floor* (3.61) or ocean floor

3.63**seasonal operation**

operation of a structure during a selected period during the course of the year, generally to avoid particular ice conditions

3.64**second-year ice**

sea ice that has survived one summer melt season

3.65**shelf ice**

sea ice formed adjacent to a glacier terminating in the ocean

3.66**stamukha**

grounded ice feature composed of *broken ice* (3.6) or rubble

Note 1 to entry: The plural form of *stamukha* is *stamukhi*.

3.67**stationary floating system**

floating unit kept in position by moorings or *dynamic positioning* (3.15)

EXAMPLES: Ship-shaped vessels, spar, buoy-shaped platforms.

3.68

strudel scour

incision in the *seabed* (3.62) caused by a natural water jet draining through hole(s) in the ice

Note 1 to entry: Strudel scours are usually found in river deltas when freshwater flows on the surface of sea ice.

3.69

system ductility

ability of a structure to deform and dissipate energy which takes into account material *ductility* (3.13), the ability of structural components to maintain inelastic load-carrying capacity, and structural redundancy

3.70

unconsolidated layer

unconsolidated rubble layer

part of an *ice ridge* (3.35) keel or ice rubble found below the *consolidated layer* (3.9) that consists of unbonded or very weakly bonded ice blocks

4 Symbols and abbreviated terms

4.1 Symbols

A	accidental action
E	environmental action
f_c	concrete compressive strength
f_y	representative yield strength
G	permanent action
G_1	gravity and hydrostatic permanent action
G_2	deformation permanent action
Q	variable action
Q_1	long-duration variable action
Q_2	short-duration variable action
γ_s	steel resistance factor
γ_c	concrete resistance factor
η	concrete efficiency factor

4.2 Abbreviated terms

AL	abnormal-level
ALE	abnormal-level earthquake
ALIE	abnormal-level ice event
ALS	abnormal (accidental) limit state
CPT	cone penetrometer test

DP	dynamic positioning
EER	escape, evacuation and rescue
EL	extreme-level
ELE	extreme-level earthquake
ELIE	extreme-level ice event
FE	finite element
FLS	fatigue limit state
FPSO	floating production, storage and offloading facility
FY	first-year, with reference to ice
GBS	gravity-based structure
HPZ	high pressure zone
HSE	health, safety and environment
HVAC	heating, ventilating and air conditioning
IM	ice management
IMO	International Maritime Organization
L1, L2, L3	exposure levels of structures
LAST	lowest anticipated service temperature
LOST	lowest operational service temperature
MY	multi-year, with reference to ice
MIZ	marginal ice zone
NA	not applicable
ND	no data
NDT	non-destructive testing
QC	quality control
RCS	recognized classification society
SAL	single anchor loading
SALM	single anchor leg mooring
SLS	serviceability limit state
SPM	single point mooring
SSI	soil-structure interaction
TLP	tension leg platform
ULS	ultimate limit state
WMO	World Meteorological Organization

5 General requirements and conditions

5.1 Fundamental requirements

Offshore structures for use in arctic and cold regions shall be planned, designed, constructed, transported, installed, assessed in service and decommissioned in accordance with ISO 19900 supplemented by this document.

Physical environmental parameters shall be determined in accordance with ISO 19901-1, ISO 35106 and the further requirements of this document. Seismic events shall be characterized in accordance with ISO 19901-2. Marine soil investigations for characterization of the seabed soil conditions and for geohazard evaluation shall be performed in accordance with ISO 19901-4 and ISO 19901-8.

Actions, action effects and resistances for steel, concrete and floating systems shall be determined in accordance with ISO 19902, ISO 19903 and ISO 19904-1 respectively, and according to the further requirements of this document. Foundation behaviour shall be determined in accordance with ISO 19901-4. Requirements for marine operations, stationkeeping and topsides in arctic and cold regions are provided to complement the requirements of ISO 19901-6, ISO 19901-7 and ISO 19901-3 respectively. Seismic actions shall be determined in accordance with ISO 19901-2.

This document provides requirements, recommendations and guidance on ice-related parameters and ice actions for steel, concrete and floating systems, and for man-made islands. The above documents should be used jointly with this document to develop appropriate physical environmental parameters, actions, resistances and designs for structures in arctic and cold regions.

The structure and all its subsystems shall be designed to allow for operation in a safe and environmentally sound manner. Conditions associated with arctic and cold regions that can influence the functional and operational requirements shall be identified and addressed in the design. Design aspects influencing the health and safety of personnel and the state of the environment throughout the design service life shall be identified and addressed appropriately.

5.2 Design methods

For designs performed in accordance with the design process and limit states design verification procedure provided in this document, levels of safety and performance are established in Clause 7.

An alternative rational design method based on theory, analysis, and recognized engineering practice may be used in lieu of the design process and formulae provided in this document, provided that levels of safety and performance are at least equal to those established in Clause 7.

Where possible, data from full-scale measurements of ice actions shall be used to verify new designs. Physical models and mathematical models may also be used to determine the response of structures to ice actions, in combination with ocean current, wind and wave actions. If ice model tests are used in the design process, the designer is advised to seek independent verification of the results obtained as well as seek expert guidance regarding the most appropriate physical ice modelling techniques.

5.3 Site-specific considerations

5.3.1 Hazards

All hazards that can be reasonably foreseen during all phases of the design service life shall be identified and evaluated, see ISO 19900:2013, 5.6.

Identification, investigation and determination of site-specific conditions for sea ice and icebergs shall be made in accordance with ISO 35106, with due consideration to the phenomena and effects described in 6.5 and 8.2.

Hazards can also include low ambient temperature, icing conditions, snow and ice accumulation, ice encroachment and permafrost.

5.3.2 Climate change

Changes in storm frequency and magnitude, ice conditions, ocean circulation, air temperatures, permafrost, wave heights and water levels can occur during the design service life of the structure. Consideration for such changes should be included in the design.

For interpreting climate change effects on historical ice and metocean data, see ISO 35106.

5.3.3 Structural configuration

In addition to functionality, the configuration of the structure should consider the following:

- a) robustness in abnormal and accidental design situations;
- b) protection of risers and conductors;
- c) arrangement, protection and operation of the stationkeeping system;
- d) concept for oil storage and export;
- e) wet or dry storage system;
- f) layout of facilities and separation distances from hazards;
- g) potential for future expansion under phased development;
- h) potential for platform removal;
- i) environmental constraints;
- j) capability of local construction facilities and materials;
- k) available construction season for offshore operations;
- l) marine access, e.g. re-supply, offloading and, escape, evacuation and rescue (EER);
- m) arrangement of topsides with respect to icing and snow accretion.

Consideration should be given to choices for structural configuration (e.g. plan shape, profile) and orientation, with due account for ice conditions, prevailing wind and ice drift directions, and the potential for ice rubble build-up. The topsides should be arranged with respect to the functional and operational requirements, such as re-supply, offloading, flaring and EER, and with respect to wind and ice encroachment.

Operational measures can be used for reducing the frequency and/or severity of ice events and for mitigating ice action effects, see 5.5.

The reliability of EER, platform supply, and offloading systems can potentially be improved through:

- IM;
- methods to reduce ice rubble accumulation;
- use of large crane booms to reach over accumulated rubble; and
- duplication of facilities on opposite sides of the platform.

5.3.4 Winterization

5.3.4.1 Objective

Winterization is the process of ensuring that a structure is suitably prepared for and capable of operation in low-temperature conditions. The objective is to provide a safe working environment for personnel, and appropriate conditions for performance of materials and for functionality of systems and equipment.

The effects of temperature shall be accounted for in the selection of structural materials, machinery lubrication, sealants and topsides winterization. The effects of thermal changes on structural behaviour and human capability shall be considered as part of the design and operation of the structure.

Different low temperatures can apply for different positions in or on the structure. At each position there can be a temperature in each of three categories, see 5.3.4.2. The low temperature for each position shall be the lowest of those applicable for the transportation, installation, operation, and decommissioning phases of the life of the structure.

5.3.4.2 Low temperature categories

Low temperatures are specified in three categories of application as follows:

- a) extreme-level (EL) minimum temperatures; these temperatures apply for safety-critical equipment. EL is described in 7.2.2.6;
- b) lowest anticipated service temperature (LAST); these temperatures apply for structural materials, in particular for determining test temperatures for steel, see 11.9. In arctic and cold regions, LAST for each position shall be determined as the EL minimum temperature, except that LAST shall not be taken as warmer than -10°C for positions in air or exposed to sea ice.
- c) lowest operational service temperature (LOST); these temperatures are specified by the owner for winterization of non-structural, non-critical systems, equipment, and materials.

5.3.4.3 Low temperature zones

Low temperatures for each of the three low temperature categories can be considered at individual positions within three zones.

- a) In air (exposed). The low temperatures shall be determined from the ambient atmospheric air temperature at the location of the structure, see 6.3.1. The same value normally applies for the entire zone, but it can be specified to vary with height above sea level.
- b) In water and below the seabed. The low temperatures shall be determined from the ambient water temperature profile, see 6.4.4.4, and from shallow geotechnical investigation. Temperatures lower than the water temperature should be considered for positions near the water surface and exposed to sea ice. The possibility of permafrost below the seabed should be considered.
- c) Enclosed. The low temperatures for enclosed or internal structures which are permanently heated may be higher than for the in-air zone if risk assessment of heating systems and consequences of failure periods demonstrates adequate reliability of continued safe operation or standby. Localised cryogenic storage or other cooling conditions shall be taken into account.

Within each zone, the specified low temperatures at different positions can be different. If one single temperature value is intended to be used for a zone or an area within a zone with expected spatial temperature variations, the low temperature from the position with the lowest temperature shall be used for the entire zone or area.

5.3.4.4 Winterization measures

Winterization measures for topsides are provided in Clause 15.

Winterization measures should be considered to ensure the safe operation of all systems and equipment, thereby ensuring the safety of personnel. Winterization measures shall also ensure that personnel can conduct the required tasks in an ergonomically sound way, with respect to temperature, wind, visibility and restrictions imposed by personal protective equipment. Further guidance on winterization principles can be found in documents such as DNVGL-OS-A201^[36]. Further guidance on the working environment for personnel is provided in ISO 35101.

Selected options should not result in adverse environmental consequences, see 5.1.

Safety-critical equipment shall be documented to function as intended down to EL minimum temperature.

5.4 Construction, transportation and installation

5.4.1 General

The construction, transportation and installation of offshore structures shall be planned to minimize the risks to personnel and equipment due to adverse environmental conditions associated with cold regions.

5.4.2 Construction planning

The planning of construction activities shall include adequate consideration for periods of low ambient temperatures. Materials and equipment shall be adequately protected by the provision of heating or insulation.

5.4.3 Transportation and installation

Evaluation of draft limitations shall be performed for all regions through which the structure can be transported in order to reach its final destination.

Consideration shall be given to the specification of all marine spread equipment and the ability of personnel to safely perform the required transportation and installation activities during periods of low ambient temperature, low visibility and other relevant environmental conditions. Limiting environmental conditions shall be specified for all critical offshore activities, and the associated weather windows shall be included in the planning and execution of such work. Contingency planning for all critical offshore activities shall be included to ensure safe transportation and installation.

Marine operations associated with the transportation and installation of the structure shall be in accordance with ISO 19901-6.

5.5 Operational measures

If operational measures such as IM and, for floating systems, disconnection are planned with respect to prevailing or anticipated ice conditions and hazards, ice actions can be mitigated or the frequency of ice events can be reduced, see 8.2.7.

The implementation of an ice alert system, see 17.1.2, and emergency response plans for ice hazards, see 18.1, should be considered because of the uncertainties in ice events and actions, and especially if either or both of the following applies:

- a) operational procedures related to ice conditions and hazards are planned;
- b) very unlikely, high consequence ice events are reasonably foreseeable.

Very unlikely events have a lower probability than events for which a design situation is specified, see 7.1.5. Actions are calculated only if a design situation is specified, see 7.2.2.

5.6 Environmental protection

The environment in arctic and cold regions can be more sensitive and vulnerable to pollution than other environments. Structures intended for such environments shall be designed to minimize the potential for polluting the environment as far as is reasonably practicable.

A structure should be designed to contain spills that can result in release of contaminants to the environment. Structural systems requiring active operations to avoid pollution should be kept to a minimum. Harmful environmental impacts should also be minimized in the construction, transportation, installation and decommissioning phases.

Special attention should be given to containing fluids and materials used for commissioning in order to avoid potential harmful releases to the environment.

Fluids and materials that, if released, can pollute the environment shall be contained in tanks having double barriers. The structure shall be designed to facilitate environmental monitoring, which is addressed in ISO 35103. A protocol should be established for inspection, maintenance and repair of any tanks containing fluids or materials that possibly can pollute.

Means for the containment and clean-up of polluting fluids shall be available at the site and be proven to operate under the expected physical environmental conditions.

In the case of permafrost or freezing conditions, provision should be made to ensure the integrity of ballast tanks, and to avoid upheaval buckling of conductors and buried flowlines.

5.7 Serviceability requirements including vibration

In addition to normal serviceability requirements for structural design such as those described in 7.2.2.2, measures should be taken to ensure that structural vibration during normal operations does not cause crew discomfort.

5.8 Decommissioning and reclamation

The structure shall be planned, designed, constructed and maintained so that future decommissioning and/or reclamation can be completed safely and with adequate protection of the environment.

6 Physical environmental conditions

6.1 General

6.1.1 Physical environment requirements

General guidelines on metocean information are given in ISO 19900 and specific requirements in ISO 19901-1. Clause 6 of the present document outlines the physical environmental parameters necessary for arctic offshore structure design. ISO 35106 specifies requirements and provides recommendations and guidance for the collection, analysis and presentation of relevant physical environmental data for arctic activities, including design and operations. Operations include planning and execution.

All operating conditions and physical environmental design parameters of relevance for the design of offshore structures shall be identified and assessed. Data and analysis methods shall comply with the requirements of ISO 19901-1 and ISO 35106. These requirements can include a minimum duration of site-specific data, the type of data and a definition of extreme design parameters.

All relevant environmental data, as well as applicable physical, statistical, mathematical and numerical models, shall be applied as the basis for design. When considering these parameters, potential allowance should be made for a changing climate, see 5.3.2.

The following information shall be determined:

- a) normal environmental conditions that are required to carry out checks for serviceability limit states, to develop actions and action effects to determine when particular operations can safely take place, and to plan construction activities (fabrication, transportation and installation) or field operations (e.g. drilling, production, offloading, underwater activities);
- b) long-term distributions of physical environmental parameters, in the form of cumulative conditional or cumulative marginal statistics that are used to perform design checks for fatigue limit states or to

make evaluations of downtime/workability/operability during a certain period of time for the structure or for associated items of equipment;

- c) extreme and abnormal physical environmental parameters which are used to define design situations and which are required for developing extreme-level (EL) and abnormal-level (AL) environmental actions;
- d) joint probability distributions of relevant physical environmental parameters, for accurate specification of ice events and for determining action combinations;
- e) regional environmental oscillations, cycles, and long-term trends associated with the parameters in a) to c).

The relevant physical environmental parameters can be dependent on the chosen structural form.

Experts in the field of metocean and ice technology shall be involved with the analysis of data and its interpretation in order to ensure that reliable and appropriate physical environmental parameters are obtained. This includes parameters for identifying hazards and hazardous events for developing appropriate design situations, and for determining design values of principal and companion actions.

6.1.2 Physical environmental data monitoring programmes

Appropriate physical environmental parameters shall be monitored and forecast during the design service life of the structure to ensure safe operational procedures. For specific requirements, see ISO 35106.

6.2 Daylight hours

The varying amount of daylight hours in arctic regions is a consideration for initial data collection and for the operations of offshore facilities. Due consideration of the effect of this parameter shall be incorporated in operational planning.

6.3 Meteorology

6.3.1 Air temperature

Atmospheric air temperatures will vary both as a function of elevation above sea level and as a function of averaging interval. When considering effects of low atmospheric air temperatures, relevant elevation and averaging interval for the application in consideration shall be used.

Air temperatures for enclosed zones should be estimated based on atmospheric air temperature and the effect of enclosure and heating, with due consideration of risk of heating failure, heat flux and cool-down times before restart of heating.

Probability distributions of low air temperatures should be determined for zones and positions as needed for quantifying EL minimum air temperatures and other low temperatures for winterization, see 5.3.4. For estimation of EL minimum temperatures and LAST in exposed or enclosed areas, temperatures averaged over 3 hours shall be used as a basis.

6.3.2 Wind

Wind-related parameters shall be determined in accordance with ISO 19901-1. When calculating wind actions on structural elements, increase in dimensions, weight and change in the shape and surface roughness of the structure due to snow or ice accumulations shall be taken into account.

6.3.3 Wind chill

An appropriate measure of wind chill shall be calculated, reflecting the combined effects of air temperature, wind and potentially humidity. The effect of wind chill upon human capability, machinery heat loss and topsides winterization shall be considered.

For wind chill, the effects on working environment shall be determined according to ISO 35101 and data collection requirements shall be carried out according to ISO 35106.

6.3.4 Snow

Snow accretion shall be assessed in relation to action effects on offshore structures and in relation to safety-critical systems such as EER craft, escape and evacuation routes, ventilation and communication systems.

Estimates of snow accumulation can be obtained from observations on similar existing structures in the same area or from available theoretical models. When theoretical models are used, they shall be suitably calibrated against observations. Snow actions shall be determined based on local conditions (temperature, wind, structure, precipitation). In relation to safety-critical systems, any impact on performance thereof shall be assessed.

The joint effect of snow and ice accretion shall be considered.

General information and further requirements related to actions from snow are given in ISO 35106.

6.3.5 Ice accretion

The extent of ice accretion from sea spray (sea spray icing), freezing rain/sleet/snow or drizzle, freezing fog or cloud droplets (atmospheric icing) shall be considered in the design and operability of the structure.

Ice accretion shall be assessed in relation to action effects on structures and in relation to safety-critical systems such as EER craft, escape and evacuation routes, ventilation and communication systems.

In relation to safety-critical systems, any impact on performance thereof shall be assessed. Further requirements and general information related to actions from sea spray and atmospheric icing are given in ISO 35106.

6.3.6 Visibility

Information on factors affecting visibility (e.g. fog, blowing snow, daylight hours) particular to the site of the offshore structure shall be obtained. Its effect upon operations and physical environmental monitoring shall be considered.

6.3.7 Polar lows

When considering statistics from waves and winds, the effects of polar lows shall be taken into account. Data sources for winds and waves (recorded or hindcast) do not typically include the effects of polar lows.

When considering the frequency and occurrence of polar lows, allowance should be made for a changing climate, see 5.3.2.

6.4 Oceanography

6.4.1 Water depth

The water depth at the site, including its variation, shall be determined. The range of water levels and its effect on ice action location shall be used to determine the most adverse effect on the foundation or structural component under consideration. For shallower water depths, ice can ground around a structure and cause changes in ice design scenarios for the structure and transportation systems, create operational problems and affect EER procedures.

For the purpose of design or assessment, water depth can be considered to consist of a more or less stationary component relative to a reference datum (e.g. lowest astronomical tide or mean sea level) and a variable component being the variations in time relative to this level. The variations can be due to astronomical tide, storm surges caused by wind and atmospheric pressure, sea floor subsidence, tsunamis and climatic changes. The design implications of positive and negative storm surges should be considered in the specification of actions on the structure, in the operation of the structure and for vessel operations planning.

6.4.2 Waves

Wave parameters for open water shall be determined in accordance with ISO 19901-1.

Ice coverage on the sea surface affects wave growth, propagation and decay. The effect of ice cover should be considered when determining extreme and operational wave parameters, especially when numerical models are employed to determine these parameters.

The effect of increased speed and elevation of ice features due to waves shall be taken into account in determining the combined wave-ice actions upon the structure.

6.4.3 Ocean currents

Parameters related to currents, including tidal effects, shall be determined in accordance with ISO 19901-1.

6.4.4 Other oceanographic factors

6.4.4.1 Marine growth

Marine growth shall be determined in accordance with ISO 19901-1.

When calculating the effect of marine growth in ice covered regions, consideration should be given to local conditions and their effect on the periodic cleaning of marine growth on the parts of the structure exposed to ice. Increased marine growth near areas of warm water discharge should be considered.

6.4.4.2 Tsunamis

The design implications of tsunamis shall be determined in accordance with ISO 19901-1.

Consideration should be given to the effect of ice cover on tsunami wave parameters.

6.4.4.3 Dissolved oxygen

Higher dissolved oxygen content can be encountered in cold water regions. Since higher oxygen levels can enhance corrosion, local data should be collected to assess this hazard when relevant for the structural materials used.

6.4.4.4 Water temperature and salinity

The temperature at which water freezes is a function of water salinity. At normal ocean water salinity, considered to be 35 g/kg, water freezes at $-1,9^{\circ}\text{C}$. This shall be considered as the coldest water temperature that can be found in regions affected by sea ice. Water temperature profiles should be established from the water surface to the seabed.

Probability distributions of low water temperature profiles should be determined for positions as needed for quantifying EL minimum water temperatures and other low temperatures for winterization, see 5.3.4. EL minimum temperatures and LAST in water can be selected as the coldest monthly mean temperature minus 3.5 times the monthly temperature standard deviation.

6.5 Sea ice and icebergs

6.5.1 General

Information required to characterize site-specific ice criteria shall be determined for the location of the structure under consideration. This information should consider all phases of the structure's life, including transportation to and from the site.

Data should be obtained from direct observations at a location, interpretation of satellite imagery, or historical information at the geographic region of the structure, platform or facility. Where local ice data are unavailable or are not representative of relevant severe ice conditions, or where ice incursions are infrequent, data from nearby sites or geographical regions with similar ice environments may be used. Numerical or statistical modelling may be used to extend these data sets, with due account for

uncertainties. Long-term trends and provisions for a changing climate, see 5.3.2, shall be taken into account.

Interrelationships between the parameters listed in 6.5.2 to 6.5.5 and other physical environmental parameters should be considered, where relevant for the development of design criteria.

6.5.2 Ice types

The types of ice expected, i.e. first-year (FY), second-year, multi-year (MY), shelf or glacial, shall be determined. If a distinction cannot be made between second-year and MY ice, old ice can be specified. Statistics, such as probability distributions and parameters thereof, shall reflect the occurrence, concentration, dimensions, physical properties and mechanical properties of all relevant ice types.

Inter-annual and seasonal variations in the presence of ice types shall be considered.

6.5.3 Ice morphology

The occurrence and geometry of specific ice features, such as icebergs, ice islands, rafted ice, rubble fields, leads or polynya, pressure and shear ridges, stamukhi, landfast ice, pack ice, shelf ice and glacial ice, shall be determined on the basis of field measurements at the site or representative data from nearby sites. Statistics, such as probability distributions and parameters thereof, and appropriate ice feature frequency and dimensions shall be determined.

The occurrence of grounded ice features, such as grounded rubble piles and beach pile-ups, shall be determined to obtain appropriate ice feature frequency, extent, size, potential ice gouge depth and stability. This information shall be used in the determination of ice actions, design of flowlines and their burial depth, access to facilities, logistics, and evacuation systems.

The consolidated layer thickness of ridges, rubble fields and stamukhi shall be determined directly from regional data or estimated from data for other regions with suitable correction to local conditions.

Inter-annual and seasonal variations in ice morphology shall be considered.

6.5.4 Ice movement

Statistics of movement rates for pack ice, ice floes, floating ridges, rubble fields, icebergs, ice islands and landfast ice, where relevant, shall be determined on the basis of field data. The statistics can include probability distributions, means and extremes. If field data do not exist for these parameters, numerical modelling or analysis of the interaction of winds, waves, ocean currents and ice may be performed to obtain this information, with due account for uncertainties in the data and modelling procedures.

Inter-annual and seasonal variations in ice presence, polynyas and physical parameters shall be considered.

The areal density of ice features and the probability distribution of ice drift velocities should be estimated on a consistent basis with respect to the inclusion or exclusion of grounded ice features. Grounded features should be included for both areal density and ice drift or for neither of these parameters.

6.5.5 Ice properties

Appropriate mechanical and physical properties of ice shall be used for design and operational measures. The considerations of 8.2.8 shall apply.

6.5.6 Ice monitoring

Real-time information on ice conditions shall be included in the physical environmental data monitoring programme, for example, to operate IM systems and EER procedures for the platform or facility. See ISO 35106.

6.6 Seabed considerations

6.6.1 Earthquakes

The complexity of a seismic action evaluation and the associated design procedure for an arctic offshore structure depends on the structure's seismic risk category as determined in accordance with ISO 19901-2. Acceleration levels taken from the maps provided in ISO 19901-2 define the seismic zones, which can be used to determine the appropriate seismic design procedure. The selection of the procedure depends on the structure's exposure level as well as the severity of ground motion.

Where seismic events are a design concern, appropriate site-specific dynamic seabed-structure interaction analyses shall be carried out (see 9.10).

6.6.2 Permafrost

An investigation into the presence of permafrost shall be performed at platform locations and at any sites where structures make contact with the sea floor. Offshore structures founded on permafrost require special studies in order to understand the performance of the soil under time-varying actions induced by earthquakes, waves or sea ice. The potential effects of thaw consolidation of ice-rich permafrost as a result of production of warm hydrocarbons should be considered in the design of all structural foundations.

6.6.3 Ice gouge

Ice gouges occur due to the interaction of ice features such as ridges, icebergs, and stamukhi with the seabed. Data on ice gouges shall be obtained to determine the frequency of ice gouge occurrence as well as depth, width, length, and direction information of individual features. Ice gouge statistics shall be used for design in regions where the seabed is used for the laying and burial of flowlines and umbilicals, subsea facilities and platform tie-ins.

6.6.4 Strudel scours

Strudel scouring shall be investigated for structures and other facilities in regions near the mouths of rivers.

7 Reliability and limit states design

7.1 Design philosophy

7.1.1 Governing principles

The complete structure and its components including foundations shall be designed so that they function with adequate reliability for all physical environmental, accidental and operational actions and design situations to which the structure can be subjected during all phases of the life of the structure. These phases include construction, transportation, installation, service in place and decommissioning. The required reliability depends on the exposure level, see 7.1.4, which is determined by the life-safety category and the environmental and economic consequence category of the complete structure or component.

Design shall be in accordance with the limit states approach as specified in 7.2. This requires that action effects arising from design actions shall not cause the structure or its components including foundations to exceed the limits specified for the relevant limit state. Resistances and their relevant partial factors shall be determined in accordance with this document and its referenced documents. Actions shall include, but not be limited to, ice, seismic, oceanographic, meteorological, permanent and variable actions.

Hazardous events shall be defined and evaluated for the hazards identified in accordance with 5.3.1. Extreme and abnormal environmental events, see ISO 19900:2013, 7.1.6, shall each be considered as separate hazardous events. When considering a specific hazardous event, design situations shall be defined as described in ISO 19900:2013, 5.6. A typical design situation is generally dominated by one type of hazardous event with associated companion environmental conditions, and the design is verified for the relevant limit state. Partial factors for the action combination associated with ultimate limit states (ULS) and abnormal limit states (ALS) shall be in accordance with 7.2.4.

7.1.2 Life-safety categories

Life-safety category shall be determined in accordance with ISO 19900:2013, 6.2.

The life-safety category addresses the safety of personnel on the platform and the likelihood of successful evacuation before a design environmental event occurs.

7.1.3 Consequence categories

Consequence category shall be determined in accordance with ISO 19900:2013, 6.3.

The consequence category should also consider the potential risk to life of personnel brought in to respond to any incident, the potential risk of environmental damage and the potential risk of economic losses.

7.1.4 Exposure levels

Exposure level depends on the life-safety and consequence categories. Exposure levels shall be determined in accordance with the process set out in ISO 19900:2013, 6.4.

All manned, non-evacuated platforms and high-consequence platforms or structures are designated L1; unmanned, low-consequence platforms or structures are designated L3; other platforms or structures are designated L2.

NOTE Platform is defined in ISO 19900:2013.

Structural components of arctic and cold regions platforms or structures may be categorized differently from each other and from the overall platform or structure, if different life-safety and consequence categories are demonstrated, in which case their exposure level can be different.

7.1.5 Safety and reliability

Safety and reliability is addressed by design verification, supplemented by operational measures.

Design verification by the limit states design method is addressed in 7.2. Operational measures, see 5.5, can be a requirement of the design, reducing the EL and AL ice actions, and can mitigate risks arising from very unlikely events.

A design situation shall be defined for each EL ice action and AL ice action, and the structural design shall be verified. For very unlikely events, see 5.5, operational measures can be used to further mitigate life safety and other risks in accordance with the owner's risk management policy.

When deciding on which events require verification of the structural design, and which can be managed by operational measures alone, the uncertainties associated with low probability events shall be taken into account.

7.1.6 Limit states

Limit states are divided into four categories as described in this document, see 7.2.1.1, and in ISO 19900:2013, 7.1.

Due to the significance of AL ice actions in arctic and cold regions, this document places emphasis on the abnormal aspect of the ALS.

7.1.7 Alternative design methods

Alternative design methods may be used if the reliability of the structure and its components is shown to be equivalent to or better than that of the limit states design approach as set out in 7.2 and Table A.7-1.

7.2 Limit states design method

7.2.1 Limit states

7.2.1.1 Categories of limit states

The limit states are divided into the following four categories:

- a) ultimate limit states (ULS) — for strength and resistance to extreme-level actions, as described in 7.2.2.1;
- b) serviceability limit states (SLS) — for stiffness and adequate performance under normal functional use;
- c) fatigue limit states (FLS) — for adequate endurance for the accumulated effect of repetitive or cyclic action effects;
- d) abnormal (accidental) limit states (ALS) — for adequate reserve capacity and energy dissipation capability in situations of abnormal environmental and accidental events.

For the limit states design method, the reliability relevant to the exposure level is achieved through design verification to ultimate limit states (ULS) and abnormal limit states (ALS).

7.2.1.2 Ultimate limit states

The ULS requirement ensures that no significant structural damage occurs for actions with an acceptably low probability of being exceeded during the design service life of the structure. Significant damage is associated with impairment of structure function.

ULS design situations shall be based on environmental events which result in extreme-level environmental actions. For ice, both local and global actions shall be considered.

Representative resistances shall be factored by resistance factors to obtain the design resistances. Alternatively, the representative material properties shall be factored by material factors to obtain the design material properties.

Design procedures shall be based primarily on linear elastic methods of structural analysis. Some localized inelastic behaviour of the structure and its components is acceptable, for example, as permitted in Clause 11 for fixed steel structures and Clause 12 for fixed concrete structures. Structure interaction with foundation soils may be modelled non-linearly, considering non-linear elastic or plastic behaviour of the soil. Procedures and further provisions for floating systems are described in 13.4 and 13.5.

The safety for each ultimate limit state shall be verified by ensuring that the effect of combined factored actions does not exceed the factored resistance.

7.2.1.3 Serviceability limit states

Exceedance of SLS can result in the loss of capability of a structure to perform adequately under normal functional use. The structure shall satisfy serviceability limits for vibration and deflection, including limits for habitability and crew comfort.

The specification of actions and limits for SLS is generally the owner's responsibility. SLS shall also include considerations that can lead to long-term structural degradation, such as corrosion of reinforcement in concrete.

For SLS, the structure should satisfy the requirements of this document when structural members are subjected to localized ice damage. Examples include: concrete cracking and shrinkage, for which partial action factors are provided in ISO 19903; loss of concrete cover due to ice abrasion; removal of paint and removal of corroded steel due to ice abrasion; and localized damage due to vibration induced by ice and other physical environmental factors.

7.2.1.4 Fatigue limit states

Exceedance of FLS for offshore structures results from cumulative damage due to repeated actions. All actions over the design service life shall be considered, including the transportation phase to the site. For ice actions, cyclic variations are generally associated with compressive and flexural ice failure.

Fatigue analysis shall be based on a cumulative damage assessment in accordance with the relevant ISO document to ensure that the cumulative damage does not exceed the defined FLS.

7.2.1.5 Abnormal (accidental) limit states

The ALS requirement is intended to ensure that the structure and foundation have sufficient reserve strength, displacement or energy dissipation capacity to sustain large actions and other action effects in the inelastic region without complete loss of integrity.

ISO 19900:2013, 7.1.6 identifies two types of hazardous event related to ALS, namely accidental events and abnormal environmental events. Accidental events and accidental situations are described in ISO 19900. For abnormal environmental events, ALS design situations shall be based on events which result in abnormal-level environmental actions. For ice, both local and global actions shall be considered.

Partial factors for structure and foundation resistance, or overall safety factors, may be reduced from their ULS values or set to unity, as permitted by this document and its referenced documents.

The safety for each abnormal and accidental limit state shall be verified by ensuring that the effect of combined actions does not cause global failure or collapse of the structure or any of its vital parts.

7.2.2 Actions

7.2.2.1 General

Permanent actions (G), variable actions (Q), environmental actions (E), repetitive actions leading to fatigue, and accidental actions (A) are defined in ISO 19900. Further details on their specification are found in ISO 19902, ISO 19903 and ISO 19904-1.

For structures in arctic and cold regions, the design shall be based on EL and AL environmental actions for hazardous events arising from the relevant design situations. The environmental action shall comprise a principal action combined with relevant companion actions as described in 7.2.3.

Representative values shall be assigned to each EL and AL action. The main representative value is the characteristic value, which is a value associated with a prescribed probability of being exceeded by unfavourable values during a reference period, which is generally one year.

In arctic and cold regions, there can be additional accidental events that should be evaluated, such as ice-driven ship impacts on a structure.

7.2.2.2 Serviceability-level ice actions

Unless the owner has specified otherwise, the representative value of the serviceability-level ice action used for SLS shall be determined based on an annual probability of exceedance not greater than 10^{-1} .

7.2.2.3 Extreme-level ice actions

The representative value for the EL ice action shall be determined for each ULS design situation based on an annual probability of exceedance not greater than 10^{-2} .

The EL ice action is not applicable for hazardous events with an annual probability of occurrence of less than 10^{-2} .

Ice events associated with the EL ice action are termed extreme-level ice events (ELIE), see 8.2.3.

7.2.2.4 Abnormal-level ice actions

The representative value for the AL ice action shall be determined for each ALS design situation based on an annual probability of exceedance related to the exposure level. For L1 structures, this shall be determined based on an annual probability of exceedance not greater than 10^{-4} .

For L2 structures, the annual probability shall be not greater than 10^{-3} . AL ice actions need not be considered for L3 structures.

The AL ice action is not applicable for hazardous events with an annual probability of occurrence of less than 10^{-4} for L1 structures (10^{-3} for L2 structures). Further guidance is provided in A.7.2.2.

Ice events associated with the AL ice action are termed abnormal-level ice events (ALIE), see 8.2.3.

7.2.2.5 Dynamic ice actions

Dynamic amplification of ice actions shall be considered with respect to the structure and foundations, and the potential to cause soil liquefaction, see 8.2.1. If relevant, dynamic ice actions and ice-induced vibration shall be characterized with respect to design actions for the ULS and the ALS, and for action effects for the SLS and the FLS.

7.2.2.6 Other environmental actions

Representative values of actions for all other environmental events shall be determined at the extreme-level (EL), based on an annual probability of exceedance not greater than 10^{-2} , and at the abnormal-level (AL), based on an annual probability of exceedance not greater than 10^{-4} for L1 structures and 10^{-3} for L2 structures. It is not necessary to consider abnormal-level events for L3 structures. For seismic actions, the extreme-level earthquake (ELE) and abnormal-level earthquake (ALE) event probabilities shall be as specified in ISO 19901-2.

Effects due to temperature differences within the structure or component are to be considered in all relevant limit states.

7.2.2.7 Accidental actions

Actions arising from accidental situations shall be addressed in accordance with ISO 19902, ISO 19903 and ISO 19904-1 depending on the structure type. Accidental situations are defined in ISO 19900.

7.2.3 Principal and companion environmental actions

Environmental action combinations for each environmental design situation shall consist of the principal action accompanied by companion environmental actions. The principal action is the action arising from the hazardous event that defines the design situation, such as the EL ice action or AL ice action for ice events. Alternatively, the joint probability of environmental actions may be used, see below.

Potential combinations of principal and companion environmental actions are given in Table 7-1. Companion environmental actions additional to those listed should be considered based on site-specific conditions.

The effect of varying water levels, see 6.4.1, shall be considered in the calculation of principal actions and in the specification of companion actions. The wind-driven component of storm surge should be considered as stochastically dependent on the wind if the principal action depends on the wind. Tidal elevations should be considered as stochastically dependent on the current where the principal action depends on tidal currents.

Where site-specific data are available, the joint probability distribution of the principal and relevant companion actions should be used to determine the magnitude of the combined EL or AL environmental action.

Table 7-1 — Companion EL environmental actions

Principal action (EL or AL)	Companion EL environmental action		
	Stochastically dependent	Stochastically independent	Mutually exclusive
Waves	Wind, wind-driven current	Tidal and background current	Sea ice (for ice concentration $\geq 8/10$)
Waves	Wind, wind-driven current, ice (for ice concentration $< 4/10$)	Sea ice (for ice concentration $< 8/10$)	—
Swell	—	Waves, wind, wind-driven current, tidal and background current, sea ice (for ice concentration $< 8/10$)	Sea ice (for ice concentration $\geq 8/10$)
Tsunami	—	Waves, wind, wind-driven current, tidal and background current, sea ice	—
Wind	Waves, wind-driven current, sea ice	Swell, tidal and background current	—
Wind	Wind-driven current, sea ice	Tidal and background current	Waves, swell (for ice concentration $\geq 8/10$)
Current (tidal and background)	Sea ice	Waves, swell, wind, wind- driven current	Waves, swell (for ice concentration $\geq 8/10$)
Current (wind-driven)	Sea ice, waves, wind	Swell, tidal and background current	Waves, swell (for ice concentration $\geq 8/10$)
Sea ice	Wind, wind-driven current, tidal current	—	Waves, swell (for ice concentration $\geq 8/10$)
Sea ice	Wind, wind-driven current, tidal current, waves (for $< 4/10$ sea ice concentration)	Waves, swell (for ice concentration $< 8/10$)	—
Earthquake ^a	—	Waves, swell, wind, wind- driven current, tidal and background current, persistent ice cover	—
Large icebergs or other large ice features	Wind, wind-driven current, tidal and background current	Waves ^b , swell ^c	—
Isolated ice features (e.g. ice floes, ridge fragments, stamukhi, bergy bits, small icebergs)	Wind, wind-driven current, tidal and background current, waves ^b	Waves ^b	—
Snow	—	Wind, waves, current, sea ice, icebergs ^c	—
Ice accumulation (including icing and ice accretion)	Wind, waves ^c	Wind, waves, current, sea ice ^c	—

^a For the AL earthquake, it is normally sufficient to consider only ice likely to be present when an earthquake occurs.

^b The principal action from small icebergs or ice floes and the companion wave actions can be stochastically dependent.

^c Categorisation of companion actions for snow and icing should be assessed for site-specific conditions.

In the absence of specific consideration of joint probability distributions, other applicable statistical techniques may be used to estimate combination factors that capture site-specific correlations between the principal and the companion actions.

In the absence of site-specific data and in the absence of statistical modelling and analysis, the combination factors provided for companion environmental actions in Table 7-2 may be used. In this approach, the representative EL value of each relevant companion action shall be multiplied by the relevant factor from Table 7-2 and added to the EL or AL value of the principal action as determined by the design situation. The values specified in Table 7-2 are conservative to account for significant correlations between companion and principal actions.

Further considerations for floating systems are provided in 13.4.

Table 7-2 — Combination factors for companion EL environmental processes

Principal action	Factor for representative EL companion environmental action	
	Companion action is stochastically dependent on the principal action	Companion action is stochastically independent of the principal action
EL action	0,9	0,6
AL action	0,5	0,4

7.2.4 Combinations of actions and partial action factors

The limit states action combinations specified in Table 7-3 shall be used in design. For each action combination, the design action shall be calculated as follows:

- the representative value of a combined environmental action, E , or accidental action, A , shall be multiplied by a partial action factor not less than that specified in Table 7-3;
- representative values of permanent and variable actions shall be multiplied by partial action factors which either shall be not less than specified in Table 7-3 or shall be taken from ISO 19902, ISO 19903 or ISO 19904-1 for the respective structure types.

These partial action factors apply to both local and global actions. ISO 19900 provides further information on the classification of types of action.

The combination of actions and the partial action factors for earthquakes shall be in accordance with ISO 19902 for fixed steel structures and in accordance with ISO 19903 for fixed concrete structures. Further guidance is provided in 8.4.

Partial action factors and action combinations for SLS and FLS shall be in accordance with ISO 19902, ISO 19903 or ISO 19904-1 as relevant to the structure type.

Action combination 1 shall include checks for design situations both with and without environmental action, E .

For design situations where an EL action is the principal action, the action effects shall be checked for ULS (action combinations 1 and 2 in Table 7-3), except that in the damaged condition they shall be checked for action combination 3 only.

For design situations where an AL environmental action or accidental action is the principal action, the action effects shall be checked for ALS only (action combinations 4 and 5 in Table 7-3).

The partial action factors for environmental actions other than earthquakes specified in Table 7-3 have been calibrated to the reliability targets given in Table A.7-1. When these partial action factors are applied to ULS and ALS action combinations for arctic offshore structures and their components, including foundations within the scope of this document of exposure levels L1 and L2, the reliability targets given in Table A.7-1 are deemed to be achieved. Further considerations for floating systems are provided in 13.4.4.

As an alternative to Table 7-3, partial action factors may be derived using a calibration procedure, such as the one described in A.7.2.4, involving a full probabilistic description of actions and resistance, and a demonstration that the reliability targets of Table A.7-1 are met.

Table 7-3 — ULS and ALS partial action factors and action combinations

Action combination		Limit states partial action factors						Accidental action <i>A</i>
		Permanent action <i>G</i>		Variable action <i>Q</i>		Environmental action <i>E</i>		
		Gravity and hydrostatic (Dead) <i>G</i> ₁	Deformation <i>G</i> ₂	Long duration <i>Q</i> ₁	Short duration <i>Q</i> ₂	EL	AL	
Ultimate limit states								
1	Gravity and deformation — long and short duration	1,30 ^a or 0,90 ^b	1,00	1,50 ^a	1,50 ^a	0,70 ^c or 0 ^b	—	—
2	Extreme environmental	1,10 or 0,90 ^b	1,00	1,10 or 0,80 ^b	—	1,35 (L1) ^{c,d} 1,10 (L2) ^{c,d,e}	—	—
3	Damaged condition ^f	1,10 or 0,90 ^b	1,00	1,10 or 0,80 ^b	—	1,00	—	—
Abnormal (accidental) limit states								
4	Abnormal environmental	1,00	1,00	1,00	—	—	1,00 ^c	—
5	Accidental	1,00	1,00	1,00	—	—	—	1,00

^a For the gravity and deformation action combination, a partial action factor of 1,20 may be used for permanent hydrostatic pressure and for physically limited variable actions.

^b The lower partial action factor applies for permanent *G*₁ actions when the permanent action resists overturning or uplift, for variable *Q*₁ actions when there is a reversal of variable action effects, and for environmental actions *E* if this produces a more unfavourable total design action effect.

^c The representative value of the environmental action to which the partial action factor applies shall be calculated as the combination of a principal action and appropriate companion actions, as described in 7.2.3.

^d The limit states partial action factor for actions arising from the ELE shall be as defined in ISO 19902 for steel structures and in ISO 19903 for concrete structures, and 1,0 for all other structures.

^e For L2 exposure level, all partial action factors for all action combinations are as for L1 except for the EL factor in the extreme environmental action combination.

^f Damaged condition or progressive collapse limit states are defined generally for structures in ISO 19900 and for particular types of structures in ISO 19902, ISO 19903 and ISO 19904-1.

8 Events and actions

8.1 General

The events and actions used for design shall consider all phases of the life of the structure, including construction (fabrication, transportation, and installation), service in place, and decommissioning. Specific consideration shall be given to the local physical environment for structures in arctic and cold regions.

Actions can be classified as described in ISO 19900:2013, 8.2.1. The classification includes:

- permanent actions;
- variable actions;
- environmental actions;
- accidental actions;
- repetitive actions.

Hazards shall be taken into account in accordance with 7.1.1 and ISO 19900:2013, 5.6. Hazardous events can include extreme environmental events, accidental events and abnormal environmental events.

Metoccean events such as wave events, wind events and ocean current events are considered in ISO 19901-1. Seismic events and actions are considered in ISO 19901-2. Actions arising from these events are considered in ISO 19902, ISO 19903 and ISO 19904-1. Provisions for the treatment of ice actions and their combination with other types of actions are given in 7.2.3 with the further requirements of Clause 8.

The design of arctic offshore structures shall include consideration of global ice actions relating to the overall integrity of the complete structure and its components, including, if relevant, foundation and stationkeeping system, and local ice actions for specific components or portions of the structure.

Allowance for possible weight increase and changes in the centre of gravity of a platform due to ice accretion during fitting out (if performed in arctic or cold regions) and transportation shall be considered. The allowance shall reflect the time of year and geographical area.

Differential strains or lock-in stresses due to temperature changes between construction and permanent locations shall be considered in the design.

8.2 Ice events and actions

8.2.1 General principles for calculating ice actions

Structures or components subjected to ice events shall be designed for ice actions with annual probabilities as specified in 7.2.2, appropriate to the limit state and exposure level. In the absence of data to quantify the potential for ice events, ice actions shall be assessed if there is a reasonable probability of interaction. All reasonably foreseeable interaction scenarios with potentially adverse consequences should be considered in this respect. Reference should also be made to 8.3.2 for wave-induced ice motion.

Direct ice actions and actions arising from the interaction between the ice and the structure shall be considered for both global and local actions. Such actions can include:

- a) static, quasi-static, cyclic and dynamic actions (EL and AL);
- b) cyclic and dynamic actions that can cause structural fatigue, soil liquefaction and personnel discomfort; and
- c) spatial events such as ice rubbing, pile-up, ride-up and other ice mechanisms that can hinder operations.

Global ice actions and their point of action shall be determined in accordance with 8.2.4 so that the integrity of the structure can be assessed. This includes resistance to sliding and overturning, capacity of the foundation, fatigue and foundation liquefaction. Local actions shall be considered in accordance with 8.2.5.

Methods based on full-scale action and response data from measurements on instrumented structures shall be used for the determination of representative ice actions on offshore structures, with due account of their applicability, and of the uncertainties in the data and the methods used in their interpretation. Where no data are available at the location of interest, measurements from other regions may be extrapolated using knowledge of the ice regimes, metocean aspects, climate, brine volume, ice strength and other relevant physical properties of ice. Small-scale ice strength data obtained locally, preferably in situ, can be of assistance in the extrapolation. Physically-based models and scale model tests may be used to complement the full-scale data, with due account of uncertainties in their application.

Further requirements relating to ice actions are found in 10.3 for man-made islands, in 13.4 for floating systems and in 14.3 for subsea structures.

8.2.2 Representative values of ice actions

The design shall be carried out for EL ice actions and AL ice actions, as specified in 7.2.2.3 and 7.2.2.4.

Representative values of ice actions shall be calculated using probabilistic methods or deterministic methods for the ice parameters relevant to the event.

8.2.3 Ice events and design situations

Ice events shall reflect:

- the relevant ice scenario, limiting mechanisms and ice failure modes for the geographical location of the structure, with reference to the provisions of 8.2.4, 8.2.5, 8.2.6 and 8.2.8; and
- the structural configuration and the relevant operational scenarios, including seasonal operation, ice detection, physical IM, manoeuvring of the structure and disconnection, with reference to the provisions of 8.2.7.

Ice actions are estimated for all ice events, from which the EL and AL ice actions are identified, when required by 7.2.2.3 and 7.2.2.4. The events associated with the EL and AL ice actions are termed ELIE and ALIE, which can involve the conditions listed above and the associated parameters. ELIE and ALIE can be used to conduct quality checks for calculated EL and AL ice actions if probabilistic methods are used, or

to directly estimate EL and AL ice actions if deterministic methods are used. When several ice and operational scenarios are relevant for a particular structure, those resulting in the largest ice actions for each design situation shall be considered in the design.

Where applicable, ice scenarios for consideration shall include structures interacting with:

- a) FY ice features (level ice, rafted ice, landfast ice, floes, ridges, rubble fields, refloated stamukhi);
- b) old ice features, including second-year and MY ice features (level ice, floes, ridges, rubble or hummock fields);
- c) icebergs; and
- d) ice islands (ice shelf fragments).

Metocean and ice information provided in Annex B can be used to assist with the development of ice scenarios. The relative importance of potential ice scenarios and ice events shall be determined based on the structural configuration and relevant operational scenarios.

Other types of event can occur with companion actions as described in 7.2.3. Subsidiary conditions that can act in combination with the ice features or can influence the nature of the interaction include:

- seasonality;
- ocean currents, including tidal effects;
- wind;
- waves;
- water depth.

8.2.4 Global ice actions

The determination of global ice actions shall be based on methods that incorporate relevant full-scale measurements, model experiments if they can be scaled reliably (see also 16.5), or theoretical methods (analytical or numerical) that have been calibrated using experiments or full-scale measurements. Each of the following conditions shall be considered, and the governing ones shall be used to determine ice actions:

- a) quasi-static actions due to level ice (FY, rafted, or old ice), where inertial action effects within the structure can be neglected;
- b) dynamic actions due to level ice (FY, rafted, or old ice), where inertial action effects within the structure are influential and a dynamic analysis is required;
- c) quasi-static actions due to ice rubble and ridges, where inertial action effects within the structure can be neglected;
- d) impacts from discrete features such as icebergs, ice islands and large old ice or FY ice features;

- e) quasi-static actions from features lodged against the structure, driven by the surrounding ice or directly by metocean actions;
- f) adfreeze action effects, including the frozen-in condition; and
- g) thermal action effects;

The following limiting processes shall be considered.

- 1) Limit stress, which is the process that occurs when there is sufficient energy or driving force to envelop the structure and generate ice actions across its total width. Limit stress actions are governed by local ice failure against the structure, accounting for the presence of any ice rubble.
- 2) Limit energy, which is the process that occurs when the interaction is limited by the kinetic energy of the ice feature. Such actions are likely to arise due to impacts of icebergs, refloated stamukhi, thick ice floes or ice islands. Such features can either occur in open water or be surrounded by pack ice.
- 3) Limit force, which is the process that occurs when the interacting feature is driven against the structure by metocean actions, and the actions are insufficient for the ice to fail locally and envelop the structure. Such actions are likely to arise where large ice features interact with a structure under the action of wind, current or pack ice pressures, or a combination of these actions.

Ice crushing, shear, flexure, splitting and buckling failure modes should be considered in the calculation of global actions for each of the above limiting processes. Where relevant for the scenario, ice conditions and limiting processes, the following factors shall be considered in determining ice actions:

- event frequency;
- geometry of the ice or ice features;
- geometry of the structure;
- mass and added mass of the ice feature and structure;
- mechanical properties of the ice or ice feature;
- adfreeze bond between ice and the structure;
- inertial effects (and added inertia) for both the ice and the structure;
- velocity and direction of movement of the ice features;
- pressured ice conditions;
- ice rubble build-up, and implications for ice encroachment, structure freeboard requirements and actions transmitted to the structure;
- clearing of ice around the structure;
- ice jamming between the members of a multi-leg structure;
- compliance and damping of the structure and stationkeeping system;

- dynamic and hydrodynamic effects;
- degree of contact between the ice and the structure;
- friction between the ice and the structure;
- ice-on-ice friction;
- thermal effects in the ice;
- environmental actions of wind, current and pack ice pressure available to drive the ice, and their persistence;
- surface morphology and the presence of snow on the ice; and
- influence of shoals and other barriers.

8.2.5 Local ice actions

Local ice actions shall be based on relevant full-scale measurements or established theoretical methods. Due account shall be taken of geographical differences and water level changes in their specification.

Local ice actions shall be considered for all parts of the structure contributing to its overall integrity and stability, or for which damage can lead to progressive failure as required in 7.2.2.3 and 7.2.2.4. For steel structures, local actions shall apply to the design of sheet piling, plates, stiffeners, frames and bulkheads. For concrete structures, local actions shall be considered for wall thickness, steel reinforcement and abrasion (see Clause 12). Regardless of structural material, local actions shall be applied to corners, structural discontinuities and appendages where these contribute to overall structural integrity.

Design contact areas shall be considered based on the local structural configuration, including, for example, frame spacing, plate thickness and appendage dimensions. The dimensions and placement of the local contact areas shall be selected to ensure that the most critical cases are addressed.

Ice encroachment can impede access to parts of the structure or generate local actions on parts of structure without impeding its overall integrity and stability. Ice encroachment shall be considered in the determination of local actions on parts of structures and mitigation measures.

Local ice actions shall be considered in the context of background actions on adjacent panels or areas of the structure.

8.2.6 Dynamic ice actions

The time-varying nature of ice actions and the corresponding ice-induced vibration shall be considered in the design. The potential for dynamic amplification of the action effects due to lock-in of ice failure and natural frequencies shall be assessed. Particular attention shall be given to dynamic actions on narrow structures, flexible structures and structures with vertical faces exposed to ice action.

Structural fatigue and foundation failure as a consequence of dynamic ice actions shall be considered.

8.2.7 Operational measures to reduce ice actions

Operational measures may be used to mitigate ice actions and action effects on fixed, floating and subsea structures provided the structural reliability is verified to be adequate over the design service life, in accordance with Clause 7. Operational procedures can include physical IM, disconnection and removal, clearing of ice accumulations, installation of rubble and spray-ice barriers (see 16.3), and seasonal operation.

Operational measures used to reduce ice actions and action effects shall be applied in the context of an ice alert system, involving mandatory responses (including shut-in and move-off for floating systems) to specified ice scenarios and possible hazardous events (see 17.1.2 for general provisions, and 13.2.4 for floating systems specifically). For IM operations, the requirements of Clause 17 and ISO 35104 shall be satisfied to ensure that ice hazards are identified, threats are assessed correctly, the ice regime is altered appropriately, and other operations are undertaken successfully. Data requirements shall satisfy ISO 35106. Additional requirements for floating systems are given in Clause 13.

Mitigation of ice actions shall be demonstrated through changes to the magnitude and frequency of ice actions for all applicable ice scenarios and ice events. The effectiveness of operational measures shall be based on documented experience and personnel qualifications, and the approach shall reflect the uncertainty inherent in the input data and modelling techniques.

When operational procedures are invoked according to 8.2.7, design and operational requirements should be developed and verified together to ensure that the requirements of Clause 7 are satisfied.

8.2.8 Physical and mechanical properties of ice

Appropriate physical and mechanical properties of ice shall be used in the calculation of ice actions. The following provisions apply.

- Ice properties shall be appropriate to the geographical location and season under consideration.
- Appropriate full-scale test data shall be used, when available, with due account of their applicability.
- Ice property tests should follow accepted practice (see A.8.2.8).
- When reliable methods exist to predict the mechanical properties from physical properties, these may be used.
- Small-scale field and laboratory test data should be used with caution.

The following physical and mechanical parameters can be used in adjusting and interpreting full-scale ice load data for the calculation of ice actions:

- a) compressive and shear strength;
- b) flexural strength;
- c) tensile strength;
- d) fracture toughness;

- e) friction;
- f) adfreeze strength;
- g) internal cohesion and friction of fragmented ice;
- h) elastic modulus; and
- i) density.

8.3 Metocean related actions

8.3.1 Metocean actions on structures

8.3.1.1 General

Procedures for determining actions and action effects caused by metocean conditions for different types of structure shall be in accordance with the relevant structure-specific International Standard on offshore structures prepared by TC 67/ SC 7.

Additional metocean requirements are provided in 8.3 for structures located in arctic and cold regions. These requirements fall in three categories:

- a) effects of snow and ice accumulation on the structure, its members and decks above the waterline;
- b) particular structure types and shapes employed in such environments;
- c) wave-induced local ice loading.

8.3.1.2 Snow accumulation on the structure

The expected effects of snow accumulation upon the topsides shall be accounted for in the ULS and ALS analyses of the structure. Snow accumulation can modify the aerodynamic and hydrodynamic properties and dynamic response of the structure and its parts.

Snow accumulation is not necessarily evenly distributed on the topsides. Differential snow accumulation on the topsides can also modify the buoyancy and stability of floating structures.

8.3.1.3 Ice accumulation on the structure

8.3.1.3.1 General

The expected effects of ice accumulation, including icing and ice accretion, shall be accounted for in the ULS and ALS analyses of the structure. Icing of structures or structural members can result from fog, freezing rain, wet snow, green water trapped on decks, wind- and wave-driven seawater spray, or tidal variation. Icing modifies the aerodynamic and hydrodynamic properties, static stability and dynamic responses of the structure. Icing can also modify the buoyancy and stability of floating structures.

Icing can be measured in terms of the thickness, volume or mass of ice adhering to the structure. Such estimates can be obtained from observations of icing on similar existing structures in the same area or from available theoretical models. When theoretical models are used, they should be suitably calibrated against observations.

8.3.1.3.2 Wave and current actions

The effect of icing on wave and current actions shall be determined. Icing can increase the wave and current actions on structural components within the splash zone of a structure due to changes in projected area, volume and surface roughness.

Accumulation of ice on a structure can cause large increases in projected area and volume around and above the mean waterline. It can also make circular cylinders effectively rough. Where these effects are present in the design situation, they should be accounted for in the areas, volumes and drag coefficients used in the calculation of environmental actions. Any of these effects can cause large action increases on a member above that in the absence of ice. Advice on the selection of drag coefficients for the Morison equation is given in ISO 19902. Advice on the use of diffraction analysis for large volume structures is given in ISO 19903, ISO 19904-1 and ISO 19902. Where computational fluid dynamics are used, the method should be verified against good quality model tests.

8.3.1.3.3 Wind actions

Wind actions shall reflect the presence of icing. The effect of icing on drag actions due to wind shall be analysed in the same way as Morison drag actions due to waves and currents are treated in 8.3.1.3.2.

8.3.1.3.4 Dynamic and static responses

Icing can affect the dynamic and static responses of structural members, appurtenances and complete structural systems and, consequently, the following factors shall be considered.

- a) Calculation of actions exciting dynamic response shall be modified to account for ice accumulation on the structure.
- b) Strouhal numbers for the assessment of vortex-induced vibration of members shall be similarly modified.
- c) Masses of members and systems and any added masses shall be adjusted in accordance with the icing. Consequences for additional vertical actions, stability, static position, reductions of structure freeboard and righting moments of floaters shall also be considered.

8.3.1.4 Particular considerations for large volume structures

The non-linear effects that control water surface elevation beneath a structure standing on large columns are not easily treated theoretically. In the case of fixed arctic offshore structures, wave focusing due to the presence of large caissons and/or earth mounds can further complicate the wave-structure interaction. Model testing should be carried out to assess the required air gap under the deck of a platform.

The effect of the shape of the structure shall be taken into account for determining the extent of wave actions. This can be particularly significant for structures with sloping faces and conical forms.

8.3.1.5 Freeboard and deck elevation

Deck elevations, structure freeboard and bow wall or ice deflector height shall account for the wave-induced vertical motion of the water surface and incident ice features. Account shall be taken of ice accumulations on the structure, the underside of the topsides deck or the substructure. The routing of all risers, caissons, J-tubes and other appurtenances shall minimize the risk of impact by such ice features. Further guidance is provided in 15.1.1.3.

Non-linear wave-structure interaction tends to increase water surface elevations around the structure. Consequently, ice can impact the structure and topsides at levels higher than most numerical schemes predict. The area of ice strengthening shall take this into account.

8.3.2 Wave-induced velocity of ice features

Velocities of ice features impacting a structure shall be determined from the incident wind, wave and current. Presence of the structure can significantly modify the fluid velocity field around it and hence the velocities of ice features. Methods to estimate the velocities depend on the ratio of the wavelength of the incident wave to the dimensions of the ice and the structure. For floating structures, the relative velocity can be important. Field measurements should also be used if available.

Slopes and changes in water depth, both natural and due to structure geometry, can focus and steepen incident waves through refraction, thereby increasing velocities at the water surface. If the tops of underwater mounds or caissons are less than half a wavelength below the free surface, the possibility of their influence shall be taken into account.

NOTE Small ice features can impact structures with an accelerated velocity due to breaking or near-breaking waves. Such situations can also arise in cases of shallow water near shore due to shoaling waves. In addition, these situations can arise for gently sloping structures such as man-made islands and extended berms.

8.4 Seismic actions

8.4.1 General

Offshore structures in arctic and cold regions shall be designed for ELE and ALE in accordance with the provisions of ISO 19901-2. In addition, steel structures shall comply with ISO 19902 and concrete structures shall comply with ISO 19903.

This document contains specific provisions for seismic actions and effects for foundations in 9.10, for man-made islands in 10.4, for steel structures in 11.7, for concrete structures in 12.3.6, for subsea structures in 14.4 and for topsides in 15.3.

Ice and seismic events may be considered as stochastically independent. The combination of ice and seismic events should be made through an assessment of their joint probability, in which the duration of events is reflected.

8.4.2 Companion seismic actions

Probabilities associated with the simultaneous occurrence of extreme-level and abnormal-level ice actions of short duration and seismic actions can be very low. In such cases, it is not necessary to consider companion seismic actions for EL and AL ice actions.

8.4.3 Companion ice actions

When offshore structures in arctic and cold regions are designed for extreme-level earthquakes (ELE) and abnormal-level earthquakes (ALE), appropriate companion ice actions shall be included.

There is a very low probability for the simultaneous occurrence of extreme- or abnormal-level seismic events and ice events of short duration. Accordingly, the specification of companion ice actions is likely to involve ice conditions of long duration only. The companion actions provided in Table 7-1 may be disregarded when the joint probability of seismic and ice events has been established.

8.4.4 Factors influencing seismic actions and effects

The speed of the ice relative to the structure shall be considered in the specification of companion ice actions.

Ice accretion, landfast ice and/or grounded ice rubble adhering to the structure shall be considered when calculating the mass of the structure used for seismic analyses. The local restraint can result in changes to the natural modes of the system, and potentially induce large local and global actions.

The presence of a surrounding ice sheet shall be considered in the calculation of hydrodynamic added mass.

If liquefaction of soil can occur, this shall be included in the analysis. This analysis shall take into account possible warming of the soil due to changes in climate and due to local heating from oil and gas production.

8.4.5 Seismic isolation and damping systems

Seismic isolation and damping systems may be used for arctic offshore structures to meet the requirements of this document, provided they are designed to operate reliably under the expected environmental conditions. Further requirements for seismic isolation and damping systems are provided in 15.3.5.

9 Foundation design

9.1 General

The reliability of foundations for structures in arctic and cold regions requires consideration of factors additional to those usually addressed in offshore geotechnical practice. The ice-loading environment can be such that high horizontal actions can occur. Depending on the shape of the structure, these high actions can be eccentric and cyclic with magnitudes, frequencies and durations of loading that are different from

those caused by other environmental conditions such as waves and earthquakes. These same ice action conditions and resulting action combinations can result in structural forms different from those that are designed for temperate waters, so that the experience base for overall performance of arctic offshore structure foundations can be limited.

Stability of frozen soils through the life of the structure shall be considered. Climate (past and present) has resulted in the occurrence of widespread permafrost even in deep water in some arctic and cold regions. Identification and characterization of permafrost becomes a particular task of the soils investigation and can require specific sampling procedures and expertise. Hydrocarbon exploration and production activities, as well as installation and operation of structures, can result in permanent or cyclic thermal changes to permafrost. Lower ground temperatures also increase the probability of the presence of frozen gas hydrates at relatively shallow depths in cold climates.

Furthermore, soils in cold regions are likely to have been affected by glacial episodes in recent geological history. There can, therefore, be a greater likelihood of the occurrence of boulders and gravels in certain geological environments. Current geological processes, such as ice gouging of the seabed by moving ice keels, can change sea floor topography and can affect the properties of soils and the actions imposed on buried structural components and flowlines.

Quick clays, or highly sensitive clays, can be encountered in certain nearshore arctic locations. A characteristic of quick clays is a natural moisture content that is considerably in excess of the liquid limit, as a result of which the soil possesses negligible remoulded shear strength.

9.2 Geotechnical data acquisition and identification of hazards

9.2.1 General

Marine site investigations shall be performed for all offshore structures in arctic and cold regions. The purpose of the investigation shall be to provide relevant bathymetric, geophysical and geotechnical data necessary to characterize the site conditions and for the determination of representative material properties. The investigation shall be performed utilizing the skills of professional personnel in the fields of geology, geophysics, cold regions engineering, seismology and geotechnics, and should include an evaluation of all relevant existing data.

ISO 19901-4 provides guidance on methods of investigation. ISO 19901-8 specifies requirements and provides recommendations for marine soil investigations. ISO 35106 describes data requirements to support arctic operations, which overlap the data needs for design, and should be considered in planning the geotechnical data acquisition program.

Soil studies in arctic and cold regions require additional data gathering to ensure that the structure foundation can be adequately designed, especially in terms of dynamic soil properties. This includes special geophysical as well as geotechnical studies.

Investigations shall consider both far-field and near-field seabed conditions.

9.2.2 Marine soil investigations

In addition to the provisions of ISO 19901-4 and ISO 19901-8, soil investigations in arctic and cold regions should determine the impact of the following on the design of the structure:

- presence of ice gouges;
- presence of boulders and boulder beds;
- permafrost;
- strudel scours;
- over-pressurized geological strata; and
- gas hydrates.

The geotechnical investigation programme shall be established in conjunction with the geological and geophysical data. The investigation should include borehole drilling and sampling, in situ testing and laboratory testing. The presence of shallow gas and gas hydrates needs to be considered when designing the investigation programme.

The investigation shall cover the area and the soil/rock layers of significance to the structure and its foundation. Particular attention shall be given to determining the disposition and properties of shallow soils/rocks, as relatively thin layers of weak soils/rocks near the seabed can have a significant influence on foundation stability of gravity structures under ice loads. It shall also cover the zone of expected thermal disturbance for locations where permafrost is present. Special attention shall be given to minimizing both thermal and mechanical sample disturbances when sampling permafrost.

9.2.3 Bathymetry survey

Bathymetric data shall be obtained to provide information about the relief and elevations of the sea floor, and can assist in determining the likely draught of ice features reaching the structure.

9.2.4 Geophysical survey

Geophysical data shall be obtained to assist in the identification and delineation of relevant geological features, and shall be interpreted in conjunction with available bathymetric and geotechnical data to permit cross-checking and verification.

Additional features pertinent to arctic and cold regions include the depth, frequency and distribution of ice gouges and the presence or otherwise of shallow permafrost and gas hydrates. In areas of shallow permafrost, consideration shall be given to the use of special geophysical investigation techniques such as the incorporation of shorter receiver arrays or the application of resistivity methods.

9.3 Representative values of soil properties

Representative strength and deformation parameters shall be determined for all relevant soil layers, and for the relevant temperature ranges and stress ranges, taking due account of stress history, anisotropy and soil disturbance effects.

ISO 19901-4 provides further guidance on generic principles and guidelines for selecting representative values of soil properties in line with the partial-factors format or partial-factor design (PFD) approach.

9.4 Design considerations

9.4.1 General

The provisions of ISO 19903 apply to shallow foundation design for gravity-based structures. The following additional factors shall be taken into consideration in the design of foundations for offshore structures in arctic and cold regions:

- potential for permafrost or gas hydrates in the seabed;
- potential variation in sea floor relief and soil properties due to ice gouging;
- potential for grounding of ice in shallow water;
- potential for gouging around structures due to stamukhi or movement of grounded ice.

Geotechnical foundation engineering depends on the extent and reliability of the basic soils data, their interpretation, method of analysis, type of structure, type of action, and monitoring and maintenance. All of these considerations influence the choice of resistance or material factors and combinations of actions applied to foundations.

The transfer of actions between the structure and the adjacent soil shall be analysed with respect to all limit states and all phases in the life of the structure, including the removal of the structure, when required.

The sensitivity of the calculated results should be analysed making due allowance for reasonable variations of the assumptions made in the computation models, and variations in material properties and static and cyclic actions and effects.

In the analysis of the interaction between soil and structure, consideration shall be given as to whether the stiffness of the structure should be taken into account. The analysis should be based on appropriately selected representative deformation properties of the soil.

All significant effects of ice and companion environmental actions shall be considered, including the stability of adjacent seabed slopes. Possible interaction effects between structures should be considered.

Relevant drainage conditions shall be determined for the designs under consideration.

Where permafrost, shallow gas or gas hydrates are anticipated or proven to exist, the design of the foundation shall make appropriate allowance for these conditions. Locations where soil deposits include gas hydrates that can affect the integrity of the structure should be avoided. The effects of thawing of permafrost and gas hydrates on soil strength and foundation stability shall be considered.

In areas with subsea permafrost or where development can induce freezing of soils, the design process shall involve analysis to evaluate the influence of the structure, its storage, and wells on the soil. Such analyses can include: evaluation of thawing and freezing; deformation analyses of the creep characteristics of permafrost; and deformation analysis to evaluate the extent and time dependence of

foundation settlements and the ramifications of the time-dependent reduction in foundation shear strength as a result of thawing during the design life of the structure.

The potential for the development of grounded ice rubble around the structures that can impose ice actions, influence the path of the actions and create ice gouges in the seabed shall be considered.

The design shall consider the potential influence of ice gouging on the variability in sea floor relief and the requirement for site preparation. Ice gouging can also affect the strength and compressibility of near-surface sediments.

Physical testing complemented by numerical modelling should be considered where there is uncertainty in the mode of resistance of new foundation solutions and/or the ground conditions differ from those where there is precedent for a particular foundation type.

9.4.2 Action factors

Action combinations that give the most unfavourable result shall be selected in each of the stability mechanisms and deformation analyses performed.

In order to demonstrate that the design resistance is equal to or greater than the design action effect and that large cyclic and permanent displacements cannot occur due to cyclic action effects, the ultimate limit state shall be analysed with the appropriate cyclic action effect history, including ice actions.

9.4.3 Material and resistance factors

Either the material factor or the resistance factor approach may be used. Designers are encouraged to use sound engineering judgment and precedent cases, as well as relevant industry experience and due diligence, to investigate which method is more suitable to a particular application. Wherever feasible, designers are encouraged to investigate the applicability of both methods to determine which approach best meets the geotechnical design requirements.

9.4.4 Dynamic action effect analysis

Offshore structures in arctic and cold regions shall be designed for cyclic actions from ice in addition to cyclic actions from waves and seismicity. Ice failure against the structure can generate cyclic actions at multiple frequencies, depending on the stiffness of the structure and its foundation. General guidance is provided in ISO 19901-4 and in ISO 19903.

9.4.5 Ultimate limit states

It shall be demonstrated that the design resistance of the soil under and around the foundation is sufficient to resist the design action effects. The development of the design resistance over a period of time shall be assessed.

Displacements of the foundation due to design action effects should be considered when checking the ultimate limit states of the structure or vital equipment, such as conductors, casings and risers.

9.4.6 Serviceability limit states

Settlements, differential settlements and horizontal displacements of the structure, and their development over the design service life of the structure, shall be calculated. The settlements and displacements calculated shall not exceed specified limits that are established in advance for each structure and its equipment. Both the effects of foundation actions and the effects of oil and gas extraction on subsidence shall be considered.

Assessment of settlements and displacements shall include potential subsidence of the foundation due to local thaw in the permafrost layer, if present.

In permafrost regions, thermal effects of hydrocarbon drilling and production should be included in deformation analyses to take into consideration the consequences of thaw and consolidation of permafrost and gas hydrates. These effects can also impact other design cases. The possibility of corrosion, erosion or other deterioration of the foundation and soil during the presumed design service life shall be considered.

9.4.7 Fatigue limit states

Where structures are exposed routinely to ice crushing actions, fatigue behaviour of foundations and slopes shall be considered. Fatigue analyses shall be based upon unfactored representative soil properties, with due regard for cyclic effects on soil stiffness and strength.

9.4.8 Abnormal limit states

Abnormal-level ice events are defined in 7.2.2.4.

The foundation, as well as any skirts or other structural components for the transfer of actions to the soil, shall be designed so as to prevent local yield in the components or in soil spreading, which can lead to collapse.

In dynamic analysis for progressive failure, a range of probable values of all soil properties shall be considered to account for soil-structure interaction (SSI) effects.

9.4.9 Construction and installation

The construction and installation procedures shall be compatible with the geotechnical parameters used and the design assumptions. Planning and design of installation and removal should consider the operational constraints on marine construction imposed by the duration and unpredictability of the open-water season.

The construction and installation phases shall be inspected and recorded. If at any time the inspection reveals any foundation condition that differs from that assumed in the design, revision or remedial work shall be carried out as necessary to satisfy the requirements of this document.

9.5 Gravity-based structures

9.5.1 Arctic considerations for foundation design

Foundations of gravity-based structures shall be designed in accordance with ISO 19901-4 and ISO 19903 as applicable, with due account taken of the following particular considerations for offshore arctic and cold regions:

- eccentricity of action;
- alteration of action path due to ice rubble build-up;
- gas hydrate dissociation and gas accumulation under foundations, the consequential effects on long-term capacity and methods to mitigate the risks;
- presence of, influence of, and changes to, permafrost.

General theories of bearing capacity and sliding should be used with caution and should be considered only for geologic settings where it can be demonstrated that the soil conditions are relatively homogeneous and isotropic, where loading conditions are simple and where loading rates are such that the pore water drainage (undrained or drained behaviour) is understood. In such cases, theories of general bearing capacity such as are presented in ISO 19901-4 may be applied.

Torsional actions (around a vertical axis) can occur as a result of eccentric ice actions and can result in sliding failure.

Theories of general bearing capacity are not applicable to large-area foundations subjected to combined horizontal, vertical, overturning and torsional actions, or supported on layered, anisotropic soils of varying strength. Analyses of such combined actions/soil conditions require numerical or physical modelling.

Foundations overlying ice-gouged areas can be subject to non-uniform pressures due to differences in shear strength (short-term) and compressibility (long-term) of ice gouge infill and surrounding sea floor sediments.

9.5.2 Installation and removal

Special attention shall be given to permafrost and its effect on penetration of dowels, skirts or ribs into the seabed during installation. It shall be demonstrated that the planned penetration can be achieved, and that the maximum moment due to uneven penetration resistance is less than the available ballasting moment.

Freeze-back of permafrost, and potential enhanced adhesion of permafrost to penetrating elements shall be considered where removal is anticipated. An analysis shall be made of the likely upper bound action effects on the underbase and the skirts to ensure that removal can be achieved with the means available.

9.6 Piled structures

Piles that are driven or drilled and grouted shall be designed in accordance with ISO 19901-4, with due account taken of the following particular considerations for offshore arctic and cold regions:

- down-drag due to thaw subsidence;
- adfreeze of soil to shaft;
- creep;
- frost heave;
- installation in frozen ground.

The pile penetration shall be sufficient to resist design compressive and tensile action effects for all actions, including down-drag caused by thaw subsidence of permafrost.

9.7 Design of anchors for floating systems

9.7.1 General

Anchors for floating systems shall be designed in accordance with ISO 19901-4 and ISO 19901-7, with due account taken of the following particular considerations for offshore arctic and cold regions:

- installation and removal difficulties in frozen soil;
- gas hydrate dissociation and accumulation under anchors, and consequential effects on long-term holding capacity;
- thawing and freezing of the permafrost;
- creep and strength changes in the permafrost zone under sustained actions.

For permanently moored systems, the design value of the resistance to failure in the soil surrounding anchors should normally exceed the breaking strength of the anchor and/or chain line. The design resistance should be calculated on the basis of site-specific geotechnical data.

For temporary moored systems where the structure is not subjected to ice actions, the design resistance can be less than the breaking strength of the anchor and/or chain line.

9.7.2 Drag anchors

Consideration shall be given to the effect of permafrost on anchor penetration during installation. Consideration shall also be given to potential for slacking of the mooring line catenary due to

- a) thawing and freezing of the permafrost,
- b) creep and strength changes in the permafrost zone under sustained actions.

The holding capacity of a drag embedment anchor in soil is the maximum horizontal steady pull that can be resisted by the anchor at continuous drag. In calculations for an embedded anchor, the holding capacity shall include the resistance of the chain or wire rope as it moves through the soil, but shall exclude the friction of the chain or wire rope moving on the sea floor.

9.7.3 Suction anchors

9.7.3.1 Installation

Suction anchors are installed by means of actions generated by the weight of the anchor and an underpressure applied inside the anchor. For penetration, this action necessarily exceeds the maximum anticipated side shear resistance and the bearing capacity of skirt tip and stiffeners.

The penetration analysis shall consider both the intact and remoulded shear strengths of permafrost. In cases with internal stiffeners, higher shear strengths in permafrost zones can cause the soil plug to stand under its own weight over a larger height than in non-frozen soils, leading to reduced shear strength along the inside of the skirt wall. It can also lead to a larger soil heave, for which compensation should be made by an anchor height in excess of the target penetration depth.

In sand, penetration resistance is normally reduced by the gradients from the flow of water in the sand inside the anchor when underpressure is applied. In cases with permafrost, it should be recognized that the drainage through the permafrost layer can be lower, potentially blocking the drainage inside the anchor. In this case, the penetration resistance is not reduced and larger underpressures are required. It should also be checked that the underpressure does not draw water into the sand layer beneath the permafrost layer, with the consequence that the soil plug moves up inside the anchor.

The high underpressures that can be required for anchor penetration shall be taken into account in the structural design of the anchors.

9.7.3.2 Capacity

Suction anchors achieve their vertical capacity from their weight, shear strength along the outside skirt wall and reverse bearing capacity of the soil plug at skirt tip level.

When determining uplift capacity of the suction caisson, reverse end bearing is mobilized when the soil plug is still intact, i.e. passive suction is activated at the base of the suction caisson. The self-weight of the soil plug will only come into play when the seal of the soil plug is breached, and is usually higher than the reverse end bearing mobilized.

The shear strength along the outside skirt wall normally increases with time after installation, due to increased effective stresses and thixotropy. Special consideration shall be given to the effect of permafrost on this set-up, since permafrost can influence the stress and drainage conditions in the soil outside the anchor after installation, the thixotropy and the reconsolidated strength parameters.

In cases where the shear strength along the inside skirt wall is relevant, consideration shall be given to inside skirt friction in permafrost. This includes the potential for increase in the height over which the soil plug can stand under its own weight.

Consideration shall be given to the effect of permafrost on the potential for gapping at the active side of the anchor.

Consideration shall be given to potential for slacking of the mooring line catenary due to:

- a) thawing and freezing of the permafrost;
- b) creep and strength changes in the permafrost zone under sustained actions.

9.7.4 Piled anchors

Piled anchors shall be designed in accordance with ISO 19901-4, with due account taken of the particular considerations for offshore arctic and cold regions.

Consideration shall be given to the potential for slacking of the mooring line catenary through the soil due to:

- a) thawing and freezing of the permafrost;
- b) creep and strength changes in the permafrost zone under sustained actions.

Consideration shall also be given to possible gapping in permafrost zones for laterally loaded piled anchors.

Special attention shall be given to fatigue design of the pad-eye, including the effects of pile driving.

9.7.5 Removal

Consideration shall be given as to whether increased set-up and break-out resistances can develop in permafrost zones relative to those for non-frozen soils.

9.8 Scour

The possibility of seabed sediment transport shall be considered, as well as the effects of the structure in modifying the flow and transportation regime during installation and in-place conditions. If there is a risk of scour due to wave or current effects or ice gouging occurring around and within the foundation footprint, precautions shall be taken based on one of the following principles.

- The foundation shall be designed so as to tolerate the scour of material from the seabed.
- Adequate scour protection shall be placed during installation.
- The foundation shall be regularly observed, and scour-resistant materials immediately placed where necessary to ensure stability with respect to limit states.

9.9 Inspection and performance monitoring

An inspection programme should be considered as an integral part of the foundation design. Where it is deemed necessary, the inspection programme should include the use of instrumentation to monitor critical aspects of the foundation performance during installation and operation.

The scope of the inspection and the frequency of observation depend on the following:

- type of structure;
- anticipated and observed performance of the structure;
- documented behaviour of similar structures in the area;
- physical environment conditions.

If at any time during the design service life of the structure the inspection programme reveals conditions or behaviour that are detrimental to the integrity of the foundation or structure, maintenance or remedial action shall be carried out as necessary.

9.10 Seismic analysis

Soil studies in seismic, arctic and cold regions require additional data gathering to ensure that the structure foundation can be adequately designed, especially in terms of dynamic soil properties. This includes special geophysical as well as geotechnical studies with guidance as provided in A.9. These tests are in addition to the typical soil tests performed for structures in non-seismic regions.

Seismic design of pile foundations for seismic actions shall be performed in accordance with ISO 19901-2 and ISO 19901-4. Additional provisions for piled structures in arctic and cold regions are listed in 9.6.

Shallow foundation structures shall be analysed for dynamic SSI. SSI analyses can be executed by the direct method or the impedance method. Some limited guidance is available in ISO 19903.

10 Man-made islands

10.1 General

Man-made islands are generally suited to shallow-water arctic and cold regions. This document covers all man-made islands, including both stand-alone islands and land extensions, some of which are described in A.10.2. Ancillary structures used for access and transport (causeways) or protection (ice barriers, breakwaters) are also included. The provisions of Clause 10 cover man-made islands in the open sea but do not address all the issues associated with islands constructed in rivers.

Man-made islands shall be designed with due consideration of ice, structural, geotechnical and coastal engineering principles, with adequate knowledge of local conditions.

10.2 Island types

Man-made island and land extension types include:

- sacrificial beach islands;
- slope-protected islands;
- sheetpile-retained islands;

- caisson-retained islands;
- hybrid islands;
- underwater berms;
- barriers and breakwaters;
- causeways; and
- coastal pads.

10.3 Design considerations

10.3.1 General design considerations

10.3.1.1 Planning

Advance planning should be undertaken to ensure that construction is practical within the seasonal and operational constraints of the proposed island location and that there is marine access to that location for the limited arctic construction season.

Construction of man-made islands typically requires large volumes of fill and a controlled rate of construction where clay materials exist in the seabed.

10.3.1.2 Design requirements

The design of a man-made island shall take into account all actions and action effects on the structure during the construction, installation, operation and decommissioning phases (see 10.7). Adaptive design may be used where long-term conditions are uncertain, provided that adequate monitoring is put in place.

The structure and its foundation shall be designed against failure or collapse to ensure safe operation and deformational response within the limits required for its intended purpose under the provisions specified in Clause 7.

Design of steel and concrete elements in sheetpile-retained islands, caisson-retained islands and hybrid islands shall be in accordance with Clause 11 (steel) and Clause 12 (concrete), with further guidance in EN 1993-5 for sheetpile design. The design of sheetpiles in arctic and cold regions should consider the additional effects that ice actions can have in temporarily (or cyclically) reducing anchor and tie-back actions.

The methods of analysis, the actions and action combinations and the soil response parameters selected for design shall be appropriate for the intended structure and the proposed site. Specialist advice should be sought for the calculation of soil forces or reactions on structures subject to lateral actions.

10.3.2 Considerations for man-made islands

10.3.2.1 General

In shallow-to-medium water depths, ice can ride up or pile up on island slopes until it encroaches onto the working surface, which can lead to reduced access of quaysides and evacuation routes, and damage to equipment on the island. The risk of encroachment can be mitigated by passive and active defense systems (see 10.3.3.3).

A low freeboard can lead to wave overtopping onto the working surface of a man-made island. The island elevation and slopes should be sufficient to reduce wave overtopping to acceptable limits (see 10.3.5.1).

10.3.2.2 Shape and orientation

The plan-view shape and orientation of a man-made island should be designed to accommodate the particular operational or service requirements.

Normal and extreme ice and oceanographic conditions shall be taken into consideration when designing the island orientation. Factors for consideration shall include: wave and ice actions; wave overtopping; and the prevailing and extreme winds, currents and ice movements. In some cases, particularly in river channels, deltas or nearshore locations, the actions of ice, waves and currents can vary significantly by direction, thereby requiring slope protection that varies around the structure. At other sites, natural actions can be omni-directional, thereby requiring omni-directional protection.

10.3.2.3 Facilities

In designing the layout of island facilities, including topsides, care shall be exercised to minimize the potential for damage or disruption associated with ice actions, ice encroachment, wave actions, wave run-up and overtopping. In addition, the prevailing wind direction or wind directions shall be taken into consideration when determining the locations of facilities occupied by humans relative to facilities prone to the release of toxic gases.

10.3.2.4 Spill containment

General requirements for environmental protection are provided in 5.6. The environmental impact of surface operations and spills should be considered over the design service life and decommissioning of the structure.

If the island is constructed of permeable fill material, measures to mitigate the consequences of a spill shall be incorporated into the design. Mitigative measures can include providing a fluid-impermeable surface with containment structures or providing a subsurface geomembrane. If a geomembrane is used for spill containment, it shall be designed for arctic and cold regions conditions. Water levels, the freeze-front and decommissioning shall be taken into consideration in the design.

10.3.2.5 Marine access

The facility should be designed with alternative marine access routes that facilitate access and evacuation under the anticipated ice and metocean conditions.

Operating and design wind, wave, current and storm directions shall be considered when designing the docking and evacuation facilities. In cases where storms or ice can arrive from multiple directions, these facilities should be provided at more than one location on the island or protected with an offshore breakwater.

10.3.3 Design for ice

10.3.3.1 Ice-structure interaction scenarios

Actions associated with continuous ice crushing on steep and vertical faces shall be considered for the fill material design.

Ice events for consideration in the design of a sloping interface shall include flexural failure, rubbing, confined ice sheets, ride-up over ice rubble, adfreeze/frozen-in effects, and ice actions on bare slopes. The effects of ice rubble accumulations on the side slopes shall be considered not only in terms of actions, but also in terms of possible impacts on structure operations.

Components of man-made islands subjected to direct ice interaction shall be designed for ice actions as specified in 7.2.2.3 and 7.2.2.4 for the appropriate exposure level. Reference should also be made to 8.3.1.4 and 8.3.2 for wave-induced ice motions.

In addition to the provisions of Clause 8, extreme and abnormal design situations can include river ice events. Such events shall be considered in the design of the island to the extent that they are relevant to the prevailing ice regime.

10.3.3.2 Ice actions

See 8.2 for provisions relating to global ice actions. The effects of grounded ice rubble on ice failure modes and net actions on the structure should be recognized; see also 16.3.

Local ice actions and their effects shall be considered. Additionally, the overall stability of a damaged component shall be accounted for in the design by the use of sacrificial areas on non-critical sections.

The effects of dynamic and cyclic actions on fill material, foundations and retaining wall tie-backs and anchors shall be considered, including drained, undrained and liquefied soils, and the frozen state.

Actions associated with ice encroachment should be computed or estimated as a function of distance from the island edge for a ULS design situation as per 7.2.1.2. Both ice ride-up and ice pile-up mechanisms should be considered and the maximum of the two should be taken.

10.3.3.3 Ice encroachment

Actions and effects caused by ice encroachment, in combination with storm surges, shall be considered in the island design. Naturally-formed pile-ups may be used to mitigate ice actions and effects.

The design shall incorporate suitable defensive measures to prevent and/or accommodate ice encroachment, see 16.3.3. Defensive measures can be active (which include a combination of ice monitoring, ice forecasting and active IM) or passive.

Passive ice protection structures, if employed, shall be designed for the extreme and abnormal ice and wave conditions anticipated at the project site. The design of passive ice protection systems should incorporate knowledge gained from full-scale experience, theory and model tests, with due account for uncertainties in ice model test application (see also 16.5).

10.3.4 Geotechnical considerations

10.3.4.1 Geotechnical data acquisition

Investigations shall be performed to obtain geological and geotechnical data compatible with the requirements of 9.2. Further guidance is provided in A.9.2.

Seabed soil design verification shall meet all design and construction requirements.

Investigative methods and procedures used to characterize the site conditions and to define the relevant bathymetric, geological and geotechnical design parameters shall be undertaken in accordance with ISO 19901-4 and ISO 19901-8.

The geotechnical surveys for foundation design and design parameters developed for stability, deformation and thermal analyses shall be representative of all seabed materials within the zone of significant stress influence of the man-made island and within the zone of expected adverse thermal disturbance for locations where permafrost is present.

Delineation and characterization of sources of fill material and rock armour for man-made islands should be undertaken well before planned construction, to ensure that design requirements are compatible with what can be achieved in practice. Investigative methods and procedures used to determine the quality, quantity and relevant geotechnical properties of the fill material are similar to those for marine soil investigations in ISO 19901-8.

Geotechnical sampling, bathymetry and geophysical surveys are all required to properly delineate and characterize sources of fill. The volume of available material should be determined, as well as the grain size distribution and mineralogy of the materials. Mineralogy is especially important if it is suspected that carbonate content of fills is high or that particles are particularly angular or crushable.

A specialist assessment shall be sought to source rock armour in sufficient quantity and sized to meet the design requirements.

10.3.4.2 Fill characterization

Potential sources for fill material shall be confirmed to meet all design and construction requirements. If key strength and deformation parameters of the fill can be expected to change following excavation, transport and island placement, those parameters shall be confirmed by in situ testing following construction. Key properties of the fill affecting strength and deformation include, but are not limited to, frozen state, density (void ratio), grain size and permeability.

10.3.4.3 Cyclic actions

Design and construction of fill used for man-made islands shall consider the strength reduction as a result of pore pressures arising from cyclic actions, including the potential for liquefaction of fills. The fill used shall resist all dynamic actions including, but not limited to, operational, ice, wave and seismic actions.

10.3.4.4 Thermal changes

Site investigations shall include data on the initial seabed thermal regime where permafrost is known to exist or is expected to form. The existing thermal condition and changes over the design service life shall be taken into account in the design of the island and in the stability and deformation analyses. Geothermal modelling can be used for this purpose.

10.3.4.5 Failure modes

Gravel slopes and man-made island foundations shall be designed for global sliding, decapitation, passive edge failure, slope failure and structural containment component failure (as applicable). The elevation of the island work surface should be sufficient to avoid passive edge failure and to restrict wave overtopping and ice encroachment to acceptable levels.

Subsea berms can also be prone to erosion of the upper surface (loss of height) through action of moving ice or waves.

Sheetpile wall retaining systems shall be designed to accommodate local ice actions without damage to the interlock between sections as a result of plastic yielding. Structural and geotechnical failure shall be verified. Integrity of the sheetpile profile and the interlock between sections shall be verified for local ice actions. Frozen fill or soil behind the sheetpile may be accounted for where justified by analysis or monitoring.

Ice actions causing reductions in tie-back anchor loading, which can occur as single events or as cyclic actions, shall be considered in the design.

Consideration should be given to scour of slope and seabed materials, and consequent failure of slopes, retaining systems or armour materials.

10.3.4.6 Deformation

Deformation of the island and the underlying seabed shall not exceed the tolerable limits established for serviceability, ultimate and abnormal limit states. Settlement and displacement during island

construction and operation shall be addressed based on the actions defined in 8.2. The assessment of deformation shall include, but not be limited to:

- immediate settlement, primary consolidation, and secondary compression (creep);
- thaw settlement, frost heave or permafrost degradation;
- actions that can be considered using static analysis, as well as dynamic and/or cyclic actions from ice and waves;
- lateral deformation;
- reservoir depletion or depressurization.

Selection of the method of analysis shall account for anticipated modes and mechanisms of deformation, intended island configuration, foundation materials and design situations.

10.3.4.7 Soil improvement

Improvements to the soil may be used to ensure that design criteria are met and to protect against liquefaction, including removal of layers of weak soil identified through field measurements.

10.3.5 Coastal engineering

10.3.5.1 Design for wind, water levels, waves and currents

The elevation of the island work surface and marine access facilities shall be high enough to prevent inundation during an EL environmental event. Overtopping due to splash and spray shall be assessed in the design of the perimeter. Provisions for water-level fluctuations are presented in 6.4.1.

Flooding may occur for the AL environmental event, as long as hydrocarbons and other pollutants are secured, and personnel are evacuated or kept safe, e.g. by ensuring that accommodation and temporary refuges have sufficient elevation above AL event water levels.

The design of a man-made island shall take into account the effects of the local wave climate. Provisions for analysing the local wave climate are presented in 6.4.2. Wave actions can cause liquefaction of loose hydraulic fills and this should be considered in the design.

Provisions for analysing the local wind climate are presented in ISO 19901-1.

Islands located near a river mouth or a region with large current velocities shall be designed with consideration given to the actions generated by the local currents and scour potential. Provisions for analysing the local current climate are presented in 6.4.3.

The influence of regional climatological trends on the environmental actions and state of the materials should be assessed.

When an island is located in a riverine environment, the periodic monitoring activities noted in 10.6 shall be designed to identify damage caused by strudel scouring at the edge of the structure, see 14.2.3.

10.3.5.2 Side slope profile

The island side slope and its protection system shall be designed to account for geotechnical stability as well as the anticipated wave and ice actions at the site. Wave overtopping rates and ice encroachment potential shall be determined to ensure that the side slopes limit flooding and ice incursions on the island work surface to acceptable levels. Optimization of the island slope profile can be based on experience with similar structures or platforms in the region or through model testing, with due account for uncertainties in ice model test application (see also 16.5).

10.3.5.3 Wave run-up and overtopping

Wave run-up, impact and overtopping of the island slope shall be evaluated, given the selected slope protection system, side slope profile and extreme wave conditions. This can be performed using hydraulic model studies or engineering analysis.

10.3.6 Slope protection

10.3.6.1 General

The design of man-made islands shall address the various types of damage that can occur to the slope protection system, including loss of island fill, wave overtopping and ice encroachment. The island design should incorporate components that have redundant protection mechanisms and that fail progressively in a local sense rather than globally. Timely inspection and repair efforts shall be included in the operational plans to secure the long-term serviceability, stability and personnel safety on the island.

Potential concerns for the design of slope protection include low temperatures, freeze-thaw cycling, ice and wave impacts, scour at the seafloor, abrasion from ice, sand and gravel, and corrosion of reinforcing steel, exposed forged eyes and steel linkages.

Since design guidance for slope protection in arctic and cold regions is not readily available, consideration of local experience, observations and adaptive design is recommended. Numerical studies or large-scale physical modeling should be undertaken to support design of slope protection under ice and wave conditions.

10.3.6.2 Quarry stone

Large quarry stone revetments can be used to provide slope protection in ice environments. Quarry stone shall meet the strength, toughness, abrasion and density requirements of the design to ensure stability and longevity. Actions from waves and ice shall be reflected in the design of such structures through assessments of stone size, armour size, and number of layers. Stone size shall be sufficient to ensure that the removal of individual stones by ice shall not jeopardize the functional effectiveness of the armour system before such damage can be assessed and, if necessary, repaired.

10.3.6.3 Sand- or gravel-filled geotextile bags

Geotextile bags filled with sand or gravel can be used as slope protection in areas where they are capable of withstanding the anticipated wave and ice conditions with an acceptable level of damage. The bag

fabric shall provide a service life that is compatible with the design service life, or a monitoring and maintenance programme shall be in place to replace damaged bags. In the design, damage due to exposure to ultraviolet radiation and the direct impact of ice, driftwood and construction equipment shall be assessed. Geotextile bag armour shall be underlain by a strong and permeable filter fabric to ensure that the island core material is not washed out from beneath the armour by wave action.

Bag stability under direct wave and ice impact shall be analysed through engineering methods. The use of physical model studies should be considered where large uncertainties exist.

10.3.6.4 Linked concrete mats

Linked concrete mats can be used to protect man-made island slopes. The design of slope armour systems using linked concrete mats shall consider the day-to-day and design wave and ice climates and shall be closely aligned with the design of the island slope profile. Calculations shall be performed to determine the effects of local and global actions on the concrete blocks and links. The mats shall be restrained from downslope movement under wave and ice actions, and shall not experience uplift of a sufficient magnitude to jeopardize the integrity of the underlying fill material or the mats themselves. A durable filtration medium shall be installed under the concrete mat to contain the island fill material.

To minimize cracking and reduce chloride penetration, the concrete employed should be made as impermeable as possible through the use of high cement content, a low water-cement ratio, and the inclusion of pozzolan or silica fume. In addition, air entrainment of 5 % to 9 % is recommended. Design of the concrete mix shall be performed based on local conditions by a competent engineer.

10.3.6.5 Linked steel mats

The application of linked steel mat armour is similar to that of linked concrete mat armour (see 10.3.6.4). Because the density of steel is approximately three times that of reinforced concrete, the steel block thickness can be about one-third that of the concrete block to preserve the same lifting and installation plan.

The underlayer design, including the use of durable filter fabrics, are the same as those for the linked concrete mat armour.

10.3.6.6 Pre-cast concrete units

Pre-cast concrete armour units can be used to provide island slope protection against both waves and ice. The design of pre-cast concrete armour shall consider the armour stability, underlayer design and the ability of the units to resist breakage under the anticipated wave and ice impact actions.

10.4 Seismic design

Seismic design shall conform to ISO 19901-2 and consider both global and local failures of the island fill materials and retaining system. The following issues shall be addressed in relation to earthquakes:

- a) global design to prevent global failure due to an earthquake;

- b) local design of components, such as slope protection, in order that local failure during an earthquake does not lead to global failure;
- c) retaining systems, which in general are critical to the overall structure and should be designed to prevent local and global failure.

Man-made island fill material can freeze during winter or become permanently frozen. Both the frozen and unfrozen states shall be considered as appropriate.

Seismic-induced liquefaction of soils within or below the man-made island shall be considered.

Man-made islands can be prone to tsunami run-up, and this effect should be considered if applicable.

10.5 Construction

10.5.1 Operational requirements

Construction of man-made islands in ice-covered regions should take into account the limited construction windows and other logistical limitations, in particular ice conditions (see ISO 35106), working environment (see ISO 35101), and IM (see ISO 35104).

10.5.2 Fill quality control

Functional requirements for the fill used to construct man-made islands should be defined early in the design process, and include:

- bearing capacity and settlement of foundations or equipment placed on the island;
- maximum settlement of the fill;
- stability under ice actions (lateral loading on the island) which could be static or cyclic; and
- resistance to seismic actions (liquefaction and shakedown settlement).

These functional requirements determine the minimum quality of the fill that can be placed in the island (in terms of grain size) and the minimum density of the fill.

Quality control requirements during construction include monitoring of the grain size distribution of the fill. Best practice is to measure grain size distribution in the fill source, and during transportation between the fill source and the island, so that only acceptable fill is placed within action-resisting parts of the island. The in situ material as placed should also be sampled and tested to confirm the grain size distribution. Natural variability occurs and multiple samples should be taken at all stages.

In situ fill density shall be tested to ensure that the fill is sufficiently dense to meet the functional requirements. The number of tests shall be sufficient for statistical characterization of natural variability.

Soil improvement (densification) can be carried out to improve the in situ density of the fill to meet design requirements. The soil improvement system should consist of a trial area to confirm the effectiveness and optimise the areal spacing of treatment locations. The actual improvement of the entire island shall be checked by testing, at a minimum of 10 locations or every 500 m².

The cone penetration test (CPT), ISO 22476-1, is the preferred method of testing. Alternative methods shall be demonstrated to be suitable.

10.5.3 Armour rock quality control

Armour rock shall be sufficiently massive and resistant to degradation during construction and while in operation to fulfil its purpose. Quality control during construction shall include measurement of the size of a statistically representative number of rocks placed on the island. Durability depends on the rock type (mineralogy) and can be tested at the quarry to ensure it meets the specifications.

10.6 Monitoring and maintenance

10.6.1 General

The scope of a monitoring and maintenance programme shall be assessed as an integral part of the island design. The plan for monitoring requirements depends on the type of slope protection, fill properties, containment and stability calculations. The monitoring plan may be updated during the service life of the island.

Guidance is provided in 16.4 on monitoring of ice actions and structural stability.

10.6.2 Monitoring of the physical environment

Sufficient data regarding physical environmental conditions should be acquired in accordance with ISO 35106 to support an evaluation of the actions to which the structure has been subjected and an assessment of the causes of damage (if any) which the structure has sustained. The environmental conditions that should be recorded over the design service life of the structure include:

- ice encroachment events;
- any other ice interactions with man-made islands and natural structures;
- wind speed and direction;
- temperature;
- water level and sea states; and
- ice data, including ice thickness, ice drift, ice feature types and frequency.

Data shall be applicable to the structure site. Provided that the applicability requirement is fulfilled, data acquired at one site may be used to fulfil the environmental monitoring requirements for multiple structures in the vicinity.

10.6.3 Structural monitoring

Appropriate geotechnical instrumentation should be installed and monitored throughout the design service life of the island to measure specific aspects of foundation and fill behaviour under static and cyclic actions. These measurements should include, but not be limited to, the following:

- settlement, tilt, and horizontal deformation;
- pore-pressure response; and
- temperature in the fill and foundation materials.

For islands using sheet pile containment systems, monitoring for local damage should be carried out so that repairs can be implemented.

10.6.4 Slope and slope-protection monitoring

The slope protection system shall be inspected at least once per year, and after each event or season that has the potential to inflict significant new damage to the structure. In the case of slope protection systems that employ armour units, items for consideration in the inspection should include slope deformation, scour at the toe of the slope, armour unit damage and armour unit displacement.

In the case of slope protection systems that employ sacrificial beach islands, the dimensions and properties of the remaining sacrificial material shall be assessed.

10.6.5 Maintenance

Following the annual or special inspection of the slope protection system, an evaluation shall consider whether the protection system is still capable of protecting the structure during the design events.

If collected monitoring data or an assessment indicates that the actual island performance is not in accordance with design criteria or specified response limits, the design shall be reassessed for ongoing adequacy in the light of such data or assessment. In cases where it is determined that the current state of the structure should be enhanced to ensure future operational reliability, appropriate remedial actions shall be implemented to restore structural reliability to meet design requirements.

10.7 Decommissioning and reclamation

Further to 5.8, when planning decommissioning and/or reclamation policy for a man-made island, the following provisions should be addressed.

- a) **Materials:** Materials used to construct the structure and to protect its slope should either be amenable to substantially complete removal at the time of decommissioning or reclamation, or pose no significant threat to human life, safe navigation, or the natural environment if allowed to remain at the project site after decommissioning or reclamation.
- b) **Buried items:** The location of each item that is buried in the structure fill and that can pose a significant threat to human life, safe navigation or the natural environment if allowed to remain at the field after decommissioning or reclamation should be determined with sufficient accuracy to

facilitate removal of that item at the time of decommissioning or reclamation. This provision applies equally to items buried during construction of the structure or subsequently during its design service life.

- c) Record-keeping: Written records documenting the as-built configuration of the structure as well as all changes thereto should be maintained throughout the design service life. These records should include the locations of all items buried in the structure fill.
- d) Safety: The safety of personnel and equipment during decommissioning or reclamation operations, when protection against metocean and ice actions has been partially or totally removed, should be considered in formulating the plan for decommissioning or reclamation. The operations should be carried out in accordance with all of the safety provisions outlined in the plan.
- e) Environmental protection: Decommissioning or reclamation operations should be carried out in accordance with the environmental protection measures outlined in Clause 5.

11 Fixed steel structures

11.1 General

Offshore fixed steel structures in arctic and cold regions shall meet the requirements of ISO 19902 supplemented by ISO/TS 35105 and the requirements of this document. Such structures include tubular steel frame structures, monopiles, braced monopiles, stiffened-plate gravity-based structures, steel-concrete (composite) gravity-based structures and any combinations of these. The design of non-tubular structural components that behave as beams, columns or beam-columns shall be in accordance with ISO 19901-3.

11.2 General design requirements

11.2.1 Plastic design

When inelastic response is invoked in order to resist specified accidental actions, EL or AL environmental actions, the steel structural elements shall have the ductility and toughness to resist the actions throughout the event scenario. Redistribution of action effects may be assumed to take place as long as sufficient material ductility is present.

11.2.2 Resistance factors

The partial resistance factors for use with offshore fixed steel structures in arctic and cold regions shall be specified in accordance with ISO 19902.

11.2.3 Fracture control

Fracture control shall be considered in all material selection and structural design activities. Appropriate toughness shall be established in accordance with ISO 19902 and the additional requirements of 11.9.

11.2.4 Temperature effects

The effects of restrained thermal expansion due to differential temperatures in the structure shall be considered.

11.2.5 Damage due to freezing water

Structural and mechanical systems shall be protected from damage due to freezing water by insulation, heating, drainage, provision of crushable materials or other suitable means. Any active system to prevent damage due to freezing water shall be configured to achieve an acceptable level of structure or system reliability. The acceptable level of structure or system reliability should be determined according to the principles set out in Clause 7.

11.3 Structural modelling and analysis

11.3.1 General

At each stage of analysis, the idealization of the structure and the level of sophistication of the analytical model shall be compatible with the anticipated behaviour of the structure and the accuracy of the required results; see ISO 19902.

11.3.2 Interactions

When required, ice-fluid-soil-structure interaction, as well as the dynamic properties of the foundation soil, shall be modelled.

11.3.3 Dynamic analysis

The dynamic effects of operational actions and actions due to ice, waves, wind, currents, earthquakes and impacts shall be taken into consideration. Dynamic effects are important when the resonant frequencies of a structure or of one or more of its components lie in the range for which the actions and action effects cause dynamic amplification. Particular attention should be given to the potential for ice-induced vibration of steel structures when vertical or near-vertical components are exposed to ice actions.

Dynamic analysis can include the effects of damping, such as internal structural damping of the materials and energy dissipation at the joints.

The water-ice-structure interaction shall be taken into account by considering the hydrodynamic forces, the effects of waves radiating energy to infinity (hydrodynamic damping), the drag effect and energy dissipation of the ice. If necessary, frequency-dependent impedance functions shall be used to represent boundary conditions for complex fluid-solid-structure interactions, including those involving ice.

11.4 Strength of tubular members and joints

Structural members and joints between members that are located in an area where they can be subjected to ice actions shall be designed to resist local ice actions combined with relevant global actions.

Due consideration shall be given to the potential for damage to tubular members and joints caused by ice actions. Damage tolerance requirements shall be in accordance with ISO 19902. The residual strength of tubular members suffering local damage can be calculated in accordance with of ISO 19902.

11.5 Strength of stiffened-plate panels

Stiffened-plate panels shall be designed to resist the actions to which they are subjected, including in-plane bending, tension, compression, shear and actions normal to the plane of the panel. Special attention shall be given to local ice actions.

The design of stiffened-plate panel configurations should be in accordance with an appropriate standard, see A.11.5. Membrane action is permitted provided the plate and stiffener are proportioned to allow for plastic deformation. Membrane action for stiffened plates is permitted under local EL ice actions (see 8.2.5), provided the structure continues to fulfil its functionality and ability to resist further actions. For events associated with EL and AL local ice actions, the plate and stiffener arrangement should be verified using non-linear finite element (FE) analysis or a physical testing program.

Where in-plane compression due to global structural action effects acts in combination with out-of-plane local ice actions and/or where the consequences of plate rupture are high, the use of membrane action is not permitted. The stiffened-plate panel design shall meet the requirements of the relevant standard, see A.11.5, with respect to elastic deflection criteria.

11.6 Strength of steel-concrete composite walls

11.6.1 General

The provisions of 11.6 apply to composite ice-resisting walls consisting of external steel plates and concrete infill, with interconnection provided by shear connectors, stiffeners, transverse web members, longitudinal web members, or combinations thereof. These walls can also include standard concrete reinforcement. ISO 19902 provides requirements for the design of grouted tubular members and tubular joints, which may also be used to design concrete-filled members and joints.

The requirements of ISO 19903 shall govern the placement of concrete, the determination of concrete material properties, and any other areas applicable to concrete that are not covered by, or are in conflict with, this document.

Composite walls shall be designed to resist bending and shear due to actions normal to the plane of the wall (transverse actions), see 11.6.4, and to resist in-plane tension, compression and shear due to actions parallel to the plane of the wall (vertical or horizontal), see 11.6.5.

The steel components of the composite wall shall be designed to resist the effects of all actions, including those resulting from concrete casting, that are applied to the wall prior to the attainment of concrete strength sufficient such that composite action is achieved.

Consideration shall be given to the effects of restrained deformations due to temperature changes and to the effects of thermal gradients through the thickness of the wall. Where concrete can be demonstrated to fill all voids within the stiffened panels, it may be considered that the panel stiffeners and girders are laterally restrained with respect to local buckling.

Each component of a composite wall (external plate, concrete infill, web plate, stiffener, shear connector, reinforcement, etc.) shall have a design resistance greater than the design action effect, or combination of such effects, to which it is subjected. Provision shall be made to ensure that premature buckling of the external steel plates does not occur.

Lower bound plasticity methods, upper bound plasticity methods and empirically derived formulae may be used to determine representative resistances, provided that the applicability of the methods has been verified experimentally.

11.6.2 Analysis methods

Either an elastic analysis or a plastic analysis shall be used to determine the force distribution within a member due to local actions. An analytic method shall be used that is appropriate for the type of composite wall system being designed. Additional guidance on analysis methods is provided in A.12.3.

A plastic analysis may be used, provided that the applicability of the method is verified and sufficient ductility of the member is ensured. A plastic analysis can be used for:

- flexural members;
- members that allow interface slip (i.e. strain compatibility is not enforced between the external steel plates and the concrete infill);
- regions adjacent to supports or concentrated actions, or where there are abrupt changes in cross-section;
- other situations where arching/strut-and-tie action can be justified.

11.6.3 Material properties

The material properties for concrete and deformed reinforcing steel shall be determined in accordance with the requirements of ISO 19903. The material properties for structural steel shall be determined in accordance with the requirements of this document and ISO 19902.

11.6.4 Design for out-of-plane actions

11.6.4.1 Flexural strength

The maximum usable unfactored strain at the extreme concrete compression fibre shall be assumed to be 0,003, unless special provisions are made to provide confinement to the concrete. In this case, the designer shall document the increase in usable strain.

When it is assessed that plane sections remain plane, it may be assumed that the relationship between the compressive stress and strain of the concrete is parabolic, trapezoidal or any other shape that results in substantial agreement with comprehensive tests.

When it is assessed that plane sections remain plane, the stress in the external steel plates and in any internal steel components that provide flexural resistance (webs, stiffeners, reinforcing, etc.) shall be

calculated as $1/\gamma_s$ times the value of stress determined from strain compatibility based on a stress-strain curve representative of the steel, where γ_s is the steel resistance factor.

When a plastic analysis has been used to determine the distribution of forces in a member, the maximum compressive stress achievable in a concrete diagonal compression strut shall be assumed to be equal to $\eta f_c/\gamma_c$, where f_c is the concrete compressive strength, γ_c is the concrete resistance factor and where the concrete efficiency factor, η , has been experimentally determined.

When a plastic analysis has been used to determine the distribution of forces in a member, the stresses in the external steel plates and in any internal steel components that provide flexural resistance (webs, stiffeners, reinforcing, etc.) shall not exceed the stress at which yielding is assumed to occur (i.e. f_y/γ_s , where f_y is the representative yield strength).

The tensile strength of concrete shall be ignored in the calculation of the design flexural resistance.

Transfer of action effects from the external steel plates to the concrete infill shall be achieved using shear connectors, transverse webs or transverse stiffeners. Transfer of action via interfacial friction shall be disregarded unless shear friction reinforcement (headed studs or other mechanical connectors) is provided.

11.6.4.2 Shear

The shear resistance of a composite wall shall be provided either by the concrete infill alone or by the concrete infill in combination with one or more of the following:

- longitudinal web plates that carry shear directly to the supports;
- transverse web plates that act as shear reinforcement;
- overlapping headed steel studs that act as shear reinforcement;
- standard reinforcing bars that act as shear reinforcement;
- through-thickness rods that act as shear reinforcement;
- discontinuous longitudinal webs that act as shear reinforcement.

The shear resistance of a wall subject to concentrated transverse actions shall be the lesser of the resistances determined assuming:

- a) beam action, with a critical section extending in a plane across the entire width; or
- b) punching action, with the critical section extending around the perimeter of the loaded area.

11.6.5 Design for in-plane actions

The design values of axial and of in-plane resistances shall be determined using rational methods that have been verified experimentally. Consideration shall be given to the transfer of action effects between the concrete core and the external steel plates, and to preventing buckling of the external plates in compression.

11.7 Seismic design

11.7.1 Framed structures

A fixed steel offshore structure for arctic and cold regions can take the form of a braced caisson, free-standing caisson, jacket, monotower, steel gravity structure or jack-up as defined in ISO 19902.

Guidance on procedures and criteria for seismic design is provided in ISO 19901-2.

Seismic design of braced caissons, free-standing caissons and jacket structures shall be in accordance with ISO 19902, taking into account any guidance given therein in respect of seismic reserve capacity and recommendations for ductile design.

Seismic design of all other steel structures shall also be in accordance with ISO 19902, except that the seismic reserve capacity factor shall be developed for the structure on a case-by-case basis. Alternatively, the structure shall be shown to achieve ALE and ELE performance requirements using explicit structural analysis.

11.7.2 Stiffened-plate structures

Steel stiffened-plate structures are typically of gravity-based structure (GBS) design. The general principles for seismic design presented above shall be implemented, specifically the requirement for elastic performance under the ELE and for non-collapse condition under the ALE.

The key consideration for seismic design is the ductile performance of the steel stiffened-plate structures under the ALE. Ductile performance shall be demonstrated by explicit structural analysis combined with proper detailing of connections to ensure ductility. Alternatively, steel stiffened-plate structures may be designed to perform elastically for the ALE, including the design of the connections, and this eliminates the requirement to demonstrate ductile performance.

11.8 Fatigue

Cyclic stresses caused by ice actions shall be included in the fatigue assessment.

Responses of the structure to cyclic ice actions that have the potential to cause the fatigue failure of structural members and welded connections shall be considered.

The resistance to low cycle, high amplitude cyclic stresses shall be assessed using methods that are valid in this region of behaviour.

11.9 Materials, testing and NDT

11.9.1 Material selection

Material selection for steel shall be in accordance with ISO 19902. Material selection for the components of stiffened-plate structures shall be developed in accordance with the principles defined in ISO 19902.

11.9.2 Test temperature

For structures in arctic and cold regions, the LAST value used for material selection and testing should be defined in accordance with this document, see 5.3.4.2, if not specified explicitly in the regulatory requirements for the region.

Temperatures for testing of steel shall be based on LAST but when calculating test temperatures based on ISO 19902 for structures in arctic and cold regions, the LAST shall not be taken as warmer than $-10\text{ }^{\circ}\text{C}$. If a test temperature based on ISO 19902 is calculated to be colder than $-60\text{ }^{\circ}\text{C}$, special consideration should be given to material thickness and to service conditions such as structural redundancy and joint probability of low temperature and internal stresses, in order to establish an appropriate test temperature. In such cases, the test temperature should not be warmer than $-60\text{ }^{\circ}\text{C}$.

11.9.3 Toughness and NDT

The minimum toughness and non-destructive testing (NDT) requirements shall be in accordance with ISO 19902, except that test temperatures related to LAST shall be in accordance with 11.9.2.

11.10 Coatings

A coating may be employed as a corrosion barrier and/or to provide abrasion resistance and a low friction interface with ice. The durability and life expectancy of the coating shall be assessed in determining the long-term corrosion and abrasion resistance requirements of the structure.

11.11 Corrosion and abrasion protection

11.11.1 Cathodic protection

For a structure exposed to sea ice interactions, sacrificial anode systems should be designed and placed to prevent damage by ice and ensure functionality. The design of cathodic protection systems shall be based on established methods.

11.11.2 Ice abrasion

If the structure can be severely abraded by ice, the design shall assume uncontrolled corrosion losses. For structures where ice abrasion occurs, additional wall thickness shall be provided, or another suitable system or combination of systems shall be used to protect the structural members.

11.11.3 Knife-line corrosion

The weld metal, heat-affected zone (HAZ) and parent plate chemistry shall be selected such that metallurgical and electrical potential differences between adjacent metals are minimized in order to avoid selective weld region attack.

11.12 Welding

Welding consumables shall be selected with due consideration given to minimizing preferential corrosion of welded connections.

12 Fixed concrete structures

12.1 General requirements

12.1.1 General

Fixed concrete offshore structures for use in arctic and cold regions shall be designed in accordance with ISO 19903 and the further requirements of this document.

Ice- or iceberg-resistant concrete structures can be subject to large current and wave actions in addition to large ice actions.

12.1.2 Structural requirements

The potential for abrasion due to moving ice and spalling/cracking due to ice impact shall be considered, and measures shall be taken to keep these deteriorations to an acceptable level throughout the design service life of the structure. This can be achieved either by proper concrete design and detailing or, if warranted, by protective steel cover sheets (armour) in the area of concern. In particularly severe environments, a combination of the two can be selected.

The quality of the concrete and the overall design of the structure shall be selected to minimize any potential early degradation of the concrete due to the combined effects of abrasion induced by moving ice, freeze-thaw attacks and corrosion of reinforcement. If this cannot be done, suitable measures should be in place to minimize degradation or its effects (e.g. increasing concrete cover, providing steel armour).

Design should favour smooth external surfaces in areas subjected to moving ice, and local design should aim to avoid the crushing and destruction of protruding details.

Post-tensioning anchorages and other critical details should, as far as possible, be located away from areas prone to direct ice actions.

12.1.3 Material requirements

Concrete materials shall have adequate resistance to freeze-thaw cycles, where applicable. In this selection process, resistance to accelerating effects of freeze-thaw cycles and corrosion should be considered.

Reinforcement steel with adequate toughness and ductility properties for the temperature conditions shall be chosen.

12.2 Actions and action effects

Application of the combinations of the actions and the partial factors for relevant limit states shall be in accordance with Clause 7.

The dynamic response of the structure and its foundation to ice impacts shall be determined, and its effect on the structure as a whole and on individual members shall be accounted for in the design.

12.3 Structural analysis

12.3.1 Dynamic analysis

Requirements for ice-induced vibration and other dynamic actions are found in 11.3.3.

12.3.2 Loss of intended internal pressure

When the design of any portion of the structure takes into account an intended pressure differential, the temporary loss of that differential during the operating phase shall be considered. Until the intended pressure differential is restored, special consideration should be given to the crack width limitations under such circumstances.

12.3.3 Physical representation

12.3.3.1 Soil-structure interaction (SSI)

Static and dynamic analyses of the complete structure shall be performed for ice actions. A simplified global model may be used to assess the fundamental dynamic responses. Appropriate dynamic soil parameters shall be considered in accordance with ISO 19901-4. Dynamic effects may be simulated as static equivalent actions (accelerations $\times$ mass, for instance) in the global static FE analysis, in combination with the companion static actions. Further guidance is provided in ISO 19903.

Structural and foundation damping shall reflect the state-of-the-art and recognized principles. Different (smaller) damping factors shall be used for fatigue analyses. The internal damping of the soil shall reflect strain levels and soil profiles in accordance with the provisions of Clause 9.

In particular circumstances, different types of ice actions can call for different foundation modelling; for instance, cyclic and impact actions can involve different parts of the soil stress-strain relationship.

12.3.3.2 Other support conditions

Action-resisting embedments shall be properly anchored into the concrete.

Tensile stresses in all directions relative to a tensile action shall be considered.

12.3.3.3 Thermal effects

Thermally-induced action effects within structural components containing hot stored oil shall be assessed.

12.3.4 Types of analysis

12.3.4.1 Linear elastic static analysis

Linear analytical and numerical theories give generally acceptable structural responses and action effect distributions for both SLS and ULS under relevant ice actions. Action effects due to structural imperfections shall be considered in accordance with ISO 19903.

For the assessment of the transverse shear capacity of a concrete section, the enhanced shear strength near supports is acceptable for ice actions, but it shall be disregarded for that part of the shear actions due to hydrostatic pressures; see ISO 19903 for additional provisions for handling water pressure in pores and cracks.

12.3.4.2 Non-linear analysis

Material and geometrical non-linear effects may be considered where appropriate, in particular for ALS. Where it is planned to depart from the non-linear behaviour of materials described in the referenced national standard for concrete design, material performance shall be supported by physical test results or bibliographical research on materials with relevant properties.

It can be sufficient to assess the non-linear behaviour of structural components subjected to ice actions on the basis of linear structural analyses without resorting to a full non-linear elastic analysis. In the “reduced stiffness approach”, action effects induced within the structural components may be redistributed by modifying the membrane and bending stiffnesses for tensile components to account for cracking. The final equilibrium condition after redistribution should be verified by comparing the internal stress and strain conditions for the components in tension to those of adjacent components. Stress redistribution can be determined from a fine-mesh FE analysis.

Local fine-mesh non-linear FE analysis can be used to better identify those areas where local stresses can exceed allowable elastic limits. Boundary conditions derived from the global linear FE analysis should be applied to the non-linear model at a location sufficiently distant from the area of elasto-plastic behaviour. Compatibility of forces and deformations at the interface of different FE models shall be verified for the type of action under consideration.

12.3.5 Analysis requirements

12.3.5.1 Analysis of construction stages

Built-in stresses due to the sequence of construction, the pre-stressing sequence and the temperature history shall be taken into consideration in the analysis of construction stages.

12.3.5.2 In-service serviceability analysis

The SLS aspects of importance relate to crack width determination and potential corrosion and containment issues.

Depending on regional ice conditions, ice-related actions can be included in the combinations of actions for the SLS analysis if they are frequent or occur with a short return period.

Limitation of displacements and motions shall also be considered with respect to serviceability.

12.3.5.3 Fatigue analysis

Fatigue analysis shall be performed in accordance with ISO 19903 for cyclic ice actions in addition to wind, wave and current actions.

Fatigue properties of reinforcement steel, embedded steel, welds, etc. and concrete shall be satisfactory under the low temperatures prevailing in arctic and cold regions.

12.3.5.4 Accidental and abnormal analyses

Sequential limit state modes can potentially develop for AL actions. Non-linear analyses shall be conducted in accordance with 12.3.4.2. For sections where reserve strength and ductility are mobilized, the components or sections shall meet the ductility requirements of 12.4.1.9.

Oil containment should be addressed specifically as part of the analysis requirements for L1 exposure level structures. AL action effects shall not lead to loss of containment of oil storage compartments.

12.3.6 Seismic design

The requirements of ISO 19901-2 shall be satisfied for concrete structures in arctic and cold regions. Seismic design of concrete structures requires elastic performance for the ELE and a no-collapse condition for ALE. A key consideration is the ductile capacity of large columns often used in concrete GBS structures, as failure of a column can lead to a global collapse mode. Ductile performance of concrete structures can be obtained provided that ductile design and detailing are implemented.

Alternatively, concrete structures may be designed to perform elastically for the ALE, in which case the ELE criterion is satisfied implicitly. In such cases, the design should still incorporate a ductile mode (and not a brittle mode) of failure.

For composite steel and concrete structures, the approach described in this clause shall also be used.

12.4 Concrete works

12.4.1 Design

12.4.1.1 Design principles for shell members

Arctic offshore structures are frequently subjected to concentrated actions on shells. Shells shall be designed to prevent buckling, taking into account the likely geometrical imperfections that decrease the buckling resistance and enhance induced shell moments.

12.4.1.2 Design principles for fatigue

The design shall recognize the contribution of time-varying ice crushing actions to fatigue utilization; see 8.2.6.

12.4.1.3 Design principles for durability

Freeze-thaw cycles and ice abrasion are two major mechanisms that can jeopardize the durability of concrete in arctic or cold regions. These mechanisms are addressed in 12.4.1.4.

12.4.1.4 Durability considerations

12.4.1.4.1 Freeze-thaw cycles

Concrete can deteriorate when subjected to recurrent freeze-thaw cycles, leading to degradation in the internal micro-structure and the mechanical properties of the concrete. The part of a structure subject to the largest number of freeze-thaw cycles is that closest to the water surface.

Durable concrete for offshore structures in arctic and cold regions shall meet the following requirements:

- low permeability;
- low water-cement ratio;
- air entrainment; and
- very high-quality aggregate.

Low permeability prevents the absorption of water into the concrete. Air entrainment improves the resistance of the concrete to freezing and thawing because the protective pores reduce the pressure of freezing water in the cement stone.

12.4.1.4.2 Abrasion

When moving ice acts against a structure, it can cause abrasion of the concrete. The design of the structure shall make due allowance for such abrasion. The concrete mix should be designed to minimize the degradation due to abrasion.

All corners and edges of concrete structural components shall have a chamfer of at least 25 mm.

For concrete exposed to abrasion and scouring actions, the minimum 28-day strength for test cylinders shall be a minimum of 60 MPa, and the aggregates shall be abrasion-resistant.

12.4.1.4.3 Concrete cover

The effect of wear and abrasion due to repetitive ice action shall be accounted for in the definition of the concrete cover.

12.4.1.5 Design principles for buckling

Compression members shall be designed for buckling, if necessary. Adequate constraint for the compression reinforcement should be provided by through-thickness reinforcement to ensure no pull out or push out effects. Specific consideration should be given to curved components under hydrostatic or ice pressure.

For structures or portions of structures where buckling can be significant, the influence of displacements and geometric imperfections shall be taken into account when sectional forces are determined. The stiffness used in the analysis should reflect the distributions of stiffness anticipated under the action combinations corresponding to the limit state under consideration.

12.4.1.6 Design principles for imposed deformations

Deformations associated with thermal effects, differential thermal settlements and the action of ice formation within cellular compartments of the structure shall be considered.

12.4.1.7 Design for fire resistance

The potential for reduced fire resistance where cover has been increased to provide abrasion resistance should be recognized and addressed. Additional reinforcement can be required for this combination.

12.4.1.8 Partial factors for materials

The material factors shall be such that a safety level consistent with that required by Clause 7 is achieved.

12.4.1.9 System ductility

The entire structure shall have system ductility sufficient to survive accidental actions and abnormal environmental events.

Under specified abnormal environmental or accidental actions, the sectional forces throughout the structure shall continue to satisfy the static equilibrium requirements imposed by the permanent actions.

Under the influence of specified AL environmental or accidental actions, one or more structural components or sections can exceed their ULS. This is acceptable provided that the remaining structural system can continue to resist the actions that are expected before repairs are completed (i.e. the damaged condition). If this approach is adopted, the integrity of the oil storage system shall be maintained.

Components that can be overloaded during an abnormal environmental or accidental event shall be designed to ensure that they possess adequate energy-absorbing capacity. Sufficient energy-absorbing capacity can be achieved when the resistance of a component at six times its yield deflection still exceeds 50 % of its representative resistance.

In evaluating system ductility, the concrete cover shall be assumed to spall in regions where the design resistance has been exceeded during the abnormal or accidental event.

When system ductility is being evaluated, the strength of the pre-stressing bars shall not be relied on when local bending of the bars can occur or where pre-stressing is supported by fewer than four independent units.

For abnormal-level ice actions, the failure of a structural component shall not lead to progressive failure in the adjoining components, unless it is agreed that any damage can be readily repaired. If the decision is made to leave the structure in place during decommissioning, different progressive collapse criteria can be appropriate.

The ALS evaluation shall consider combinations involving permanent and variable actions, but no other environmental action or deformation action except for pre-stress and thermal effects.

In damaged conditions, a ULS evaluation shall be performed under permanent and variable actions, but without deformation actions (pre-stress and thermal effects excepted) in combination with environmental actions, consistent with the requirements for damage tolerance in ISO 19903.

Where a detailed non-linear analysis of the structure is used to demonstrate survivability for AL ice actions, verification of the damaged condition should proceed using the same non-linear analysis and the final configuration as its starting condition.

12.4.1.10 Minimum reinforcement

The minimum reinforcement required in various components shall be specified.

In sections subjected to a combination of high compressive stresses and large shear forces, the main reinforcement shall be confined with through-wall stirrups not less than 0,4 % of the concrete area. This requirement applies when the combined axial force and bending moment exceed the strength of the concrete section, ignoring the contribution of the compression reinforcement to the cross-sectional strength. It also applies when the shear force exceeds the strength of the unreinforced concrete section without contribution from the axial force.

In walls subject to direct ice actions, minimum reinforcement criteria should be specified to provide sufficient ductility and energy absorption.

Minimum reinforcement shall account for low temperatures and should minimize the possibility of water freezing in cracks.

12.4.2 Materials

12.4.2.1 Material requirements — Concrete constituents

12.4.2.1.1 Normal-weight aggregates

Aggregate shall be free from snow and ice at the time of mixing.

12.4.2.1.2 Lightweight aggregates

The use of lightweight aggregate concrete in areas subjected to ice abrasion shall be carefully considered and demonstrated by appropriate tests, because this material is generally less resistant to ice abrasion than normal-weight concrete. The moisture content in lightweight aggregate at the time of placing should be kept low enough to ensure adequate freeze-thaw resistance. A 24 h absorption limit of 12 % by volume shall be imposed.

12.4.2.1.3 Admixtures

Where water is able to penetrate the concrete matrix, air-entraining admixtures shall be added to the concrete components that are subjected to freeze-thaw cycles. In permanently dry areas, adequate frost resistance can be achieved through adoption of a low water-cement ratio.

12.4.2.1.4 Repair materials

The choice of repair material shall take due account of its ability to bond with the concrete substrate so that it is not preferentially lost if adfrozen water is pulled free from the concrete. Repair materials shall have mechanical and physical properties (i.e. strength, thermal expansion, etc.) that are compatible with the concrete substrate. The repair compound should demonstrate an ice abrasion resistance comparable with the adjacent concrete.

Vapour-permeable bonding compounds such as latex should be considered for repairs in the splash zone and above.

If coatings are applied to the concrete, these should preferably be vapour-permeable to avoid potential delamination.

12.4.2.2 Material requirements — Concrete, grout and mortar

12.4.2.2.1 Concrete

The concrete composition shall be tested to demonstrate adequate freeze-thaw resistance for arctic and cold regions.

For structural reinforced concrete exposed to chlorides under freezing and thawing conditions (marine structures in tidal zones), the following apply.

- The 28 day compressive strength shall be equal to or greater than 45 MPa.
- The water/cement ratio shall not exceed 0,40.
- The air content shall be in the range:
 - 1) 6 % to 9 % for aggregates <10 mm;
 - 2) 5 % to 8 % for aggregates 14 mm to 20 mm;
 - 3) 4 % to 7 % for aggregates 28 mm to 40 mm.

When freezing of the hardened concrete can occur during the operational phase of the structure's design service life, air-entraining admixtures shall be used.

Before concreting operations begin, tests shall be performed to determine the nature of the air-void system in concrete produced with the proposed materials, mixing systems and placing systems. The air-void parameter requirements are as follows.

- a) The specific surface area shall be greater than $25 \text{ mm}^2/\text{mm}^3$.
- b) The maximum average spacing factor shall be 0,23 mm.
- c) No single spacing factor shall be greater than 0,26 mm.

The concrete shall be tested to determine the air-void parameters in accordance with an applicable standard. The amount of air in plastic concrete mixes necessary for conforming to these air-void parameters shall be used to establish the required air content for subsequent job-site testing.

Increased air-void parameter limits may be used for concrete containing super-plasticizers and supplementary cementitious materials, provided that appropriate data from freezing and thawing tests for the materials in question are available.

During construction, the air-void parameters of the hardened concrete shall be checked at approved intervals, and the level of air content in plastic concrete shall be controlled so that the air-void parameters comply with the limits a) through c) specified above.

The primary criterion for selecting the required air content should be from a determination of hardened concrete air-void parameters.

Ducts, climbing-rod holes and other small openings in the concrete shall be filled with Portland cement grout unless alternative means of excluding water that can freeze have been provided.

Reference should be made to 12.4.1.4.2 for concrete specifications in areas exposed to ice abrasion.

12.4.2.2.2 Grout and mortar

The grout should have a low permeability, be resistant to freezing and thawing and have a compressive strength similar to that of the surrounding concrete. Expansive admixtures should be chosen to avoid the accumulation of gaseous voids, which can become water-filled.

12.4.2.3 Material requirements — Reinforcement steel

Reinforcement shall be specified to ensure that adequate ductility exists for the expected construction and operational temperatures.

In parts of the structure with potential for corrosion of the reinforcement, the required properties of the reinforcement shall be maintained through the concrete quality, cover and corrosion-resistant reinforcement materials.

12.4.3 Execution

12.4.3.1 Formwork

Formwork systems shall be constructed from materials that have satisfactory ductility at the temperatures experienced at the construction location.

Care shall be taken to ensure that all temporary recesses and block-outs in formwork are filled with cementitious grout. Structural foam or grease may be used if the void can be tolerated in the permanent condition.

12.4.3.2 Pre- and post-tensioning

Consideration should be given to having recessed anchorages suitably sealed by concrete when these are present in a region where ice abrasion or adfreezing followed by ice removal can occur.

If it is necessary to carry out post-tensioning during periods with temperatures below +5 °C, the strand shall be tested to failure at the temperatures that are expected as well as at +5 °C to demonstrate that the ductility of the strand is satisfactory.

12.4.3.3 Protective measures

Water or steam shall not be used to clean ducts. Oil-free compressed air may be used.

To prevent splitting of the concrete due to ice expansion in tendons having a significant vertical rise, provision shall be made to ensure that bleed water is not trapped at the top of the duct.

12.4.3.4 Concreting

Openings that can lead to a chimney effect in cold weather should be avoided, given that these can lead to shrinkage cracking.

12.4.3.5 Embedded components

An appropriate design guide should be used for embedded components.

12.4.3.6 Hydrotesting

Structures constructed in a dry dock, and for which the opportunity of testing all the vulnerable parts at a deep-water completion site is not achievable, shall be hydrotested in the dry dock to the maximum extent possible with appropriate means for demonstrating that adequate leak resistance has been achieved. The beneficial effects of autogenous healing may be invoked to minimize the extent of the repairs required.

12.4.3.7 Hot and cold weather works

12.4.3.7.1 Concreting in cold weather

Provisions shall be made during the curing process to ensure that the required concrete strength is reached in ambient temperatures.

12.4.3.7.2 Grouting of pre-stressing ducts during cold weather

During cold weather periods, all ducts shall be kept clear of water to prevent the formation of frost or ice in the ducts. Neither water nor steam shall be used to clean ducts, but oil-free compressed air may be used. At the start of each grouting operation, some grout shall be allowed to pass through the ducts and be wasted to ensure removal of any moisture trapped within the duct.

No grouting of pre-stressing tendons shall take place during cold weather periods unless the temperature of the ducts is above 2 °C. The temperature of the grout shall not be allowed to fall below 2 °C for at least 48 h after grouting.

12.4.3.7.3 Placing and bending reinforcement during cold weather

Field-bending of reinforcement (bending on site or in the completed works) is typically not permitted. For particular and limited instances where it is not possible to do otherwise, the following shall apply.

Reinforcing steel shall not be field-bent or -welded unless the temperature is above -10 °C.

If there is a heated bar-bending facility on site, then bar bending can proceed in cold weather.

No bar partially embedded in concrete shall be field-bent except when specified explicitly on drawings.

12.5 Mechanical systems

12.5.1 Introduction

For mechanical systems in platforms operating in arctic and cold regions, the following provisions apply.

- a) Materials chosen shall be suitable for the conditions under which they are intended to perform, such as low temperatures and subject to the magnitude of action effects (such as internal overpressure) and repetitive action effects (fatigue).
- b) The systems should be designed such that water inside or outside the systems cannot freeze.
- c) The external parts of the mechanical outfitting, including appurtenances, should be located or designed such that they are protected from ice actions, or such that their function is not hampered by the presence of ice.

12.5.2 Permanent mechanical systems

12.5.2.1 Crude oil storage systems

For wet storage systems, measures shall be taken to avoid the freezing of the water underneath the oil and in the connecting piping systems. Heating, insulation and circulation of the water are possible protective measures.

The requirement for measures to avoid possible clogging of the system due to presence of ice frazil in cold water should be assessed.

12.5.2.2 Other storage systems

The considerations for other storage systems, including permanent ballast water systems, seawater systems, drains, sumps and bilges, should be the same as in 12.5.2.1 for crude oil storage systems.

The inlets and outlets of seawater systems should be located in areas where they cannot be damaged by ice.

12.5.2.3 Risers and J-tubes

In addition to the provisions of ISO 19903, risers and J-tubes shall be routed to avoid damage by ice.

12.5.3 Mechanical systems — Temporary ballasting/deballasting water systems

The considerations for temporary ballasting/deballasting systems should be the same as in 12.5.2.1 for crude oil storage systems.

12.5.4 Attachments and penetrations

Attachments to the external surface of the concrete structure should preferably be located away from areas subjected to ice actions. If deemed feasible, the attachments or special protective structures should be designed for ice actions.

Materials and welding procedures adapted to the actual temperatures during welding and during the design service life on site shall be used.

12.5.5 Mechanical systems — Design of piping supports

For arctic offshore structures with the potential for impact by large ice features, high intensity local ice actions can cause large deformations in the structure. Piping and piping supports shall take such effects into account.

12.6 Marine operations and construction afloat

Marine operations and construction while afloat shall be conducted in accordance with ISO 19901-6.

Ice actions shall be included in the design situations for operations during temporary phases.

12.7 Corrosion control

The detailing of corrosion prevention measures should recognize the presence of mobile ice. The cathodic protection design shall take into account that it is generally not feasible to locate anodes in zones subject to ice action. Further, where steel plates are used to prevent ice abrasion of the concrete, allowance should be made for sufficient current drain from the plate when sizing cathodic protection. The extent of coating loss through abrasion should also be considered.

12.8 Inspection and condition monitoring

Special attention shall be paid to deterioration due to abrasion, scour and spalling/cracking due to ice impact and to freeze-thaw attacks.

Special attention should be paid to possible degradation of concrete protected by external steel panels and not easily accessible for visual inspection.

Inspection and condition monitoring should be conducted on an annual basis, or as required to monitor ice effects on the concrete.

13 Floating systems

13.1 General

Floating systems operating in arctic and cold regions shall comply with the provisions of ISO 19904-1, while their mooring systems shall comply with the provisions of ISO 19901-7. This document provides additional requirements and guidance for floating systems in arctic and cold regions. Particular emphasis is placed on ice actions and hull design, cold weather materials, the design of marine systems, and disconnection. In addition, the provisions of ISO 17776 shall be used when operational measures (see 8.2.7 in this document) are implemented for a floating system.

Requirements and guidance are provided for the design and operation of floating systems to support the following functions:

- production;
- storage;
- offloading; and
- drilling.

Types of floating systems considered within the context of this document include:

- a) ship-shaped hull (e.g. floating production, storage and offloading facility (FPSO), floating storage and offloading facility) or barge units;
- b) column-stabilized (e.g. semi-submersible), spar and buoy type units; and
- c) shallow-draught cylindrical structures.

The provisions of this clause are not exclusive to steel structures and can be applied to concrete structures and various composite structures.

The provisions of Clause 13 may be applied to other temporary or permanent deployments of floating systems that are used as part of oil and gas operations in arctic and cold regions. While this document does not apply specifically to mobile offshore units, see ISO 19905-1 and ISO 19905-3, the procedures relating to ice actions and IM contained herein are applicable to the assessment of such units.

The floating system includes the hull, marine systems, offloading systems, mooring or stationkeeping systems used to maintain station, and risers connecting the unit to the well head. Floating systems can also be used to support other types of subsea operations. The floating system can also include IM systems when used to reduce ice actions in the context of 8.2.7.

13.2 General methodology

13.2.1 Design and operational philosophy

The design philosophy and operational approaches for floating systems can include the following:

- a) potential to suspend operations, disconnect from moorings and risers, and move off location, to avoid adverse ice conditions;
- b) physical IM measures to actively modify ambient ice conditions and thereby mitigate ice actions.

The approaches a) and b) require ice surveillance and threat assessment, see Clause 17.

The design and operational components of a floating system and its subsea components shall be treated jointly as a system, including IM support where provided.

Where applicable, the system shall also include temporarily attached offloading tankers and attending vessels.

13.2.2 Design and operational approaches

The following design and operating approaches can be used for floating systems in ice-prone waters:

- a) active: move-off capability, physical IM capability;
- b) semi-active: move-off capability, no physical IM capability;
- c) semi-passive: no move-off capability, physical IM capability;
- d) passive: no move-off capability, no physical IM capability.

Measures that are intended to mitigate ice actions in accordance with 8.2.7, including IM, shut-in, and move-off strategies, should be properly identified, considered and quantified, along with expected levels of effectiveness and reliability, see Clause 17. Particular consideration shall be given to the effectiveness and reliability of IM measures associated with semi-passive operating approaches.

Operational strategies may be used to influence the exposure level for a floating system, see 7.1.4.

13.2.3 System considerations

All relevant issues and associated parameters for each design or assessment situation shall be taken into account, including, but not limited to:

- type of structure, e.g. permanent, temporary;
- operating period, e.g. seasonal, all-year;
- metocean conditions, e.g. winds, waves, currents, temperature, visibility, water depth;
- ice features, e.g. FY and second-year (ridges, rubble fields, landfast ice, pack ice), glacial (small ice masses, icebergs), MY (floes, ridges);
- ice conditions, e.g. ice concentration, high ice drift speeds, changing drift directions, ice pressure events;
- remoteness and proximity to shore;
- IM capability;
- brash ice and its influence on IM effectiveness;
- stationkeeping method, e.g. moored, dynamically positioned;
- operations, e.g. operating, standby, disconnecting, reconnecting;
- human factors, e.g. cold stress, isolation;
- system components, e.g. risers, subsea, offloading tanker;
- storage capacity, i.e. with or without;
- on-site maintenance, e.g. hull, stationkeeping system including anchors, ballast system.

13.2.4 Ice alert system

For floating systems, operational responses to mitigate ice hazards shall be conducted under an ice alert system, see 17.1.2. Furthermore, all floating systems shall have in place emergency response plans for ice hazards, see 18.1.

The ice alert system can involve ice detection, threat assessment, shut-in, disconnection and move-off operations. Additionally, the ice alert system for active and semi-passive systems involves physical IM operations.

13.3 Environment

In addition to the environmental information requirements outlined in Clause 6, the following factors shall be considered for the design and assessment of floating systems, particularly when IM systems are involved. These factors can include, but are not limited to:

- a) combined influence of ice, wave, wind and current action including tides, and the effect of their respective orientations on the applied actions (e.g. on an FPSO that is designed to vane into oncoming pack ice);

- b) joint effects of ice, waves and structure motions on ice actions, and the areas of the structure where ice impacts can occur;
- c) effects of low air and water temperatures and icing;
- d) beneficial effects of IM for modifying the ambient ice environment and eliminating potentially hazardous ice features within it;
- e) frequency of ice intrusions or presence;
- f) potentially adverse effects of poor visibility, precipitation and darkness on the reliability of ice detection and IM systems;
- g) complicating effects of waves on sea ice and iceberg management methods, and the presence of sea ice on iceberg towing operations;
- h) the increased importance of ice pressure events and combined ice drift velocity and thickness information, particularly for sea IM considerations;
- i) degree of variability of physical environmental parameters;
- j) allowance for flexibility in the application of operational measures to account for uncertainties as a result of lack of long-term physical environmental data;
- k) identification of the full range of ice interaction situations that can give rise to adverse ice effects on a floating system, (e.g. excessive action levels on a mooring system, hull damage from interaction with undetected small ice masses, thruster damage in ice pressure, mooring line exposure to deep draught ice keels).

13.4 Actions

13.4.1 Applicability

The provisions of 13.4.2 to 13.4.7 shall apply to actions on the hull and its components, including turret, buoy, risers, mooring lines and tension legs that materially influence the behaviour of the structure interacting with ice. The provisions shall also apply to attached loading tankers and attending vessels, where appropriate.

13.4.2 Ice scenarios

In addition to the ice scenarios outlined for all structures in 8.2.3, ice pressure events due to convergence of surrounding ice, presence of landfast ice or presence of a coastline shall be considered for floating systems.

13.4.3 System-specific ice actions

13.4.3.1 Active and semi-active systems

For active and semi-active systems, ice scenarios shall be developed and associated with design constraints for the stationkeeping system, including disconnection system capacities, mooring line capacities, anchor capacities, mooring line connection capacity, and dynamic positioning system thrust.

ALS criteria for ice shall be met through demonstration that the stability and integrity of the hull are maintained (see 13.5.1) under the AL action and that suitable emergency response plans are in place (see 18.1). The AL action shall include the AL ice action and other companion actions (see 7.2.3). The calculation of the AL ice action may include the application of measures outlined in 8.2.7 to reduce the frequency of ice events or the severity of ice actions. Emergency response plans shall be in place for active and semi-active floating systems irrespective of the applicability of AL ice actions (see 7.2.2.4).

With respect to ULS criteria, different strategies can be used when EL ice actions:

- a) are less than the stationkeeping capacity; or
- b) are limited by the capacity of the stationkeeping system.

For case b), the EL ice actions shall be defined based on the capacity of the stationkeeping system. For cases a) and b), the EL ice actions shall be consistent with the limit states approach described in Clause 7. The mitigation of ice actions by means of operational measures shall satisfy 8.2.7.

The design, use, and maintenance of barriers shall be such as to ensure they can function over the design service life of the facility (see ISO 17776). These barriers, both physical and non-physical, shall be implemented to meet the alert system requirements (see 13.2.4 and 17.1.2). Operational performance standards shall be developed in accordance with ISO 17776 to ensure that structural reliability is adequate over the design service life, in accordance with Clause 7 of this document.

Ice scenarios and the related ice parameters shall also be developed and associated with operational constraints for the floating system, including offsets, disconnection limits, heave and pitch motions, and other constraints associated with the disconnection process.

An operating envelope of ice parameters, which is the basis for the ice alert system, shall be developed to correspond with the design limitations and the operational constraints of the stationkeeping system under the various ice-operating situations. The factors on the constraints associated with the stationkeeping system and on the relationship between the corresponding ice actions (and action effects) and associated ice conditions shall reflect anticipated uncertainties.

As an alternative to the requirements of 13.4.3.1, global and local ice actions for active systems may follow the requirements for semi-passive or passive systems given in 13.4.3.2.

As an alternative to the requirements of 13.4.3.1, global and local ice actions for semi-active systems may follow the requirements given passive systems given in 13.4.3.2.

13.4.3.2 Passive and semi-passive systems

For semi-passive systems (see 13.2.2), adequate structural reliability over the design service life, in accordance with Clause 7, can be satisfied by meeting the requirements of 8.2.7, 13.4 and 17. Local and global ice actions may be mitigated by the IM measures applied (see 8.2.7), however their effectiveness, and the response of the structure to the ice actions, should be considered.

For passive systems (see 13.2.2), adequate structural reliability over the design service life, in accordance with Clause 7, can be satisfied by meeting the requirements of 13.4. If uncertainties in ice events and actions are significant, the provisions of 5.5 should be implemented.

13.4.4 Determination of global ice action effects

The hydrodynamic characteristics of the floating system shall be considered in the calculation of global ice action effects. In addition to the requirements of 8.1, the flexibility of the stationkeeping system shall be considered when determining ice actions on floating systems.

Ice actions and action effects cannot be determined with the same level of confidence and repeatability as for open-water floating systems. To that effect, due account shall be taken of the uncertainties associated with ice actions and action effects on floating systems.

Due consideration shall be given to the response of the floating system to ice actions and the corresponding changes to the ice interacting with it.

Since the partial action factors for environmental actions provided in Clause 7 were not calibrated for a full range of floating system configurations and ice conditions, site-specific calibration is recommended. The calibration should reflect uncertainties in the ice action calculation procedures, the managed ice environment (for active and semi-passive systems), and the operational measures for the stationkeeping vessel in adverse ice conditions.

Relevant full-scale data for floating systems shall be the primary reference for the calculation of ice actions on floating systems. Reference can be made to 8.2.1 for guidance on the use of full-scale data. Appropriate corrections should be made for differences in the ice conditions and ice events encountered, vessel or structure dimensions, vessel or structure shape, stationkeeping system and operational protocols.

In the absence of full-scale data, appropriately scaled physical model tests (see 16.5) and numerical and analytical models may be used to calculate ice actions and to assess sensitivities to a range of ice and operational parameters. Such models and components thereof shall be validated with and calibrated to relevant full-scale data, and account shall be taken for uncertainties in their application.

Where appropriate, data from icebreaking vessels including field trials can also be used, with due consideration of differences in the ice conditions and ice events encountered, vessel dimensions, vessel shape, vessel speed and operational protocols.

The superposition of other environmental actions should be performed with care and account for potential non-linear effects.

Independent estimation of ice actions on floating systems using different methods should be undertaken to reduce uncertainty.

Where appropriate, the approaches outlined in 8.2 can be applied to floating systems.

Relevant ice scenarios and ranges of ice conditions shall be addressed to define the design and operating envelopes. This process, known as response mapping, shall include determination of actions and action effects on all relevant elements of the floating system. The aim of the response mapping is to provide a clear link between the ice conditions (in terms of observable, measurable quantities) and the action effects on the system.

13.4.5 Risk to adjacent structures

The operation of active, semi-active and semi-passive floating systems in arctic and cold regions shall not increase the actions on adjacent structures and facilities, unless they have been assessed for such an increase in actions. Consideration should be given to the potential consequences of changes to the sea ice cover, deflection of icebergs or other large ice features, weathervaning of the structure, disconnection, move-off, failure of stationkeeping system components, and the operation of any vessels used in IM, stationkeeping and move-off operations. Measures shall be in place, whether through operations or design, to mitigate these risks.

13.4.6 Other ice action considerations

Where relevant, the following factors shall be considered when calculating the magnitude and frequency of ice actions:

- ride-down or ride-up of the ice from the initial point of contact, rubble building and any resulting changes in the interaction scenario, including ice intrusions into a turret or its components;
- rotations or changes in orientation of the floating system as a consequence of changes to ice actions, metocean conditions and ballast;
- floaters designed to weathervane to reduce ice and wave actions, and which should have the capability to do this for local sea ice conditions;
- presence of ice lodged within the structure (such as in the legs of a semi-submersible);
- ice adfrozen to the structure or components thereof;
- ice action on mooring lines, risers, propulsion systems, positioning systems, steering systems and other appendages essential to the integrity and operation of the floater;
- friction between the ice and the hull, including the effect of friction reduction methods (throughout the design service life of the structure);
- condition of the surface coating of the vessel hull used for calculating ice actions and allowing for the anticipated conditions throughout the design service life of the structure;
- buffering from surrounding sea ice (including ice floes, ice rubble, brash ice);
- ice actions on the hull resulting from managed ice;

- offloading tanker sheltering in the lee of a structure, taking into account the potential for ice pressure events and rapid changes in ice drift direction;
- actions from the offloading tanker, which shall be included when calculating the actions on the structure and stationkeeping system.

13.4.7 Action variations

The time-varying nature of the magnitude and direction of the ice action (including potential changes in failure modes and ice clearance behaviour) shall be considered where it materially influences the structural response (including stationkeeping system) to the ice action.

Both global effects (e.g. hull hydrodynamics and hydrostatics, stationkeeping system stiffness, foundation resistance) and local effects (e.g. hull response) shall be considered when calculating response to ice actions.

The effect of IM on the physical response of the floating system shall be taken into account.

The effect of slow drift oscillations due to combined ice and metocean actions shall be recognized.

13.5 Hull integrity

13.5.1 Structural philosophy

The applicable requirements of 13.5 shall be satisfied for transit and stationkeeping of a floating structure. The requirements of this document should be considered as additional to those specified in recognized classification society (RCS) rules. International Maritime Organization (IMO) requirements shall be incorporated in the design when applicable.

The stability and integrity of the hull shall be maintained for all floating systems by ensuring that the stationkeeping system and any other attachments to the hull such as risers and umbilicals represent the weakest link. This principle shall cover adverse unforeseen effects, such as failure of the IM system to deliver tolerable ice conditions and failure to disconnect. This principle should also apply for all conditions up to and including failure of the stationkeeping system, as well as in a damaged condition following accidental or AL actions. For accidental situations, the stability and integrity of the hull shall be maintained until the facility has been evacuated (see Clause 18).

The structural integrity and stability of the hull shall not be compromised by actions from the stationkeeping system or any other attachments to the hull such as risers and umbilicals. Attachments to the hull, including mooring lines, risers and umbilicals, shall represent the weakest links. For emergency situations, the integrity of the hull shall be maintained until emergency response plans have been implemented, see Clause 18.

For active and semi-active systems, appropriate ice design situations shall be developed according to 13.4.

For passive and semi-passive systems, hull integrity is ensured by satisfying Clauses 7 and 8 through the specification of EL and AL design situations.

For active and semi-passive systems, hull integrity shall be verified for situations in which the IM system fails to perform as specified in Clause 17.

For active, semi-active, and semi-passive systems, the associated managed ice conditions and disconnection may be factored into the exposure parameter for local ice actions (see 8.2.5).

13.5.2 Hull ductility

The ductility of the hull structure shall account for design values of low air and water temperatures, as outlined in 6.3.1 and 6.4.4.4. Structural steel class and grades for weather-exposed plating and for inboard framing members attached to this plating shall meet

- a) the requirements of 11.9 based on the definition of LAST in this document, or
- b) the vessel class requirements based on site-specific temperatures.

13.5.3 Structural analysis and design

The global and local structural models of the floating structure, e.g. ISO 19904-1, shall incorporate the ice actions specified in 13.4.

The following provisions apply for the ice/structure interaction analysis and for the design.

- a) Global ice actions and action effects shall be specified for the relevant design situations, with due consideration of the stationkeeping system. The floating structure shall be assessed for ULS and ALS criteria.
- b) The area of application for local ice pressures shall be selected to provide the design condition for shell plates, stiffeners, tubulars and other supporting members. Guidance on local ice pressures is provided in A.8.2.5.
- c) Ice actions on appendages shall be calculated, and the limit states should be determined for the appendage, the local structure and the floating structure as a whole. Due consideration for uncertainties in estimating ice actions on appendages should be given. Overloading of appendages should be considered as a ULS design situation for the hull structure.

13.5.4 Structural considerations

Appropriate design and assessment situations shall be developed in the context of 13.5.1.

There shall be no progressive collapse nor shall the inner hull be ruptured by AL ice actions. The interior framing of the structure (e.g. the longitudinal bulkhead and scantlings) shall prevent progressive failure in a damaged state. This should include the inner boundaries, for instance the upper strakes of longitudinal bulkheads, when in the damaged condition.

The hull shall resist emergency disconnect and re-connect actions.

FLS from cyclic ice actions shall satisfy the provisions of ISO 19904-1.

Equipment and structures essential for safe operation of the floater shall meet performance requirements for accelerations arising from impacts associated with EL and AL ice actions.

13.5.5 Condition monitoring

With reference to the provisions of 6.1.2, appropriate ice and physical environmental conditions shall be monitored and documented on a regular basis.

Continuous monitoring of global hull girder bending moments and shear forces shall be undertaken in accordance with ISO 19904-1.

The monitoring system shall be incorporated into the IM and ice-alert monitoring systems in accordance with Clause 17.

13.6 Hull stability

13.6.1 General considerations

Appropriate design and assessment situations shall be developed in the context of 13.5.1. Compartmentation, as well as intact and damaged stability shall be in accordance with ISO 19904-1 or RCS rules, and the additional requirements of 13.6.

13.6.2 Subdivision

For floaters on which hydrocarbons or contaminated water are stored, double hulls shall be provided for the appropriate compartments. All tanks used for fuel oil or for the storage of hydrocarbons or contaminated water shall be protected by double hulls.

Fluids potentially harmful to the environment should not be carried next to the external hull; see also 5.6.

13.6.3 Intact stability

Stability shall be maintained in combination with the various operational loading and ballast conditions under:

- sea spray and atmospheric icing events, distributed in the most unfavourable manner;
- snow events, distributed in the most unfavourable manner;
- ice ride-down or ride-up events;
- factors such as pack ice pressure;
- ice jamming or lodging events between the legs of a multilegged floating system.

13.6.4 Damaged stability

Damaged stability shall include consideration for flooding of adjacent compartments.

Damaged stability calculations shall include the effect of ice accumulation, whether from icing or ice encroachment onto the floating system.

13.7 Stationkeeping

13.7.1 General

The design and assessment of the positioning system for the floating system shall be in accordance with ISO 19901-7 and ISO 19904-1, where appropriate. The specification of actions on all stationkeeping systems should satisfy the requirements of 13.4.

The requirements of ISO 19901-7 dealing with the safety of adjacent structures and facilities shall be addressed in the specification of operating envelopes for active, semi-active and semi-passive systems, and for the stationkeeping design of passive systems, see also 13.4.5.

13.7.2 Design of the stationkeeping system

The stationkeeping system design should be consistent with the operating strategy, see 13.2.

Mooring lines should be routed so as to avoid direct exposure to ice actions in the splash zone and below, depending on the design ice interaction scenarios.

Ice features caught by the mooring lines can result in additional ice actions on the mooring system. These effects shall be minimized by positioning of anchor fairleads and potentially localized IM if this can be accomplished reliably. Additional actions on the mooring system arising from these scenarios shall be included in the system design.

Propulsion and dynamic positioning (DP) systems shall be designed such that ice actions do not result in a single point failure involving loss of position and/or heading.

13.7.3 Disconnection and reconnection

13.7.3.1 System description

The floating system can be configured with a system for disconnection and/or reconnection of mooring lines as well as lines necessary for hydrocarbon drilling, production and export.

13.7.3.2 System requirements

If the floating system is equipped with an arrangement for disconnection, this system shall be designed in accordance with 13.4, 13.5 and 13.6.

13.7.3.3 Mechanical requirements

Specific requirements additional to those of ISO 19904-1 shall include the following, if relevant:

- a) protection from ice for the safe operation of all systems and equipment;

- b) safe design and operation of a disconnectable turret under various ice conditions;
- c) disconnectable component of a turret (e.g. buoy) dropping to a safe distance below the structure and ice feature;
- d) local heaters;
- e) hydraulic and/or pneumatic systems for operation in arctic and cold regions;
- f) design for direct ice actions, where applicable;
- g) materials to satisfy the low temperature requirements of this document;
- h) accessibility and proper operation of all equipment under the expected situations.

13.7.3.4 Disconnection modes

Potential disconnection modes generally include:

- planned disconnection, which is adapted to situations where ice threat is detected in sufficient time to perform the entire planned disconnection sequence;
- accelerated disconnection, which is adapted to situations where the ice threat is detected in time insufficient to perform the entire planned disconnection sequence, yet more than sufficient for emergency disconnection; and
- emergency disconnection, which is adapted to situations of sudden increase in ice threat level, allowing for sufficient time only to shut down wells and to disconnect safely.

13.7.3.5 Reconnection

Particular consideration should be given to system state after disconnection, inspection, possible repair and reconnection criteria.

13.7.3.6 Design

The design of the disconnection/reconnection system should allow for timely and reliable operation. The system shall provide the reliability assumed when calculating the design action. The system shall be designed for disconnection under the combinations of ice and environmental actions relevant for the design situations. The system should also be designed for reconnection under expected ice and other physical environmental conditions.

Suitable and proper backup systems and controls shall be provided.

The system for disconnection can be designed for both (semi) automatic and manual operation.

The disconnectable component of a floating system shall be designed to allow for inspection in the reconnection sequence.

Disconnection criteria shall be defined according to site-specific hazardous ice scenarios and the actions arising from ice events associated with the relevant design situations.

The time needed to perform a successful disconnection shall be consistent with that assessed to give an acceptable level of safety, see 8.2.7 and 13.4.3.1. The ice alert and IM measures shall take full account of the applicable operations and associated time requirements for a planned or accelerated disconnect (see 13.7.3.4).

Reference should be made to ISO 19904-1 for further requirements on disconnectable mooring systems.

13.7.3.7 Move-off

The disconnected floating structure shall be capable of moving away (self-propelled, towed) from the mooring system and any other connected lines safely and in the context of the design and assessment situations. If disconnection requires that the floating structure be towed, the ability to establish a towline shall be demonstrated.

13.7.3.8 Monitoring requirements

Appropriate ice and environmental conditions shall be monitored on a continuous basis, in accordance with the provisions of Clause 17 of this document, and with ISO 19901-1 and ISO 35106.

Relevant monitoring shall be maintained in the disconnected state to ensure the safety of risers and subsea equipment and to allow for safe reconnection.

Monitoring of offsets and stability shall be performed to ensure that the floating system is operated within its operating envelope.

Monitoring of mooring line tensions and thruster actions shall be conducted. Monitoring of accelerations and under-hull transport should also be considered.

The monitoring system shall be incorporated into the IM and ice alert systems in accordance with Clause 17.

13.7.3.9 Overall considerations

For semi-active and active systems, particular attention should be given to alignment of positioning and to disconnection system capacities, and the associated ice alert measures. Alert measures shall be related to the system with the lowest capacity.

Whenever possible, the disconnection system should be reversible until the final step involving physical disconnection.

Relevant steps involved in disconnection sequences shall be described and time required to perform them shall be documented.

Operating limits related to emergency disconnection in sea ice conditions shall consider the offset rise time in the relevant design situation relative to the time required to perform the emergency disconnection and the capability of the disconnection system to function under high offsets.

Decision-making and human aspects shall be considered when determining the time required for performing the emergency disconnection or the accelerated disconnection.

13.7.4 Stationkeeping system failures

The possibility of a failure of any one mooring line or any one or more thrusters shall be considered in ice design and assessment situations in accordance with ISO 19901-7.

Further guidance is provided in ISO 19901-7 and ISO 19904-1.

For semi-active and active systems, the ice operating envelope shall be assessed on an ongoing basis as experience and stationkeeping data are acquired, and shall be reassessed in the event of a stationkeeping system failure occurring as a consequence of ice actions during the design service life.

13.8 Mechanical systems

13.8.1 General considerations

13.8.1.1 Applicability

Mechanical systems of floating production systems can be subdivided into the following main components:

- a) hull systems (bilge and ballast systems);
- b) mooring or stationkeeping systems;
- c) accommodation and associated utility systems;
- d) production and utility systems (produced water system, offloading, material handling, safety systems including fire-fighting).

ISO 19904-1 provides general requirements for mechanical systems on floating systems. Specific requirements for stationkeeping systems are addressed in ISO 19901-7 and in 13.7 of this document. Additional concerns and provisions applicable for operation of systems and equipment onboard floating systems in arctic and cold regions are addressed in 13.8.

Only those mechanical systems associated with a) and b) that normally have a strong interface with the structural design and operation of a floating system are addressed in 13.8. Other mechanical systems for floating systems are considered in Clause 15.

13.8.1.2 Systems and equipment

Mechanical arrangements, systems and equipment essential for the safety of the operation of the unit or for prevention of pollution shall take into account the expected low air temperatures for operation in arctic and cold regions. Heating and insulation systems shall be provided as required.

Essential systems and equipment, when stored or located in an exposed position, shall be rated to perform design functions at the EL minimum temperature, see 5.3.4.

Systems and equipment should be designed so that personnel exposure to cold temperatures during normal operations including routine maintenance is minimized.

Upon failure of the primary heating system, essential systems and equipment exposed to outside ambient air temperatures should be:

- provided with an independent source of heat; and/or
- fabricated from materials that are not susceptible to brittle fracture under the anticipated actions and temperatures.

Heating and insulation shall be provided in spaces where low temperatures can affect the safe working of personnel or affect the proper functioning of equipment.

For operation of systems and equipment in arctic and cold regions, consideration shall be given to the following, if relevant:

- a) requirements for piping systems, pipe fittings and valves containing fluids that can freeze at low temperatures;
- b) use of anti-freeze agents;
- c) provision of heat in addition to the insulation of external pipes and pipe penetrations;
- d) circulation of fluid in closed systems (or when emptying the system) as an option to prevent freezing in the event of loss of heat;
- e) requirements for additional protection in areas where the pipe insulation is exposed to wear/damage due to ice formation and/or removal of ice;
- f) capacity and regularity with regard to drying of air;
- g) requirements for electrical cabling;
- h) altered effect of heating/cooling systems due to use of glycol or other anti-freeze agents;
- i) provision for drainage of fire water, thereby avoiding direct risk to personnel and potential hull instability;
- j) selection of lubricants, with respect to application and function at cold temperatures.

13.8.1.3 Icing and snow

Under given climatic conditions, icing and snow can build up in exposed places on floating structures and marine equipment. Procedures shall be in place for the removal and disposal of ice and snow in such cases. Consideration shall be given to covering critical marine equipment when not in use.

See 15.1.1.4 and 15.1.2 for topsides icing requirements.

13.8.2 Hull systems

13.8.2.1 Sea inlets and cooling-water systems

Sea suction shall be designed such that they can be cleared of slush ice accumulation.

The cooling-water system shall be designed to ensure an appropriate supply of cooling water when operating in ice. The sea cooling-water inlet and discharge for main and auxiliary engines shall be so arranged that blockage of strums and strainers is prevented.

NOTE 1 A strum is a perforated metal box fitted around a bilge suction pipe opening to prevent debris from choking the pipe and bilge pump.

Where ice conditions warrant, the following shall be required:

- a) sufficient redundancy to ensure operation of the cooling system in all expected ice conditions;
- b) one or more sea inlets, situated near the centerline of the floating structure and well aft if possible, the inlet grids of which shall be designed to resist ice actions;
- c) one or more sea inlets sufficiently low to avoid ice accumulation due to pump suction;
- d) increased sea chest volume, including the requirements for auxiliary engines;

NOTE 2 A sea chest is an opening in the hull to accommodate marine system inlets and outlets.

- e) pipe for discharge of cooling water connected to the sea chest and allowing full-capacity discharge;
- f) at least one fire pump connected to the sea chest or to another sea chest with de-icing arrangements;
- g) strum holes designed with sufficient area to prevent clogging with ice;
- h) heating coils installed in the upper part of the chests.

Ballast water may be considered for cooling purposes in special circumstances only.

13.8.2.2 Ballast system

Functional ballast systems shall be developed for use under the anticipated physical environmental and operating conditions over the design service life.

Due to potential for freezing, tanks located fully or partly above the ballast waterline, the line of minimum draught, fore and aft, shall be given special consideration.

13.8.2.3 Marine systems instrumentation

All marine systems instrumentation, including the following, shall be designed for the cold environment:

- oil-gas instrumentation;
- hydraulic instrumentation;
- air instrumentation;
- process control;
- safety control.

13.8.2.4 Lighting

Lighting systems used to support floating system operations shall be designed for ambient low light conditions. Where applicable, searchlights for operation in cold environments should be considered.

13.8.2.5 HVAC and air systems

The following shall be considered in the design and proper operation of the heating, ventilating and air conditioning (HVAC) systems in cold environments:

- ventilation air intake;
- control of humidity;
- demister equipment;
- dampers;
- automatic damper shutting in the event of fan failure, loss of pressure and fire and gas detection;
- icing of ventilation equipment.

13.8.2.6 Starting arrangements

Starting arrangements shall be commensurate with the operating environment.

13.8.2.7 Propulsion, thrusters and steering for self-propelled floaters

The propulsion machinery, gear boxes, shafting, propellers, thrusters, steering gear and pintles shall be designed for transiting and stationkeeping in the operating environment. Consideration shall be made in the design for slowing and jamming of the propeller by ice.

Marine propulsion systems for moored disconnectable facilities (FPSO, floating storage unit) should be adequate for the operating environment, considering design service life and required maintenance.

13.8.3 Offloading systems

Hardware associated with offloading shall be designed to reflect the cold weather environment, cold weather operations, icing, the ice environment and associated metocean conditions, ice actions on the hose, as well as ice actions on the floating production system, the offloading vessel and the offloading system.

Provision shall be made for planned and emergency disconnections where operating limits are exceeded, and should be governed by an ice alert procedure.

13.9 Operations

13.9.1 General

Operations associated with the safe functioning of the propulsion and steering systems, hull systems (bilge and ballast systems), and stationkeeping systems, are addressed in 13.9.

13.9.2 Operations and emergency procedures manuals

A floater shall be equipped with dedicated operations manuals dealing with aspects of operation in arctic and cold regions, such as:

- mobilization to the site;
- installation on site;
- disconnection and reconnection;
- demobilization from site;
- materials and fluids used for operation at low temperatures;
- equipment requiring heating and/or insulation for proper operation;
- inspection and maintenance of equipment;
- physical environmental aspects affecting all operations, including ice alerts and IM procedures (see Clause 17);
- emergency procedures, (see Clause 18);
- requirements for standby and IM vessels;
- ice incursion onto the deck, under the hull or within the hull of the floater system;
- supply and logistics to and from the floating system.

13.9.3 Deck surfaces

Measures to prevent spillage from the main deck surfaces shall include minimum requirements, such as:

- installation of save-alls on the exposed deck and around all drip areas and containment areas;
- provision of safe means of transport on deck;
- installation of drains and scuppers to prevent the formation of ice on deck.

Proper risk analyses shall be carried out to ensure that systems function in combination.

13.9.4 Damage control

Procedures and plans shall be in place to monitor and record the proper functioning of the operations of the floater. These damage control procedures and plans should include approaches such as:

- safeguarding the function of main and fallback systems;
- functioning of mechanical and structural systems;
- frequent tours by experienced crew members;
- proper record keeping.

13.9.5 Equipment and doors

Mechanical systems on exposed decks or in cold spaces shall be checked for proper functioning on a regular basis. This can include approaches such as measurement of temperatures and turning the equipment.

Watertight doors shall be checked to ensure safe operations. In critical operational circumstances, such as during ice alerts, local repair and maintenance activities shall be suspended and watertight doors shall be shut.

The operating procedures of equipment shall be adjusted for arctic and cold regions, and the criticality of such equipment or systems shall be taken into consideration.

13.9.6 Inspection and maintenance

Operation in a cold climate requires dedicated inspection and maintenance schedules, plans and procedures. The severity and criticality of equipment failure shall be taken into consideration in the assessment of priorities.

An operational manual shall be prepared for the proper inspection and maintenance of equipment.

Inspection sequences and procedures shall reflect the distinction between immediately accessible systems and those systems that are not immediately accessible for inspection and maintenance.

13.9.7 Planning and operations

Operational plans shall reflect the remote and challenging work environments, with a focus on the safety of all personnel, the environment and the equipment. Normal and critical operational procedures shall be distinguished.

Documented procedures for the safe transfer of personnel shall be in place. The planning and execution of all logistics shall be dedicated to the intended operation. Selection of transfer equipment, clothing and other gear shall be commensurate with the environment, the equipment and transfer systems available (e.g. vessels, helicopters, accommodation ladders).

14 Subsea production systems

14.1 General

14.1.1 System components

This document deals with ice actions for the flowlines and umbilicals referenced in ISO 13628 (all parts); it does not deal with the pipeline transportation systems referenced in ISO 13623. This document also considers mudline cellars and protection structures that are used for avoidance of actions from ice features.

IM measures associated with intervention procedures for subsea facilities shall be implemented according to clause 17.

14.1.2 Exposure level for system components

An exposure level may be assigned to the entire subsea system or to components thereof. The exposure level for various components of the facility may vary depending on the nature of the material stored or transported and on their role in ensuring the reliability of the entire facility. The presence of hydrocarbons shall be considered in the assignment of consequence categories for the components of a subsea production system. Exposure levels are defined in 7.1.4.

14.1.3 General provisions for ice actions

A subsea production system may be divided into components for the assessment of ice actions; see 14.1.1, subject to the provisions of A.7.1.1.

Ice actions shall be considered in the context of other (non-ice) actions.

14.1.4 Repair

Delays in repair of or access to subsea facilities in ice environments should be mitigated through operational measures, redundancy or other design features.

14.2 Ice and seabed considerations

14.2.1 Interactions above the sea floor

The following parameters shall be included in the assessment of ice actions:

- sea ice ridge or iceberg keel draught, shape, mechanical properties and frequency;
- ice drift speed and direction;
- hydrostatic and hydrodynamic characteristics of ice features that can have an effect during keel interaction with a subsea facility;
- properties of the seabed soils and foundation, where appropriate.

The provisions of 8.2 shall also apply for subsea structures.

14.2.2 Interactions for gouging ice features

For interactions with subsea facilities or equipment below the sea floor, the following parameters should be included in the assessment of ice actions:

- location, frequency and orientation of ice gouge events, distinguishing between events in which the sea ice ridge or iceberg keel drags along the seabed (evidenced by furrows) and those in which the keel drops onto the seabed (evidenced by pits);
- ice gouge geometry, including length, width and depth, and corresponding variations along and across the impressions in the seabed;
- rise-up, the excess draft of the ice feature that typically varies along the gouge length;
- ice gouge effects, including pressures exerted on the seabed soils and consequent soil displacements;
- mechanical properties of the soil and the sea ice ridge or iceberg keel.

NOTE For correction of ice gouge frequency and draft measurements with respect to infill effects, see ISO 35106.

Ice gouge data requirements and measurements shall be according to ISO 35106.

14.2.3 Strudel scouring

The following issues should be considered in the assessment of actions due to strudel scours:

- location and frequency of strudel scour events;
- dimensions of strudel scour features and their geographical variability;
- mechanical properties of the soil.

Strudel scour data requirements and measurements shall be according to ISO 35106.

14.2.4 Permafrost

The following issues should be considered in the assessment of permafrost actions:

- spatial distribution and depth of permafrost;
- temperature and salinity of permafrost;
- thermal properties of the permafrost;
- mechanical properties of the soil and permafrost, including dynamic behaviour;
- potential changes in the above over the design service life.

Permafrost data requirements and measurements shall be according to Clause 9 of this document and to ISO 35106.

Special consideration should be given to trenching or digging in seabed soils containing permafrost, whether for installation or placement of production system components, flowlines and umbilicals, mudline cellar construction or anchoring system installation.

14.2.5 Geohazards

Effects of geohazards (e.g. shallow gas, hydrates) as a result of the cold environment, boulder beds, and specific geological conditions in arctic and cold regions shall be considered.

14.3 Actions on subsea production systems

14.3.1 General action requirements

The following shall be taken into account:

- frequency of ice actions;
- magnitude of direct (through contact) and indirect (through soil) ice actions;
- action effects and the changes produced in the state of the structures, equipment and surrounding soil that can influence subsequent ice actions and the response of the soil to such actions; and
- influence of wind, wave and current processes on ice actions, as well as action combinations involving these processes
- seismic actions, according to 8.4 and 14.4.

14.3.2 Ice protection structures

The provisions of 14.3.2 apply to structures designed to protect a subsea facility from ice action and also to any structure designed specifically to displace or otherwise fail under ice actions (i.e. sacrificial structures), thereby protecting the facility.

Direct ice actions and indirect ice actions through soil or rockfill displacements shall be considered in the design of ice protection structures.

NOTE Rockfill refers to granular material used to stabilize or protect a subsea facility.

Changes in the nature, frequency and magnitude of the ice actions, and in the action effects as a consequence of the protection structure, shall be considered.

Through appropriate design, maintenance or repair, a sacrificial structure shall perform its intended function for the design service life according to the requirements of Clause 7.

14.3.3 Mudline cellars

A mudline cellar is an open hole or depression for the burial of subsea facilities below the sea floor in order to reduce the risk from ice keels. Mudline cellars can be cased or otherwise reinforced.

Ice actions and soil properties should be used to determine the shape and depth of the mudline cellar.

The path of an ice feature can be altered by the presence of the mudline cellar. The ice feature can drop into the mudline cellar, be trapped within it for a period of time and then subsequently move out. Corresponding actions and action effects shall be considered.

The motions of the ice keel upon entering the mudline cellar shall be taken into account when assessing the frequency and magnitude of ice actions. Consideration shall be given to gouging ice features, wave-induced motions of ice features and break-up of ice features directly over a mudline cellar.

Clearance above and around the unprotected subsea structures and equipment in a mudline cellar shall be provided to reduce the frequency of ice actions to the probabilities specified in 7.2.2.

Due account shall be made for damage to the subsea facility from debris entering the mudline cellar.

The mudline cellar shall be designed, maintained and dredged to perform its function for the design service life of the system.

Equipment placed in mudline cellars shall be designed for any additional actions (e.g. hydraulic, geotechnical, accidental) and changes to the water temperature associated with its placement.

14.3.4 Risers and loading/unloading systems

The frequency of ice interactions shall be determined based on anticipated environmental conditions, operational schedules and procedures, ice detection capabilities, IM protocols, ice transport under the hull of a floating structure, disconnection systems and disconnection procedures. Disconnected risers include all subsurface components, including buoys that are released and remain attached following disconnection.

Hydrodynamic effects shall be considered in combination with ice actions.

Anchoring and positioning systems (e.g. mid-water buoyancy chambers and associated foundations) shall be considered in the assessment of response to ice actions.

Buoys used for positioning and stabilization shall be designed to resist ice actions, where relevant, according to the provisions of this document.

The flexibility of the system may be used in the assessment of response to ice actions.

Where appropriate, ice actions shall be considered for features that can remain trapped following initial contact.

When in a disconnected state, risers and anchoring systems shall be designed and operated to avoid entanglement with subsea facilities.

14.3.5 Flowlines and umbilicals

Flowlines and umbilicals laid on the seabed, as well as those partially or fully buried, are considered in 14.3.5.

Direct ice actions or ice actions through the soil shall be considered. Appropriate soil, ice gouge and ice parameters shall be considered, depending on the action. For example, the average depth across the width of an ice gouge can be appropriate for the consideration of actions through soil displacement, while maximum depth across the width of the ice gouge can be applicable for direct contact.

Changes to ice keel morphology and mechanical properties as a consequence of interaction with the soil should be considered.

The relative orientation of the flowline/umbilical to ice gouges shall be considered where this materially influences the action.

Extension, ovalization and bending behaviour (and combinations of these) under ice action shall be considered where appropriate. Due account shall be taken of welds and of the state of the line resulting from the laying procedure. Ice actions shall be considered in combination with action effects resulting from operational measures and other environmental actions.

Due account shall be taken of permafrost and of changes, such as upheaval buckling, to the flowline/umbilical and soil as a consequence of operational measures.

Ice actions and action effects shall take due account of the geometry and state of backfill or infill material as a consequence of sedimentation, littoral transport, strudel scours or operational measures. Changes over the design service life of the system shall be given due consideration (e.g. cover requirements for erosion over a buried line).

The influence of weight coatings, gravel coverings, mats and other anchoring structures on ice actions shall be considered.

Ice actions shall be considered in the design of connections. As with other actions, connections are generally designed to release prior to failure of the line or damage to the component.

14.3.6 Resistance to ice actions

Due account shall be made for the interaction between the soil and the structure when assessing the consequences of ice actions.

Structural components below the sea floor and connected to the wellhead may be considered insofar as they can affect the response of the components exposed to ice actions.

14.4 Seismic design

Subsea structures used to protect wellheads, templates and other equipment located on the sea floor from ice shall be designed for seismic actions. Such structures should follow the guidance contained in ISO 19901-2, and ISO 19902 for steel structures and ISO 19903 for concrete structures.

Mudline cellars and berms used to protect subsea equipment from ice can be subject to slope failure triggered by an earthquake. Slopes shall be engineered to prevent such a failure for seismic conditions.

14.5 Risk reduction

Risk reduction measures can include:

- disconnection of all or certain components of the facility;
- design of a preferential failure mechanism;
- removal of all or certain components of the facility;
- installation and operation of hydrocarbon leak detection systems capable of detecting small leaks beneath winter sea ice;
- active operations to remove hydrocarbons from all or part of the facility (e.g. flushing of flowlines);
- use of subsurface or subsea safety valves;
- use of temporary or permanent barriers to alter the ice regime or to prevent ice features from reaching the facility, see 16.3;
- IM measures that alter the ice regime or that prevent ice features from reaching the facility, see Clause 17.

Procedures used to reduce the frequency, magnitude or effect of the action for the facility or a component of the facility shall be in accordance with 8.2.7.

15 Topsides

15.1 Overall considerations

15.1.1 Design considerations for topsides facilities

15.1.1.1 General

Clause 15 supplements the requirements of ISO 19901-3.

Winterizing of equipment, instrumentation and piping is critical for topsides facilities design and operations in arctic and cold regions. Winterizing is also required to protect personnel working in arctic and cold climates, see ISO 35101.

Winterizing can be achieved by a variety of techniques, including the following:

- eliminating pockets or dead-ended pipes and ensuring by design that piping is self-draining;
- maintaining a flow in lines (such as fire water mains and cooling water branch lines) that are sometimes filled with static liquid;
- insulation;
- protective heating, generally combined with insulation; heating can be internal (e.g. when heating components are within a tank or vessel) or external (e.g. when heat-tracing tapes are installed on instrumentation and piping);
- use of an enclosure, generally accompanied by heating from an internal heating element or by a heating/ventilation system;
- use of chemical or mechanical seals on instrumentation;
- use of windwalls to reduce rate of heat loss;
- addition of chemicals to reduce the freezing point of fluids.

Piping for offshore platforms often involves numerous deck penetrations that can present unique accessibility challenges. The design of heat-tracing systems shall consider the installation, operation and maintenance challenges in these areas, especially the areas below decks. When a piping system passes into indoor areas, the extent of heat tracing should be evaluated to ensure that icing in the system is avoided.

Winterization characteristics that should also be considered include the build-up of atmospheric or spray ice, as well as protection for personnel and equipment from ice falling from higher equipment, flare towers and communication towers.

Sufficient capacity shall be considered in the steam, electric or hot oil-tracing system for losses, system deterioration (internal or marine fouling) and expansion for additional equipment.

Special attention shall be given to systems and equipment that generally do not require protective heating to determine whether protective heating is required during start-up, operation and shutdown periods. A list of typical systems and equipment is given in A.15.1.

15.1.1.2 Low temperatures

Low ambient air temperature and low temperatures at various positions can have a significant impact on the selection of materials for construction and for systems and equipment.

Critical systems, equipment, and materials shall function at temperatures down to the EL minimum temperature at their position. Other systems and equipment shall function to the LOST specified by the owner, see 5.3.4.

Metals that can become brittle at the LOST or, if safety-critical, at the EL minimum temperature, shall not be used in the construction of piping and equipment. Reference should be made to ISO 19901-3 in respect of low temperatures.

Some polymers become brittle and crack easily at low temperatures. These polymers should be avoided in, for example, cable insulation.

Structural materials shall be selected and tested based on the requirements of 11.9 and the LAST.

15.1.1.3 Sea and glacial ice — Impact on topsides structures

Topsides facilities, decks and working surfaces shall be designed for ice actions based on the annual probabilities of exceedance for EL and AL specified in 7.2.2.3 and 7.2.2.4 respectively. In the absence of data to quantify the potential for ice events, ice actions shall be assessed as if there were a reasonable probability of interaction. All realistic interaction scenarios with potentially adverse consequences should be considered in this respect. Reference should also be made to 8.3.1.5 for wave-induced ice motion and Clause 18 for EER equipment.

In addition, the following issues shall be considered in the design of the topsides production system, support structures, piping, equipment and fixtures:

- ice actions on the substructure inducing abnormal vibration similar to vibration experienced during seismic events;
- normal, continuous actions on the substructure associated with short-period ice-induced vibration;
- resonance between the natural (ice-induced) vibration/frequency of the structure and the vibration/frequency of rotating production equipment (i.e. compressors, pumps, gas turbine power generators).

Fatigue shall be given particular attention at cold temperatures.

15.1.1.4 Ice and snow accumulation

Ice on topsides can occur in the form of atmospheric icing or sea-spray icing. Ice accumulation and snow can also result from hail and snow falling on the production deck. Consequently, due consideration shall be given to the environmental actions (such as weight and aerodynamic actions) on the design of structures, see 8.3.1.

The weight of snow (noting that wet snow can have a density of between 400 kg/m³ and 500 kg/m³) or ice shall also be considered in the design of equipment, including insulation covering hot process

equipment and piping. Certain insulations (e.g. foam-based) can easily be crushed and become ineffective if sufficient weight is applied to them.

15.1.2 Operational measures

The effects of icing and snow build-up should be minimized through physical, chemical or thermal management methods. Egress and operations routes should be kept clear of ice and snow. Meteorological forecasting can help predict the formation of new icing and snow, which can be used to mitigate the impact on the production system operations. Special attention shall be given to the operations of topsides equipment on floating vessels where sea-spray icing can occur.

Measures initiated to remove ice shall not increase the risk of accidents from falling ice nor increase health hazards due to use of chemicals.

15.1.3 Sparing philosophy

15.1.3.1 Bulk spares

Due to the remote nature of most offshore facilities in arctic and cold regions, consideration shall be given to ensuring that sufficient bulk spares are provided for systems critical to health, safety and the environment. Serviceability-level ice events shall be considered with respect to the probability of failure of a critical system that makes the structure inaccessible by a work-boat, helicopter, etc., whereby the critical system can become inoperable for a duration that can have an adverse impact on the health or safety of the offshore personnel.

15.1.3.2 Equipment redundancy

At least two independent communication system technologies shall be provided on the facility to ensure redundant communication to shore-based facilities under adverse environmental events in arctic and cold regions.

Due to the low temperatures in arctic and cold regions, sufficient redundancy shall be provided in the HVAC (heating) system for the living quarters to ensure that in the event of a system failure, sufficient heat is available until EER plans are implemented.

Redundancy shall be provided for emergency power generation for all structures in cold regions.

15.2 Design and operational requirements

15.2.1 General

15.2.1.1 Deck elevation

For determination of deck elevation, due consideration shall be given to ice run-up, ice ride-up, ice rubble build-up or ice lifted onto the deck, impact of ice features such as icebergs with deck facilities and sea spray causing icing on the deck; see 5.3.3 and 15.1.1.3. These considerations are in addition to meteorological and oceanographic actions on the deck.

15.2.1.2 Enclosures and outdoor spaces

Consideration shall be given to enclosure and heating for process and drilling facilities. Process facilities can be fully enclosed or partially enclosed with vessels and some of the equipment located external to the modules. Rotating equipment should normally be located in a heated enclosure.

Where vessels are located outside, vessel instrumentation including level bridles and transmitters should be located inside the module, in heated enclosures or insulated and heat traced.

Drilling facilities should be fully enclosed except for the derrick or mast for which, where appropriate, it can be necessary to enclose only the drill floor, the racking board and the crown level. Bulk mud and cement tanks as well as pipe laydown areas can also be located external to the modules. A heated pipe barn fully enclosed to the v-door should be available. As a minimum, the pipe barn should be sized to store the largest casing string and spare drilling tubulars.

Consideration should be given to the ventilation of enclosed areas. Of particular concern is ventilation in the case of a possible release of gas or harmful chemicals in enclosed areas; see 15.2.7. An assessment of the ventilation requirements for enclosed areas shall be prepared as part of the design.

External bulkheads and decks shall be insulated to eliminate condensation or icing. This is particularly important for deck areas where a slippery surface can be a hazard to personnel.

Temporary or permanent wind shielding should be provided for exposed equipment requiring periodic maintenance. Laydown areas, external temporary refuge areas and evacuation vehicle/boat loading stations should also be equipped with adequate wind shielding.

Measures shall be considered to reduce the likelihood of ice or snow build-up on walkways and stair treads, for example, by the use of grating.

15.2.1.3 Heating requirements

Normally, enclosed areas associated with unmanned processes and drilling should be heated to 5 °C as a minimum.

Redundant heating equipment and systems should be considered to minimize or potentially eliminate the requirement for operator intervention or insulating and heat tracing, as described in 15.2.1.4 and 15.2.6.2.

Production structure design should consider continued fluid circulation on loss of heating systems during sub-zero conditions. This also applies to gas inerting, where purging air cannot be heated to a temperature above 0 °C. In each of these conditions, heat conservation and winterization design is critical to maintain appropriate temperatures in vessels, piping, and instrumentation.

When the air temperature is below 0 °C, it is not necessary that redundant heating equipment and systems be provided if drilling operations are suspended on loss of the primary heating systems.

15.2.1.4 Intervention

An intervention programme shall be put into place to protect equipment and piping in the event of a heating system malfunction or platform shutdown. This should include drain-down or blow-down of vessels, tanks, equipment and piping as required for the prevention of damage from ice formation and actions caused by the expansion of freezing fluids.

Backup or emergency power systems can be required to maintain critical equipment during intervention, e.g. air compressors and drain handling equipment. Heat tracing, powered from the emergency or backup power supply, can be required for certain equipment or piping that is impractical to drain. Other methods, such as circulation of fluid in piping or agitation of fluid in tanks, can also be used to prevent ice formation.

15.2.2 HVAC, utilities, and power-generating equipment

Air intakes and outlets shall be fitted with weather cowls to prevent build-up of snow or ice. Heat tracing of ventilation intake grills and louvers as well as combustion air intakes should be considered.

Provision shall be made in the design to allow for shut-in of the HVAC system when fire or gas is detected on the platform. If the HVAC exhaust system can contain flammable fumes, disposal of these shall be accounted for in the general platform design.

The HVAC system should provide control of humidity, particularly in manned spaces.

A steam system should be provided for the thawing and cleaning of process and drilling piping and equipment.

15.2.3 Electrical

Cabling used in festoons or drag chains shall be rated for offshore use in marine cold weather climates.

Motors located outdoors or subject to large and rapid variations in temperature shall be supplied with anti-condensation heaters that are energized when the motor is off. Power panels, control panels and junction boxes located outdoors shall be supplied with thermostatically controlled, anti-condensation heaters.

Motors installed outdoors in cold environments shall be supplied to specifications for arctic and cold regions. They shall be constructed with cold temperature steel casings and bearings shall have low temperature lubrication.

Batteries should be kept fully charged and stowed in a heated space to minimize the probability of freezing in cold weather.

The material used for an electrical isolator shall not become brittle at its LOST or, if safety-critical, at its EL minimum temperature. Electrical isolators are used to separate dissimilar metals.

15.2.4 Instrumentation and controls

Instruments should be installed in heated buildings or enclosures. Where this is not practical, insulation and heat tracing should be used and adequate means provided for instrument maintenance.

If steam tracing is specified, pre-traced tubing bundles with stainless steel process and tracing tubes shall be used. Heavy trace tubing bundles shall be used in applications where the process fluid becomes too viscous for proper instrument operation at normal ambient temperature.

Process connections and associated instrument piping shall be traced and insulated in the same manner (light trace and heavy trace) as the process tubing. Care shall be taken to ensure that process taps for flowmeters are traced for even heating and securely insulated.

Electric or glycol heat tracing should be used where liquids can boil if steam tracing is used.

Bulb-type and other fill-type instruments shall be specified with a fill that does not require winterization.

Adequate heat tracing should be provided for each instrument with due consideration to redundancy and the importance of the instrument.

The process characteristics of all instruments that are traced shall be determined prior to the specification of any winterization method or system. Precautions shall be taken not to overheat, to the point of vaporization, instrumentation and instrument tubing that contain bubble-point fluids. Overheating can cause equipment to function improperly.

For instrument impulse lines, consideration shall be given to how the line is to be insulated and traced, particularly for lines run in a tray.

Enclosure boxes for transmitters shall be designed for the cold environment. The electric heat tracing shall not be terminated prior to the point where the impulse line enters the box. The heaters inside the boxes are designed to keep only the transmitter warm, so there is a vulnerable section of the impulse line right at the entrance to the enclosure. Electric heat tracing shall be on the impulse line into the enclosure and shall also be tied to the transmitter sensor.

The facilities design shall include mechanisms to ensure that the motorized power sources for instrumentation, such as instrument air or gas, are adequately dried to maintain a water or hydrocarbon dew point at least 10 °C colder than the LOST (at system operating pressure) or, if safety-critical, at least 10 °C colder than the EL minimum temperature.

15.2.5 Mechanical equipment

15.2.5.1 Vessels

Vessels generally require protective heating only of the liquid space.

- Vessels in acid or other severely corrosive service shall be heated only on the external surface.
- Precautions shall be taken in determining maximum allowable temperature for vessels in acid service, because this temperature varies with the material used and acid concentrations.
- Vessel external instrument “bridles” shall also be considered for protective heating.

In vessels containing water as a separated fluid, heating shall normally be limited to the water draw-off boot.

- a) Heat is required over the entire bottom of vessels when there is the possibility of a refrigeration effect from the expansion of light hydrocarbon liquids.
- b) The presence of a flare knockout drum is an example of when the refrigeration effect should be considered.

Pressure vessels, pressure-containing equipment, and their supports shall be suitable for the LOST or, if safety-critical, for the EL minimum temperature. Impact testing of materials for vessels and their supports can be required, at test temperatures based on the LAST.

15.2.5.2 Fuel

The pour-point of a fuel should be at least 10 °C colder than the LOST or, if safety-critical, at least 10 °C colder than the EL minimum temperature. The fluid viscosity shall be considered in the design of the fuel transfer system.

15.2.5.3 Gas dehydration

Gas shall be dehydrated to at least 10 °C colder than the LOST to ensure that hydrates do not form in the system during normal operation.

15.2.5.4 Fuel gas system

Fuel gas systems shall be heat-traced from the local knockout drums to the outlet of burner manifolds and supplies to engines and turbines, to prevent the condensation of propylene or propane and heavier components. When it is intended to burn propane or heavier hydrocarbons in concentrations above 50 %, vaporizers shall be provided in the knockout drum (in addition to the heat tracing).

15.2.5.5 Insulation

The selection of insulation material should be based on the desired insulation temperature range requirement and the suitability of the material at the given applications. Insulation materials should be rated at least 10 °C colder than the LOST or, if safety-critical, at least 10 °C colder than the EL minimum temperature. Suitable vapour barrier materials shall also be specified for outdoor application.

Insulation jacket type and materials shall withstand the EL and AL actions from snow, atmospheric ice and spray ice build-up.

Inspection requirements shall be considered where vessels or equipment are insulated. Removable insulating blankets can be used.

15.2.5.6 Vibrations

Anti-vibration mounts should be considered for sensitive rotating equipment, such as gas turbines and equipment, and for equipment which induces vibration such as reciprocating compressors. The design of

the mounts should take into account the weight of snow and icing. Vibrations possibly caused by sea ice interacting with the structure should also be taken into account.

Vessel inspection requirements shall be considered where vessels are insulated. Removable insulating blankets may be used.

15.2.5.7 Pumps

For pumps that are located outside or operated when the heating system is not available, pump materials including seals and casings shall be rated for the LOST or, if safety-critical, for the EL minimum temperature.

15.2.5.8 Engine heaters

Standby or emergency engines shall be maintained in heated enclosures or shall be equipped with engine heaters to enable low temperature start-up.

15.2.5.9 Drilling equipment

Drill floor and derrick/mast equipment shall be rated for the LOST or, if safety-critical, for the EL minimum temperature. Kelly hoses, if not heat traced, shall be provided with a means to blow down when mud is not circulating through.

Where drilling risers and wellheads are exposed to low temperatures, a means to prevent the fluid in the riser from freezing shall be installed. Similarly, the injection annulus for a cuttings injection well shall be protected from freezing.

15.2.5.10 Hydraulic oils, lubricants, and coolants

Hydraulic oils, lubricants and coolants that are rated for the LOST or, if safety-critical, for the EL minimum temperature shall be used.

15.2.5.11 Seals and gaskets

Seals and gaskets exposed to operation in low temperatures shall be suitable for the service specified.

15.2.6 Piping

15.2.6.1 Pipe testing and inspection

Piping shall be designed to withstand simultaneous low temperatures and maximum operating pressures.

Piping inspection requirements shall be considered where piping is insulated. Removable insulating blankets may be used.

15.2.6.2 Heat tracing and insulation of piping

15.2.6.2.1 General

Heat tracing and insulation of piping shall be installed when any of the following conditions apply:

- pour or freezing point is warmer than the LOST;
- ice formation or hydrating within the piping occurs due to pressure reduction of moisture-bearing gases;
- corrosive compounds form if condensation occurs;
- condensation occurs in fuel-gas lines;
- flow rates are reduced to an unacceptable level due to increased viscosity of fluid;
- relief piping can become plugged due to freezing or congealing of viscous liquids; or
- liquids in tank or vessel drain lines are subject to freezing.

Protection from freezing should also be considered for piping in low areas of the modules where cold air can accumulate.

Heat tracing can use electric, steam, glycol or hot oil. Electric is preferred where precise temperature control is required or where glycol or steam is not practical.

Redundant or “double tracing” should be considered for critical lines such as relief and flare lines.

15.2.6.2.2 Steam tracing

Steam tracing shall be limited to applications that permit relatively wide temperature variations and may be used in hazardous areas where defects are easily located and repaired.

Steam tracing installations shall be laid out in an orderly manner with provision for thermal expansion and easy access to all flanges, unions, valves, traps, strainers and instruments. Valves and flanges, unions or tubing fittings shall be provided at traps so that they can be tested and readily removed.

Steam tracer supply and condensate return piping shall be valved.

Whenever practical, valves should be located so that they are accessible at grade or from permanent working platforms. When this is not practical, valves should be located so that they can be accessed with a ladder.

15.2.6.2.3 Electric tracing

Electric tracing provides more accurate temperature control. Since electric tracing is sized based on heat losses, the quality and condition of the piping insulation are a critical aspect that should be considered. Excessive heat loss at missing or poorly insulated areas can make an electric traced system ineffective.

Certain types cannot be used in all classified (designated hazardous) areas and defects are usually more difficult to locate.

Classified areas that contain electric heat-tracing systems shall be indicated on a plot drawing that designates the boundary of each classification.

Selection and installation of electrical tracing in hazardous areas should be in accordance with international or applicable national electric codes.

15.2.6.2.4 Hot oil/glycol system

Hot oil/glycol systems provide accurate temperature control where high temperatures are required.

15.2.6.3 Circulation of fluids

Piping systems such as utility water, cooling water, and fire water may be protected from freezing by circulation in lieu of heat tracing. Bleed lines may also be used to maintain sufficient flow to prevent freezing.

Cooling water, utility water and fire water lines should be insulated for condensation control.

15.2.6.4 System draining and blowdown

Piping drains should be installed in all piping low points where required for system draining. Pipe work pockets in lines should be eliminated where possible.

Where winterization by draining, pumping out or heat tracing and insulating is not feasible, connections shall be provided for blowdown of the system with compressed air or gas.

15.2.6.5 Deck drains

External deck drain boxes and associated piping should be heat traced and insulated to prevent frost build-up inside the drain.

15.2.7 Safety

15.2.7.1 General

Due consideration should be given to the effects that enclosures can have on safety issues, such as increased frequency of gas accumulation, increased explosion pressure and additional requirements for area classification and preventive measures. The size of modules with hydrocarbons should be selected to limit the explosion pressure.

15.2.7.2 Blast protection

Blast pressures used for accident scenarios and design of explosion panels should reflect the confined conditions resulting from the presence of sealed compartments.

15.2.7.3 Fire protection

The choice of fire suppression or extinguishing systems should reflect potential hazard to personnel in enclosed spaces.

15.2.7.4 Human factors/ergonomics

Material handling systems consisting of cranes, fixed davits and mono-rails should be considered.

Due to the potential of snow and/or ice settling on the production decks, cart-based material handling systems should be avoided. Because of low temperatures, solutions requiring assembly should also be avoided (i.e. A-frames).

15.2.7.5 Safety showers and eyewash stations

Safety showers and eyewash stations intended for operations at temperatures below 0 °C shall be located in a heated enclosure and water lines to the showers/stations shall be trace heated with thermostatically controlled, low voltage electric heating systems.

15.2.7.6 Changing rooms and storage

Topsides facilities for arctic and cold regions should provide changing rooms and personal storage facilities for additional cold weather items and personal protective equipment that can be required.

15.2.7.7 Safety equipment

Monitors, hose reels and deluge and sprinkler skids shall be fitted with heat tracing or cabinet heaters as required.

15.2.8 Relief and flare systems

Consideration should be given to adding pressure safety valve (PSV) outlet piping with weep holes, allowing water to drain and thereby prevent freezing. Weep holes should be large enough to ensure that rain water collecting in the tail pipe can drain out. The weep hole should be in the base of the elbow at the PSV outlet. A weatherproof cover should be installed over the weep hole.

PSV sizing should be adequate for the LOST or, if safety-critical, the EL minimum temperature.

Heat tracing or insulation should be considered to prevent freezing of balance bellows PSVs.

Rupture disk material should be selected to account for ambient temperatures, including daily variations.

The flare header knock-out drum shall be insulated and heat traced. Consideration should be given to installing heating in the flare header knock-out drums/water seal drums.

Provision shall be made for draining liquids from low points in piping and equipment. To reduce hydrate formation, low points on a flare header or relief system where liquid can accumulate should be drained.

Consideration shall be given to insulating and heat tracing the flare system piping downstream of the flare header knock-out drum in order to prevent potential ice build-up in the flare tower piping.

15.2.9 Storage tank valves

To minimize failures due to freezing within the channel of a closed ball valve, consideration shall be given to the use of pre-drilled ball valves for the storage tank drain and load valves application.

The storage tank relief system should be designed to avoid potential freezing of water accumulation. Relief valves for atmospheric storage tank overpressure and vacuum protection shall be designed to avoid any water accumulation that can lead to the seat sticking from freezing.

15.2.10 Actions on structure

For multi-leg substructures with the deck rigidly connected to the substructure, differential and multi-directional ice actions on the substructure legs shall be considered for the deck design. Typically, the exposed legs experience larger actions than the downstream legs.

Snow and ice accumulations can be significant in arctic and cold regions and shall be considered for the global deck design.

Differential temperatures between parts of a single structure (e.g. substructure to deck) can induce differential thermal contraction/expansion. If structures are constrained with respect to each other, then significant internal forces can be generated. These shall be addressed in the deck and topsides design.

To derive thermally induced topsides expansion/contraction values, EL temperatures shall be used to obtain design temperature changes relative to installation temperatures.

Where topsides facilities are founded on man-made islands or on any permafrost foundation, differential settlement should be considered in the design of structures. Provision should be made for shimming of support points to accommodate long-term settlement.

15.2.11 Provisions supply and mechanical handling

Because the structure can be inaccessible from a specific direction for an extended duration, due consideration shall be given to seasonal ice drift directions in locating the laydown area(s) and the cranes.

The operator should consider providing independent cranes and laydown areas in at least two different areas to maximize availability of supply in most ice and metocean conditions.

An approach to mechanical handling should be developed to account for the cold conditions, defining the equipment and routes that can be used for all maintainable equipment.

15.3 Seismic design

15.3.1 General

Seismic design shall be considered, where relevant, for topsides placed on bottom founded structures in arctic and cold regions. The provisions of 15.3 shall be applied to all relevant topsides structures and systems.

Seismic design shall be based on ISO 19901-2 and ISO 19901-3.

15.3.2 Seismic design of the topsides structure

The structural performance requirements for primary topsides structural steel shall be the same those as for the substructure. Little or no damage shall occur for the ELE, while no collapse shall occur for the ALE. In addition, no excessive displacements that can affect the functionality of critical systems or affect EER activities shall occur under the ELE or the ALE. Coupled analysis shall be used for dynamically sensitive topsides or structures containing passive protection systems.

Structural framing shall be configured to the extent possible with a regular pattern and complete systems to resist lateral actions. The flexural strength of columns shall exceed that of intersecting beams. Caution should be used when trying to achieve this goal by using materials with different yield strength. In such cases, the yield strength value given on the mill certificate should be used and not the nominal value.

Where process considerations require irregular framing systems, the framing shall be designed and analysed to demonstrate ductile performance in all directions.

Structural connections shall be designed in accordance with the seismic provisions of ISO 19902. The connections shall be designed for actions based on the capacity of the members framing into the connection, unless the calculated actions are less than 50 % of the member capacity, in which case the joint may be designed for the maximum calculated actions.

15.3.3 Seismic design of topsides equipment and supports

Structural connections should be designed in accordance with a code or standard with recognised seismic provisions.

The anchorage, supports, structural systems and attachments for all equipment shall be designed and constructed to prevent structural and mechanical damage such that the following shall not occur:

- movement of the equipment or components in a manner that can affect personnel safety or emergency egress (e.g. falling, sliding, and toppling risks);
- movement of equipment in a manner that can affect function of adjacent designated critical systems equipment (e.g. via impact);
- loss of containment of materials that can have significant fire or health, safety and environment (HSE) consequences.

Supports for piping and other similar systems shall be designed such that damage does not occur during an ELE and collapse does not occur during an ALE. However, damage to individual supports during the ALE is acceptable.

In-structure accelerations or spectra (vertical and horizontal) shall be used to determine seismic actions of the equipment or supports at their relative location on the topsides, based upon the structural analysis of the topsides structure described in 15.3.2. Time history analysis should be considered for dynamically sensitive equipment, such as communications towers or drilling masts.

For distributed systems, such as different modules that cross between structural systems, actions due to potential out-of-phase differential displacements shall be considered. This includes actions on the distributed system itself, as well as actions on the support system. They also apply to components required to contain hydrocarbons or maintain functionality of critical systems.

Piping containing hydrocarbons or hazardous materials shall maintain pressure integrity following the ALE. Piping spanning between flexible components, modules, skids, etc., shall have adequate flexibility to withstand movement of "anchor points". Cable trays, conduit and other similar systems shall be required to maintain their general position following an earthquake.

Prior to commissioning, field inspections of the topsides should be performed by experienced engineers to ensure that adequate seismic design has been implemented. These inspections should focus on areas of concern that are not obvious in drawings. A primary emphasis should be on differential displacement issues and design details. Potential seismic interactions should be investigated. The inspection should also include a review of field-routed items, such as small-bore piping or instrument air lines that can be damaged in an earthquake.

15.3.4 Seismic design of component interfaces

The interface of the offshore structure with other structures and equipment such as bridges or systems such as subsea pipelines shall take into account the relative motions between these systems that can occur during an earthquake.

15.3.5 Passive protection systems for seismic design

Guidance on the design and testing of seismic passive protection systems is provided in 15.3.5. The provisions shall be applied to all such systems, whether they are used to protect an entire platform or parts thereof. The guidance is aimed mainly at seismic isolation and energy damping systems.

Appropriate analysis procedures should be used for the design of the passive protection systems and for the design of a protected structure for the ELE. Such procedures include single mode or equivalent static analysis and response spectrum analysis.

Detailed non-linear time history analysis shall be used to verify the ALE performance of all structures with passive protection systems. The non-linear model shall account for the non-linearity of all passive protection devices as well as the non-linear behaviour of the protected structure, where such behaviour is expected.

The passive protection system shall be designed with consideration given to conditions such as low temperatures, wind, sea ice, waves, ice accretion, aging effects, creep, fatigue, operating temperature, and exposure to moisture or damaging contaminate substances.

Means of access for inspection and replacement of all components of the passive protection system shall be provided. An inspection plan and schedule shall be developed to establish a periodic monitoring, inspection and maintenance programme for passive protection systems.

A fabrication quality control and testing programme for passive protection systems shall be established.

Prototype tests shall be performed on each type and size used in the design. Representative sizes of each type of device may be used for prototype testing, provided that the similarity of the device to previously tested devices can be substantiated. Test specimens shall not be used for construction.

Passive devices shall be replaced following any seismic event that exceeds the ELL, unless structural analysis or testing can demonstrate otherwise.

16 Other ice engineering topics

16.1 Ice roads and supplies over ice

16.1.1 General

Ice roads provide temporary and seasonal access routes to locations otherwise inaccessible by road, and produce minimal long-term disturbance to the environment.

Floating ice roads, which can also be termed bridges, provide temporary water crossings. They are constructed from natural ice, which can be thickened artificially, if required, to allow safe passage of loads, see 16.1.5.

Grounded ice roads are supported continuously along the ground or seabed. The design and operational requirements for floating and grounded ice roads are different.

Expert guidance should be sought in determining the proper design ice thickness, construction technique and operating procedures.

16.1.2 Floating ice design criteria

Ice roads shall be designed and operated to minimize risk to life, damage to the transfer system and risk to the environment.

Static bearing capacity shall be ensured by verifying that the ice cover does not fail in flexure and the freeboard remains positive for any action up to and including the specified operational action.

NOTE Loss of freeboard is generally associated with stationary loads and causes gradual flooding of the ice cover, submergence of the load and rapid deterioration of the ice bearing capacity.

The bearing capacity of an ice road shall be assessed in one of two ways:

- a) application of the provisions of Clauses 7 and 8; or
- b) application of the prescriptive methods and parameters outlined in A.16.1.

Calculation methods shall be based on sound physical principles and previous experience shall be taken into account.

16.1.3 Ice flexural strength for design

The bearing capacity of the ice is determined by its flexural strength. Preferably, the flexural strength should be either estimated by in situ beam testing or derived from measurements of the physical properties of the ice. Otherwise conservative estimates for flexural strength can be developed by experienced ice engineers. See Clauses 7 and 8 for guidance on representative values.

16.1.4 Dynamic behaviour and dynamic amplification factor

Actions such as those arising from moving vehicles create pressure waves in the water under the ice. A floating ice sheet has a characteristic wave-propagation velocity for flexure that increases with the ice thickness and decreases with the water depth. If the velocity of the moving load approaches this characteristic velocity, the deflections under the load can be amplified relative to those for static actions.

A maximum speed for moving vehicles shall be established to prevent dynamic amplification of deflections and stresses in the ice. This is particularly important if the mass of the vehicle is close to the maximum static mass determined for the particular ice thickness.

Elastic waves in the ice can be amplified as a result of superposition with waves reflected at shoreline. As a result, shore approaches that are normal to the shoreline should be avoided. The incorporation of oblique shore approaches can be used to mitigate this effect.

16.1.5 Construction procedures

Ice road thickness shall be sufficient to meet the bearing capacity requirements of 16.1.2 prior to use.

The thickness of the ice road (or bridge) shall be measured at regular intervals along and across the road. Measurement intervals of 25 m to 50 m are typically employed. The interval shall be adequate to determine the average minimum ice thickness with sufficient confidence to ensure that thin or weak spots are located. The interval between measurements shall be decreased where anomalies are indicated or suspected.

For longer roads, it can be necessary to subdivide the road into lengths or sections, known as reaches, and then to determine the average minimum thickness for each reach.

The thickness should be determined by drilling holes through the ice using augers or thermal means and measuring the thickness using a tape or a calibrated stick or rod. Visual estimation of the ice thickness is not acceptable. Continuous thickness profiles may also be obtained using electronic methods but, if so, periodic calibration of the device shall be performed by measurements of thickness from regularly spaced holes.

Ice road thickness can be increased by flooding in order to meet the bearing capacity requirements.

Complete coverage of the road surface during the flooding process is important and thus adequate equipment, personnel and support are required. If pumps are used, they should be capable of operating at the LOST for the site. Flooding shall be conducted only when the ambient temperature is sufficiently below freezing to allow the flood water to freeze. Time intervals between applied floods shall be sufficient to allow previous floods to completely freeze before the next is applied. The thickness of each flood layer should normally be between 35 mm and 50 mm. Free flooding, whereby the water is allowed to flow freely from the pump without restraint, should be used to avoid undue stress concentrations. Dyking with snow should be used only where necessary to contain the water. Loads from other sources, such as spoil piles stored on the ice or snow banks, should also be taken into account.

16.1.6 Safe use of ice roads

Vehicles should drive below the specified maximum speed, particularly near shore approaches (see 16.1.4), and there should be a minimum separation distance between trucks and other large vehicles based on bearing capacity restrictions (see 16.1.2).

The mass of equipment and vehicles placed on the floating ice road shall be determined accurately from existing records and reliable knowledge, or shall be obtained by weighing using available highway load scales or equivalent means. This weighing requirement also applies to any equipment or vehicles used in the thickening process of the ice.

The ice road shall be inspected for wet cracks, which run the entire depth of the ice. Bearing capacity shall be verified (see 16.1.2) and appropriate mitigative action shall be undertaken where necessary to ensure safe travel.

16.1.7 Grounded ice roads

Grounded ice roads are usually suitable for construction in very shallow water or on tundra or swamp. Grounded ice roads can also be used to cross streams or channels. Typically, the ice is thickened and pushed down by its own mass onto the underlying soil. Roads can also be constructed onshore to protect the native soil, vegetation or tundra from damage by wheeled and tracked traffic.

Soil provides a stiffer support or subgrade than water for the thickened ice. The ice shall be constructed with sufficient thickness to spread the wheel loads and avoid overstressing of the tundra subgrade. In the case of offshore grounded ice roads, the value of the subgrade stiffness and strength shall be high enough to ensure that the ice is not overstressed.

16.1.8 Helicopter landings on ice

Helicopters are sometimes required to land on sea ice, for example to rescue or to provide access for personnel. In such cases, the criteria recommended for ice roads in 16.1.2 can be applied. When operating procedures such as leaving rotors on are used to reduce the risk of breakthrough, the criteria recommended for ice roads in 16.1.2 may be reduced.

16.2 Man-made ice islands

Man-made ice islands have been used for exploration drilling and relief-well purposes in arctic and cold regions. There are three basic types of ice islands:

- a) grounded ice islands, created from flooding, spray ice and chipped ice;
- b) floating or grounded ice islands, created by flooding to thicken the ice until sufficient area with sufficient bearing capacity is created;
- c) rubble manipulation, with or without flooding and spraying.

Design and maintenance criteria for man-made ice islands are provided in A.16.2.

16.3 Protection barriers

16.3.1 General

If the design ice actions on structures are contingent on ice defence and ice control methods, this shall be specified in the design and operational documentation. The operator shall ensure that these methods are properly maintained during the design service life of the structure as appropriate to the life-safety and consequence categories.

16.3.2 Ice protection structure

16.3.2.1 Grounded ice as a protection barrier

If grounded ice rubble forms around a structure, the ice actions on the structure can be reduced because changes in the ice failure modes experienced at the rubble boundaries can result in lower effective ice failure pressures, and consequently lower global ice actions. In addition, the grounded ice rubble can absorb part of, or all of, the ice action. Consolidation of ice rubble over time in the vicinity of a structure should be considered in the transmission of actions to the structure.

The action of ice on grounded ice rubble shall be determined using the principles for ice actions described in Clause 8.

The sliding resistance of the ice rubble depends on its dimensions, its mass and the characteristics of the interface between the ice blocks and the sea floor. Interface strength can be reasonably well defined if the rubble is grounded on a sand berm. If the ice rubble pile is grounded on the natural sea floor, the interface strength can be uncertain, and requires investigation and assessment of both geotechnical and ice mechanics aspects.

The sliding resistance of grounded ice rubble shall be determined using the principles of foundation sliding resistance. Further provisions with respect to failure mechanisms are given in 10.3.4.5.

Additional guidance on grounded ice as a barrier and how it can be supplemented with spray ice is given in A.16.3.

16.3.2.2 Rubble generation

Natural rubble generation can be supplemented using rubble generators, typically consisting of structures deployed on the sea floor to stimulate the rubble formation and provide protection from drifting ice impact.

Stability of rubble generators and rubble generation effectiveness should be maintained for the expected range of water level.

The potential for interaction between rubble generators and the structure, as well as other components of the production system, shall be considered.

Ice rubble generators may be considered in the assessment of ice actions if their effectiveness can be demonstrated in the context of Clauses 7 and 8.

The designer should consider ice conditions that can affect the efficiency of rubble to reduce the ice pressure or global action. For example, the accumulation of ice rubble on the face of wide structures can significantly affect the ice failure mode and the resulting ice actions.

16.3.2.3 Ice barriers

Ice rubble may be used as an ice barrier and may be supplemented with spray ice. If the seabed consists of a frictional material (e.g. sand), the ice barrier can be built with a smaller cross-section and a high freeboard to minimize the lateral ice actions. If the seabed consists of a cohesive material, large spray-ice/rubble barriers with a low freeboard can ensure adequate sliding resistance.

If a spray island/barrier is built on a smooth, level ice sheet, consideration should be given to the ice sheet impeding the drainage and consolidation of a cohesive soil.

Lateral ice actions on the spray ice/rubble barrier tend to cause failure in one of four ways:

- a) sliding along a weak plane through the ice barrier;
- b) sliding along the bottom at the ice-soil interface;
- c) sliding along a weak plane through the soil;
- d) passive edge failure.

Grounded ice islands or ice protection barriers shall be designed to resist lateral ice actions insofar as they are used for developing the design ice actions on the structure. Further provisions with respect to failure mechanisms are specified in 10.3.4.5.

16.3.2.4 Ice actions and ice/barrier interaction

When grounded ice rubble is used to limit the ice actions applied to a structure, then site-specific soil parameters, representative ice rubble properties and ice rubble geometries consistent with the structure and local ice conditions shall be used. The possibility that grounded ice rubble can be crushed or otherwise displaced after formation should be considered. Prudent design should, therefore, assess both

the potential for loss of protection from a grounded ice rubble field after formation and the ice actions that can result both during and following displacement.

Knowledge of ice rubble properties is important for characterizing the transmission of ice actions to the structure. In areas of low sail height and minimal snow cover, heat loss through rubble can be large and the refrozen layer can attain thicknesses that are double the normal ice growth for the region. The characterization of the refrozen layer is important with respect to the potential action transmission.

The strength and elastic modulus of the refrozen ice layer should be estimated from in situ measurements. Large-scale in situ tests are the best indices of strength. Measurement of salinity and temperature is not a reliable means of determining the strength of the refrozen ice layer.

The properties of grounded ice keels affect how ice actions are transmitted to the sea floor, or to an underwater berm if one is constructed. Generally, ice rubble keels have sufficient strength and stiffness to transfer most of the ice actions to the sea floor or berm.

Appropriately scaled model testing (see 16.5) may be undertaken as an alternative to verify or to supplement calculations of ice actions. Due account should be taken of the capability of the model tests to simulate processes in ice rubble and pile-up formation.

16.3.3 Methods for mitigating the effects of ice

16.3.3.1 Ice control and defence

Passive ice control and defence methods may be used for decreasing the magnitude of ice actions.

If passive ice control and defence methods are employed, they shall:

- be effective for their intended purpose;
- be implemented at all times when the structure is exposed to the ice environment;
- not adversely affect the integrity of the structure in any other way.

A wide range of passive ice control or defence options can be considered, including:

- a) cutting a trench or moat in the ice around an island or structure;
- b) placing barriers in front of the structure to initiate the formation of a grounded rubble pile;
- c) utilizing satellite structures to relieve the ice action on the production structure;
- d) using spray ice to form a protective ring or mounds;
- e) placing piles in front of the structure;
- f) designing the structure's perimeter to minimize local actions.

16.3.3.2 Mitigation of ice encroachment

Ice control and defence methods can be used to protect the structure and its facilities against ice encroachment. Mechanisms addressed should include ice pile-up and override.

Ice encroachments can generally be considered as events causing a local action, and the provisions of 8.2.5 shall apply where appropriate with respect to EL and AL local actions.

Based on the provisions of 7.1.4, reduced exposure levels may be applied to local facilities that can potentially be impacted by encroaching ice.

16.4 Measurements of ice pressure and actions

16.4.1 General

Measurements of ice pressure and actions can be necessary to assure the safety or reliability of an existing structure, in relation to pre-set ice alert levels and/or as part of an IM system (Clause 17). Measurements are also recommended as a way of improving design criteria for future structures, since empirical treatment of full-scale data is often the best approach for determining ice actions for use in design.

If an ice pressure measurement system is used for either purpose, the recorded data should be specific and appropriate for the intended purpose.

The monitoring of ice actions and effects is also considered in Clauses 10 and 13.

16.4.2 Measurement techniques

Ice pressure measurements can involve:

- a) measurements of the pressure or strain in the ice;
- b) measurements of structural and foundation response;
- c) methods for interpreting actual and nominal contact areas;
- d) visual documentation of corresponding failure process; and
- e) interpretation of the measurements.

Examples are provided in A.16.4.

16.4.3 Limitations and requirements for different techniques

The following shall be considered in the interpretation of ice measurements:

- correct set-up of the sensors;
- frequency and stiffness response of the sensors;
- compatibility between the measurement system and ice-structure interaction processes;

- edge effects on the load measurement devices;
- reading and data handling errors;
- proper calibration, and changes over time as a result of environmental conditions;
- methods for interpreting actual and nominal contact areas;
- visual documentation of the corresponding failure process.

With multiple measuring devices in use, the results should be cross-checked for consistency among the different devices.

16.4.4 Documentation of environmental conditions

Physical environmental conditions, such as wind speed, ice movement speed and direction, water level variations and ice feature dimensions (see ISO 35106), should be measured in conjunction with ice actions and pressures.

16.4.5 Observations of the ice-structure interaction process

For ice-structure interaction events, an understanding of “what happened” is fundamental for the correct interpretation of measured ice pressure data. Data on the ice feature and the ice failure mode that occurred should be documented with as much detail as possible. The use of video recording devices to provide this documentation should be considered.

16.4.6 Ice load databases and synopses

Existing ice load databases and synopses should be referenced for calculation of ice actions or for placing site-specific measurements in the proper context.

16.5 Ice model tests

16.5.1 General

Model tests with offshore structures in ice basins can be used in conjunction with other methods of ice/structure interaction analysis for obtaining ice-related design values, provided that appropriate scaling methods are used.

Ice model tests are normally performed to assess global ice actions on the structure, to verify theoretical methods or to investigate basic interaction mechanisms of ice and the structure. Ice model tests can also provide information about ice rubble formation, ice pile-up near the structure, ice jamming and ice clearing around the structure if the main processes present are scaled correctly. Special attention shall be given to tests where local processes involving compressive ice failure are planned.

An assessment should be made as to whether the problem can be investigated reliably using the proposed ice-tank modelling techniques. Attention shall be given to the ability of model ice to simulate processes in broken ice, and interactions between ice and propulsion systems.

Calibration of model results to field data and observations provide added confidence in simulation methods and scaling when model results are extended beyond field information. Particular attention should be given to the relevance of the field data to the ice model tests under consideration, and that environmental conditions and ice parameters are consistent. Confirmation that the ice failure processes are modelled correctly should also be performed in any model test programme. The reporting of ice model testing shall include all relevant ice parameters.

16.5.2 Scaling

In ice model tests, the geometrical and mechanical properties of the ice should be scaled in accordance with a similarity theory that addresses the dominant actions in the test situation. The validity of extrapolation of model scale results shall be demonstrated by comparison with full-scale measurements and observations, if possible. Errors due to scale effects shall be assessed and minimized. The particular mechanical properties of the ice that are most important for the expected ice failure mechanisms and the test objectives shall be modelled as accurately as possible.

The selection of model scale shall take into account:

- the model ice type and its properties;
- the dimensions of ice test tank;
- the dimensions of the model; and
- the processes being studied.

16.5.3 Test methods

The following issues shall be considered and modelled correctly when contributing to ice actions or other test objectives:

- boundary conditions applied to the ice sheet by the tank walls;
- ice geometry and range of ice types, such as level ice, ice rubble and consolidated portions of ridges or rubble fields;
- hydrodynamic effects;
- effect of whether the structure is moved through the ice or ice is moved past the structure;
- ice failure mechanisms, including local and global ice failure processes, and the accumulation of ice rubble or broken ice;

The main ice parameters and conditions contributing to the measured ice actions or processes shall be recorded before and after each test.

16.5.4 Model ice properties

Modelling of physical and mechanical ice properties shall be based on the actual ice-structure interaction situation investigated and according to ice properties anticipated at the production site.

In scenarios where flexural failure of ice controls the ice action, care should be taken to ensure that the flexural strength parameter is scaled properly. The time of the model test shall be such as to ensure that the target flexural strength is satisfied. The direction of flexural failure, whether upwards or downwards, should be considered in the choice of model test parameter measurements.

In ice scenarios where compression or crushing failure of ice is predominant, the compressive or crushing strength parameter shall be scaled correctly. If ice failure is through instability (buckling), attention to measure the appropriate modulus of elasticity is important, see A.8.2.8.9.

The extrapolation of model test data to full scale shall take deviations from similarity theory into account.

16.6 Offloading in ice

16.6.1 General

The use of export tankers is an economic and reliable mode of transporting liquid hydrocarbons (including LNG). In arctic and cold regions, special consideration should be given to the offloading operation, which involves the transport of the hydrocarbons via the loading unit to the tanker.

16.6.2 System reliability

The integrity of all components of the offloading system shall be ensured under all expected ice actions, direct or indirect. Global and local actions, including dynamics, shall be considered; see Clause 8.

Passive or active means can be considered to reduce global or local ice actions, provided that it can be shown that, in combination with the structural resistance of the various components of the offloading system, the intended level of safety is achieved; see 8.2.7.

IM measures developed in accordance with Clause 17 shall be in place and shall meet the operational time requirements for unloading operations. Tanker approach, connection, loading, disconnection and tanker departure operations should be considered in the assessment of IM requirements.

16.6.3 Requirements for the offloading terminal

The structural integrity of the terminal should be ensured under all expected conditions, whether operational or otherwise, according to the provisions of Clauses 7 and 8.

For floating offloading units, the risk of displacement and collision with other structures in the area as a consequence of ice events should be evaluated in the context of Clause 7.

Particular attention should be given to the design of the interface between the tanker and the terminal. Direct and indirect actions associated with cold temperatures, ice impact, pressure from ice, vessel motion, terminal motion and ice build-up on the face of the terminal shall be considered. The interface between the tanker and terminal should be designed to minimize the risk for hydrocarbon release in the case of rupture.

16.6.4 Requirements for the tanker

Tankers that are loaded under sea ice conditions should be:

- classed for polar operations by a recognized classification society;
- crewed with a complement experienced in operations in ice;
- provided with double-hull protection of all cargo and fuel tanks.

The manoeuvrability of the tanker should be consistent with the ice and environmental conditions, and operational scenarios used for the calculation of ice actions.

Operational limit conditions for the loading operations should be defined based on the terminal configuration, the IM strategy and the tanker performance.

Tanker collision with adjacent structures other than the terminal during the different phases of the loading process should be addressed in the design requirements for these structures and in the mooring arrangements.

17 Ice-specific operations

17.1 Operational measures for ice hazards

17.1.1 Mitigation of ice actions

All structures in arctic and cold regions that rely on operational measures to mitigate ice actions or to reduce the frequency of ice events (see 8.2.7) shall operate under an ice alert system (see 17.1.2) and an IM system (see 17.2) for the duration of the design service life.

17.1.2 Ice alert system

An ice alert system shall consist of a series of barriers, as defined in ISO 17776, involving definition of:

- a) a set of ice conditions or scenarios requiring operational responses, which can include vigilance or preparedness, initiation of IM activities, and emergency response plans for ice hazards, see 18.1;
- b) lead times and clear designation of roles and responsibilities associated with declaring different ice alert levels or status.

Additional measures for floating systems are provided in 13.2.4.

17.2 IM system

17.2.1 IM scope

IM involves procedures, systems and activities for which the objective is to mitigate ice actions and their consequences, and includes the following:

- a) ice surveillance, which includes detection, tracking and forecasting;

- b) identification and evaluation of ice features, conditions or scenarios that pose a physical threat to the operation or structure;
- c) an ice alert system under which the operation is undertaken;
- d) physical IM by the supporting IM vessels, including icebreaking, clearing, pushing, towing, or similar activities to reduce or eliminate the threat;
- e) other measures associated with potential reductions in ice actions.

The planning, design, implementation and documentation of all IM operations in arctic environments shall be conducted according to ISO 35104.

17.2.2 Characterization of IM performance

Where IM is used for reducing the representative ice actions on an offshore structure, the following provisions apply.

- a) The expected performance of ice detection, tracking and forecasting capabilities and the associated uncertainties shall be documented, and should reflect the actual performance of the types of systems or devices that can be used in the context of expected metocean conditions, visibility and offshore operations.
- b) The expected performance of physical IM approaches that are planned and the associated uncertainties shall be documented and should reflect actual performance of the types of vessels and systems planned for use in the context of expected metocean conditions, visibility and offshore operations.
- c) The overall performance of ice detection and management systems shall be characterized in terms of their ability to reduce or alter the frequency and nature of adverse ice events, and should reflect the influence of the other ice and physical environmental factors that can be associated with these events.

Design and operational considerations shall be used to assess the overall performance of an IM system. The required performance of an IM system shall be maintained for all of the anticipated physical environmental and operating conditions over the design service life.

The ice data used to support the IM system, the IM system data, and ice alert states shall be collected continuously over the design service life. Regular performance assessments shall be made, and modifications to the IM protocols and equipment shall be made, as required, to ensure compliance with 8.2.7. This assessment shall include key stationkeeping response data and an assessment of the ice operating envelope.

IM performance can also be evaluated in terms of its ability to extend operations, reduce downtime levels, allow disconnection, facilitate structure move-off, and enable safe and efficient reconnection.

17.3 Particular measures for floating systems

17.3.1 All systems

An ice alert system for floating systems shall meet 13.2.4 as well as 17.1.2.

The safe-learning principle (see ISO 35104) shall be implemented for all IM activities associated with floating systems.

A safe operating envelope for all floating systems shall be ensured by means of ice surveillance, ice drift forecasts and threat evaluation.

When sufficient operational experience is gained, appropriate adjustments to the operating envelope can be implemented provided that compliance with 17.2.2 is demonstrated.

17.3.2 Specific requirements for different types of floating systems

In addition to the requirements of 17.3.1 for floating systems, a safe operating envelope shall be ensured by means of physical IM (active and semi-passive systems), as well as operational constraints of the stationkeeping system and disconnection of the structure from its moorings (active and semi-active systems).

The operating envelope is the basis for an ice alert system, in accordance with 13.4.3.1 for active and semi-active systems, and 13.4.3.2 for semi-passive and passive systems.

18 Emergency response

18.1 Emergency response plans

ISO 15544 provides objectives, functional requirements, and guidelines for emergency response strategy, plans, and procedures.

Emergency response plans include plans in anticipation of possible hazardous events such as due to ice hazards, see 5.5, or failure of the IM system, and plans in response to damage caused by hazardous events. Emergency response plans for hazards, see 5.3.1, shall be in place and shall include measures to ensure:

- a) the safety of personnel for manned platforms;
- b) the security of hydrocarbons and other pollutants, such that no spill onto the ice or into the water occurs.

18.2 Emergency response measures

Emergency response plans can include measures for:

- down-manning and evacuation;
- escape, evacuation and rescue;
- shut-in and securing of wells;
- shutdown of operations and export systems;
- removing or securing any inventory of potentially polluting materials such as hydrocarbons;
- for disconnectable floating systems, move-off and repositioning, whether moored or dynamically positioned.

18.3 Escape, evacuation and rescue

18.3.1 General

Escape, evacuation and rescue (EER) measures are among the strategies for emergency response to major accident hazards, see ISO 17776, and for emergency response generally, see ISO 15544.

Precautionary evacuation or down-manning of non-essential personnel can be:

- a typical response strategy for ice hazards, see 5.5, or slowly escalating incidents; or
- a requirement of the structural design for exposure level L2 (manned, evacuated), see 7.1.4.

The EER system shall be developed in accordance with ISO 35102. The EER provisions in 18.3 focus on the structure design aspects, and complement the provisions of ISO 35102 for the complete EER system. Together they are intended to promote the successful escape from the incident, the subsequent evacuation from the platform (emergency or precautionary evacuation), and the ultimate rescue of personnel.

18.3.2 EER philosophy and strategy

An EER philosophy and strategy shall be developed in accordance with ISO 35102.

The EER strategy and EER system design shall be developed in parallel with and integrated into the structure configuration and design and shall be consistent with the operational characteristics of the facility. The EER strategy and EER system shall be developed for the reasonably foreseeable range of physical environmental and accidental event scenarios and shall be applicable for the exposure level (see Clause 7) over the design service life and decommissioning.

General provisions for hazard identification and risk analysis are provided in 5.3.1 and 7.1. Detailed provisions for the EER system shall be in accordance with ISO 35102.

18.3.3 Structure design for EER system

If a system for precautionary evacuation is required under emergency response plans for ice hazards, the design of the evacuation system and the reliability of its implementation in accordance with alert procedures shall be addressed as integral to reducing life-safety risk.

Acceptable life-safety risk shall be ensured through the reliability and availability of the evacuation system and the design parameters of the structure. The evacuation system shall be implemented under a risk management policy with respect to EER procedures and training.

During and after an abnormal environmental or accidental event, EER system components shall perform as intended for the period of time specified in the EER plan. Design verification shall address the integrity of structural protection and support of escape routes, the temporary refuge, muster locations, and evacuation facilities. ISO 17776 provides guidance on temporary refuge integrity analysis.

Annex A (informative)

Additional information and guidance

NOTE The clauses and subclauses in this annex provide additional information and guidance on the clauses in the body of this document. The same numbering system and heading titles have been used for ease in identifying the subclause in the body of this document to which it relates.

A.1 Scope

No additional guidance is offered.

A.2 Normative references

No additional guidance is offered.

A.3 Terms and definitions

The following terms used in this document are intended to have the definitions given in ISO 19900:

- accidental situation;
- action;
- characteristic value;
- consequence category;
- design service life;
- design situation;
- design value;
- exposure level;
- life-safety category;
- nominal value;
- owner;
- platform;
- representative value;
- scour.

The following terms used in this document are intended to have the definitions given in ISO 35102:

- a) escape;
- b) evacuation;
- c) rescue;
- d) temporary refuge.

A.4 Symbols and abbreviated terms

No additional guidance is offered on the symbols listed in 4.1. The following additional symbols are used in this annex. These symbols are also defined locally where they are used so that the meaning of symbols with more than one definition is unambiguous.

A	actual contact area between ice and structure
A	local contact area
A	ice floe surface area
A_N	nominal contact area between ice and structure
A_0	area corresponding to background pressure
a	coefficient relating to local ice shape
a	loaded height for local ice actions
B	beam width
B_p	empirical coefficient in random local pressure formulation
b	coefficient relating to local ice shape
b	effective beam length
b	MY ridge width
b	width of equivalent rectangle
b_k	base width of keel
b_1	bottom width of trapezoid
b_2	top width of trapezoid
C_A	local ice shape coefficient for ice feature
C_a	Cauchy number
C_{FDD}	accumulated freezing degree days
C_h	ice strength parameter for floe impact
C_i	ice strength coefficient
C_{ir}	coefficient for ice road operation
C_N	fraction of sea surface area covered by ice floes

C_P	coefficient in ice pressure relationship
C_R	ice strength coefficient
C_{R0}	strength parameter for reference area
C_w	local ice shape coefficient for planar ice feature
c	ice rubble effective or apparent cohesion
c	bottom cohesion
$c_{ice,aw}$	above-water cohesion for spray ice
c_{soil}	soil cohesion
D	diameter or width of ice feature
D	waterline diameter or width of structure
D_A	local ice shape coefficient for ice feature
D_c	core diameter
D_{ice}	total damage to structure due to ice
D^k	damage to structure due to ice scenario k
D_P	coefficient in ice pressure relationship
D_s	shaft width for conical structure
D_w	local ice shape coefficient for planar ice feature
D_{wl}	waterline diameter or width of structure
$D_{1,2}$	coefficients relating to local shape for planar ice feature
d	water depth
d	width of ice feature
E	modulus of elasticity of ice (Young's modulus)
E_f	effective elastic modulus (see A.8.2.8.9)
E_K	reduced kinetic energy of ice feature after rotation on impact
E_0	initial kinetic energy of ice feature
E_1	elliptical integral of first kind
E_2	elliptical integral of second kind
e	encounter or event
e	porosity of ice rubble
$f_X^{(x)}$	probability density function, p.d.f., for random parameter, X , specified at value, x
F	ice action
F	ice bearing action
F	action applied to cantilever free end
F_b	failure action
F_B	limit ridge building action
F_c	action component due to consolidated part of ridge
F_E	action at end of impact

F_{eq}	equivalent horizontal foundation action corrected for eccentric loading
F_G	global ice action normal to surface
F_H	horizontal component of ice action
F_{ii}	pack ice action imposed on ice island
F_k	keel action component
F_L	local ice action
F_{max}	maximum value of ice action
F_{min}	minimum value of ice action
F_N	normal action on contact surface
F_R	ice ridge action
Fr	Froude number
F_S	global ice action incorporating sheltering for multi-leg structure
F_T	tangential (friction) action during steady motion
F_V	vertical component of ice action
$F_X^{(x)}$	cumulative distribution function, c.d.f., for random parameter, X , specified at value, x
F_1	ice action on one leg of a multi-leg structure
F_0	peak value of ice action
$F_1, F_2, \dots, F_m$	individual cumulative distributions
ΔF	difference between maximum and minimum values of ice action
f	geometrical parameter for conical structures
f	frequency
f_{ar}	empirical ice pressure term
f_n	natural frequency of eigenmode
G	parameter in icebreaking component for actions on conical structures
g	acceleration due to gravity
g_r	geometrical parameter for conical structures
H_B	horizontal action on structure due to ice breaking
H_{B1}	horizontal action on structure due to ice breaking, 1st break
H_{B2}	horizontal action on structure due to ice breaking, 2nd break
H_c	clearing action for level MY ice on conical structure when lifted to full ice thickness
H_F	total horizontal action for MY ridge failure against conical structure
H_k	keel depth
H_L	action required to lift ice rubble on top of advancing ice sheet prior to breaking it
H_P	action component required to push ice sheet through ice rubble
H_R	horizontal action on cone due to ride-up
H_R	action to push ice blocks up slope through ice rubble
H_s	sail height

H_T	action to turn ice block at top of slope
H_{yc}	clearing action for MY ridge on conical structure
h	ice thickness, ice ridge thickness
h_c	consolidated layer thickness
h_E	representative ice thickness for ELIE
h_{fb}	island freeboard
h_k	distance between base of consolidated layer and base of keel
h_R	MY ice ridge thickness
h_r	ice ride-up thickness
h_r	ride-up height
h_s	snow thickness
h_v	geometrical parameter for conical structures
h_1	reference unit ice thickness
h_0	initial or known ice thickness
I_p	correction factor for effect of in-plane compression in the ice sheet
K_{lc}	fracture toughness
k	foundation modulus or sub-grade reaction
k_i	thermal conductivity of ice
k_j	ice jamming coefficient
k_n	non-simultaneous failure coefficient
k_s	thermal conductivity of snow
k_s	interference and sheltering coefficient
L	clear distance between legs of multi-leg structure
L	length
L	length of beam
L	hinge piece length for MY ridge
L_c	characteristic length of ice sheet
L_{eff}	effective foundation width
L_{3c}	final length of broken piece of MY ridge
l	latent heat of fusion for ice
l_b	breaking length of ice sheet
l_c	total length of circumferential crack
M	moment applied to foundation
M_n	modal mass
m	empirical coefficient in global ice strength relationship
m	empirical conduction coefficient that depends on snow depth in ice growth formula
m	number of scenarios or action events

m	mass of ice sample
N	component of action normal to structure surface
N_c	bearing capacity constant
n	number of events
n	empirical coefficient in global ice strength relationship
n	number of legs for multi-leg structure
n	natural mode
n	number of panels
n	number of ice layers
n	ratio of ice piece length to thickness
n_p	number of parameters
n_r	number of realizations
P	probability or annual probability
P	applied load or action
P	contribution to rubble action term for sloping structures
P	ice action per unit width on conical structure
P	ice sheet capacity or resistance
P_0	initially applied action
p	ice pressure
p_D	ridge building action, per unit width
p_F	full thickness pressure
p_G	ice pressure averaged over nominal contact area associated with global action
p_L	local ice pressure
p_T	thermal ice action, per unit width
p_u	ultimate ice strength in borehole test
p_0	average global pressure
p_{0p}	background pressure to be applied around local pressure patch
Q	variable action
q	bearing capacity per unit area
$q(\dots)$	specified function
q	range of actions as a proportion of maximum action
R	coefficient for ridge building action
R	distance to first circumferential crack
R_2	distance to second circumferential crack
R_{ii}	ice island resistance to ice actions
r	probability of hitting a panel given an event
r_c	radius of loaded area

r_T	rate of temperature increase
r_y	radius of gyration of ice feature about horizontal axis
r_z	radius of gyration of ice feature about vertical axis
S_i	ice salinity
S_{min}	lower bound factor on compressive strength
S_{max}	upper bound factor on compressive strength
S_u	representative undrained shear strength
T	period of ice action
T_a	air temperature
T_f	freezing temperature of water
T_i	ice temperature
t	time
t	interaction time
t_T	T-time or time to shut down operations of floater
t_0	present time for operations of floater
u	integration parameter
u	structure displacement
V	action
V	volume
V	ice speed
V_B	vertical action on conical structure due to ice breaking
V_{B1}	vertical action on conical structure due to ice breaking, 1st break
V_{B2}	vertical action on conical structure due to ice breaking, 2nd break
V_c	vertical action on conical structure from one hinge piece of MY ridge
V_j	individual actions in a year
V_R	vertical action on cone due to ride-up
v	ice speed, drift speed or relative speed
v	vehicle travel speed
v_b	brine volume fraction
v_c	critical vehicle velocity for dynamic magnification
v_s	sliding velocity in ice friction tests
v_t	total void volume fraction, brine and air
W	rubble weight parameter for conical structure
W_{ii}	on-bottom weight of an ice island
w	average width of rubble on slope
w	width of structure
w_B	effective width for breaking for sloping structure

w_L	loaded width for local ice actions
w_R	ride-up width for rubble on conical structure
w_T	top diameter of a conical structure, effective width for turning of blocks at top of slope
X	offset for floating structure
X_{OP}	operational offset for floating structure
$X_{1,E}$	EL or ELIE parameter value
$X_{1,A}$	AL or ALIE parameter value
X_j	parameter value
$X_{j,N}$	nominal parameter value
x	parameter in formulae for ice actions on conical structures
x	distance from centre of action
x_0	position in the random local pressure distribution
Y	coefficient in formulae for ice actions on conical structures
$Y_1, Y_2, \dots, Y_m$	actions corresponding to scenarios
y_{crit}	critical vertical deflection of ice sheet or MY ridge for breaking
y_{le}	height to which the leading edge of MY ridge is lifted
$y_{r1,A}, \dots, y_{rm,A}$	ALIE level representative actions
$y_{r1,E}, \dots, y_{rm,E}$	ELIE level representative actions
Z	action, action effect or resistance
z	distance from mid-depth of ice
z	depth below ice keel
Z	action, action effect or resistance
Z_E	EL action
Z_A	AL action
$Z_{r,E}$	representative EL action
$Z_{r,A}$	representative AL action
$Z_{r,\alpha}$	representative action corresponding to annual exceedance level, α
α	annual exceedance level
α	ice growth parameter
α	slope of structure from horizontal
α	coefficient representing decrease in ice pressure with area
α_k	keel attack angle
γ_e	effective buoyancy, expressed as a unit weight
γ_i	above-water spray ice unit weight
γ_{is}	below-water spray ice unit weight
γ_L	pressure distribution coefficient
γ_w	seawater unit weight

Δ	deflection of a beam
δ	penetration depth of structure into ice
δ	deflection
δ_0	initial deflection
$\dot{\varepsilon}$	strain rate
ε_y	eccentricity in horizontal plane
ε_z	eccentricity in vertical plane
η	average annual encounter frequency
η	angular integration parameter
θ	angle of rubble from horizontal
θ	damping coefficient
θ_k	keel angle from horizontal
λ	geometric scale factor
μ	annual exposure level, expressed as number of interactions per year
μ	ice-structure kinetic friction coefficient
μ_i	ice-to-ice kinetic friction coefficient
μ_ϕ	ice rubble passive pressure coefficient
ν	Poisson ratio for ice
ν	expected number of interactions per year
ξ	parameter relating to horizontal and vertical components of ice action
ξ_n	damping of eigenmode as a fraction of critical
ρ_A	areal density of ice features
ρ_i	mass density of ice
ρ_w	mass density of water
σ	measured or inferred strength index
σ	normal stress in Mohr-Coulomb relationship
σ_c	uniaxial compressive strength
σ_D	standard deviation of ice floe diameter
σ_{edge}	maximum extreme fibre flexural stress
σ_f	flexural strength of ice
σ_{is}	normal stress due to weight of ice
σ_{max}	maximum flexural stress in ice sheet
σ_t	tensile strength
σ_x	extreme fibre flexural stress at distance x from centre of action
σ_0	strength index for reference area
τ	shear strength
τ	duration of loading/unloading cycle

$\tau_{ice,aw}$	above-water shear strength of spray ice
$\tau_{ice,bw}$	below-water shear strength of spray ice
τ_{is}	shear strength of ice
ϕ	ice rubble friction angle
ϕ	bottom friction angle
ϕ'	representative friction angle
$\phi_{ice,aw}$	friction angle for spray ice above water
ϕ_{is}	friction angle at ice/soil interface
ϕ_{nc}	non-normalized modal amplitude at point of ice action
ω	empirically-derived ice growth coefficient

A.5 General requirements and conditions

A.5.1 Fundamental requirements

The term resistance, in this Clause 5, refers to resistance with respect to all types of failure, as explained in A.7.2.1.

A.5.2 Design methods

No additional guidance is offered.

A.5.3 Site-specific considerations

A.5.3.1 Hazards

No additional guidance is offered.

A.5.3.2 Climate change

Evidence of climate change has been documented by various scientific organizations around the world, including by the United Nations Intergovernmental Panel on Climate Change. Apparent effects include increasing annual average arctic temperature, and decreasing arctic sea ice extent in summer.

Decreasing arctic sea ice extent in summer and the consequential retreat of the ice edge has resulted in increased fetch for waves in some locations, and therefore increased wave heights in summer storms. The potential progression of this phenomenon during the lifetime of the structure at its location is one aspect of climate change that should be considered.

A.5.3.3 Structural configuration

No additional guidance is offered.

A.5.3.4 Winterization

Low temperatures are defined in this document for material testing and for winterization measures. Temperatures in the physical environment can, with very low probability, become lower than these temperatures.

EL minimum temperatures are estimated from available data for the general environment and the specifics of the position on or within the structure. LAST is provided to inform engineers of the service temperature which is unlikely to be unfavourably exceeded so that appropriate materials can be selected and tested.

A.5.4 Construction, transportation and installation

No additional guidance is offered.

A.5.5 Operational measures

No additional guidance is offered.

A.5.6 Environmental protection

Most offshore structures contain fluids in the form of fuel for machinery or electric power generation, in addition to some amounts of processed hydrocarbon fluids. Furthermore, stored processed water can contain traces of hydrocarbons. Ballast water, used during transportation and installation, can contain micro-organisms that can be detrimental to the local environment.

Double-hull specifications and other criteria related to environmental protection for floating systems are covered in the IMO Polar Code, see Reference [38].

A.5.7 Serviceability requirements including vibration

The parts of ISO 2631, References [1] to [4], deal with human exposure to whole-body vibration and shock in buildings with respect to the comfort and annoyance of the occupants. Repetitive ice actions that can potentially lead to structure vibration are addressed in A.8.2.6.

A.5.8 Decommissioning and reclamation

No additional guidance is offered.

A.6 Physical environmental conditions

A.6.1 General

As a rule of thumb, at least 10 years with good quality data can be used to capture inter-annual variations in parameters such as winds, waves and temperatures. For sea ice and iceberg related parameters, even longer time periods can be required to fully understand long term variations. Additional guidance with respect to length of record for physical environmental data is provided in ISO 35106.

The required amount of data can depend on parameter criticality, expected data quality, general understanding of the physical environment and project risk level. It is good practice for metocean and ice personnel to communicate data uncertainty to project management and design personnel. Special techniques, such as pedigree matrices, can be considered to communicate uncertainties related to data and extreme value estimates.

Physical environmental actions for a design situation are combined according to 7.2.3. It is however not always straightforward to combine actions from independent or correlated parameters, and sometimes it is preferable to calculate or simulate the combined actions directly. Good quality long-term datasets, providing simultaneous data values for all relevant parameters, are often the best bases for estimation of realistic actions. For arctic-specific applications, such datasets can be difficult to assemble. Focus should be placed on the development of simultaneous parameter values or joint distributions of key parameters contributing to the combined actions.

A.6.2 Daylight hours

Depending upon the latitude, the number of daylight hours can vary from none in the winter period to 24 h in the summer period. Platform and re-supply operations can be affected by the lack of sunlight, and sufficient lighting is a requirement for safety. Tables and figures showing daylight hours by latitude and month are available in several publications. Examples can be found in Figure 23 of Reference [48] or in Reference [49].

A.6.3 Meteorology

A.6.3.1 Air temperature

Low air temperatures are of concern for several reasons, of which the most obvious are:

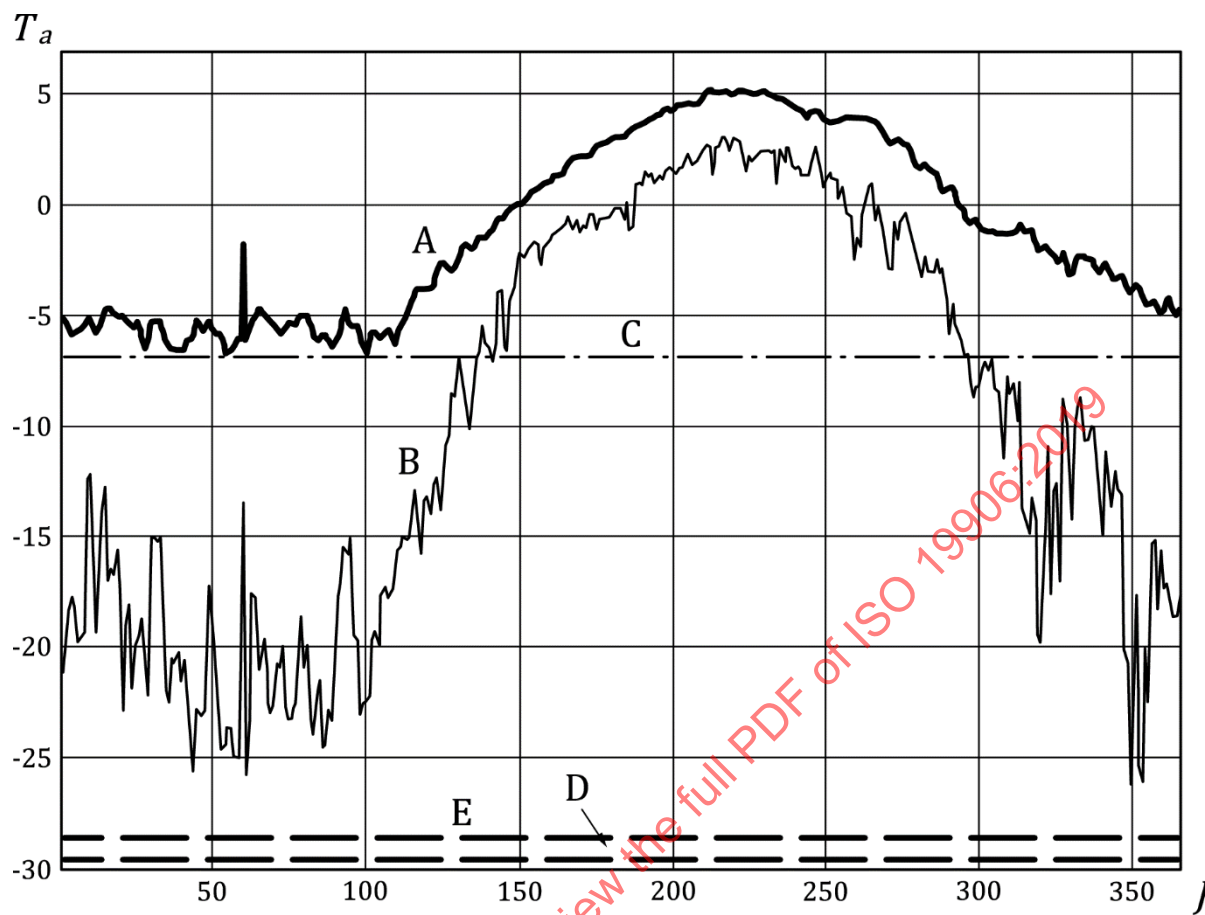
- changes in material properties;
- safety-critical equipment malfunction;
- reduced functionality of equipment required for normal operations; and
- negative effects on working environment.

Consequences of changes in material properties are both that equipment stops working as intended and that load-bearing resistance in structures is reduced. Effects on safety-critical equipment include frozen firewater and inability to launch life boats as examples. With respect to working environment, the cooling of personnel on deck is the main concern.

Data on air temperatures can be made available both from physical recordings and from numerical models. Physically, air temperatures can be recorded from meteorological stations on land, on vessels, on offshore rigs and from weather buoys. Temperature data can also be recorded from satellites, but the data will then have to be calibrated by data from other sources. Numerical models are able to reproduce long time series of air temperature variations within model domains in the form of hindcasts. The advantage of using hindcast data, besides providing long continuous time series, is that it allows data to be extracted from different elevations and it allows for comparisons between different geographical locations.

Different definitions of extreme, design and service air temperatures are found in existing codes, regulations and standards. To ensure consistent and correct use of air temperature data, designers should be aware of the following temperature definitions.

- a) Lowest Mean Daily Average Temperature (Lowest MDAT) — used in some documents, for example DNVGL-OS-C101^[35]. A relatively long time series with temperature data is required to calculate Lowest MDAT. For example, for a time series of 10-year duration there will be 10 daily average temperature values for each calendar day. By averaging the 10 values for each day, the curve for Mean Daily Average Temperature (MDAT) can be established (as shown in Figure A.6-1). Lowest MDAT is the lowest temperature along the MDAT curve. Lowest MDAT is not an extreme temperature and cannot be associated with a fixed probability of exceedance level.
- b) EL Minimum Temperature — as for Lowest MDAT, an adequately long time series of good quality temperature data is recommended to provide estimates for the EL minimum temperature. Figure A.6-1 shows daily and 3-hour values of air temperature for the same dataset. The lowest 3-h temperature each winter can be identified and then a Gumbel distribution can be fitted to all the annual minimum air temperatures. By extrapolating the Gumbel distribution, the EL minimum temperature in air can be taken as the air temperature value exceeded on average in 1 out of 100 years (i.e. annual probability of exceedance is 10^{-2}). Other distributions can be used where warranted.
- c) Some documents such as References [35] and [36] use further terms such as design temperature (structural or material), service temperature, and winterization temperature. These terms and related symbols, which are similar to but differ in detail from those used in this document, are explained in the DNVGL documents.



Key

A	Mean Daily Average Temperature	E	EL minimum 24-hour temperature
B	Lowest Daily Average Temperature	T_a	air temperature, expressed in °C
C	Lowest MDAT	J	cumulative days over the course of the year
D	EL minimum 3-hour temperature		

Figure A.6-1 — Illustration of air temperature parameters based on 51-year hindcast data from location 74°N, 43°17'E

A.6.3.2 Wind

ISO 19901-1 provides information on wind actions and action effects, wind profiles and wind spectra.

A.6.3.3 Wind Chill

For use of wind chill temperatures in relation to working environment, reference is made to ISO 35101 and ISO 35106.

A.6.3.4 Snow

Precipitation under air temperatures colder than 1 °C to 2 °C usually forms as snow crystals. Unlike rain droplets, snow can accumulate on horizontal, sloped and vertical structures. The accretion of snow can

have different natures and effects, such as causing additional mass, uneven mass distribution and potential loss of vessel stability, changed structural shapes, obstruction and changed friction.

ISO 19901-1 provides general information on snow accumulation on buildings and topsides, while ISO 35106 provides recommendations on calculations of snow accumulations.

A.6.3.5 Ice accretion

A.6.3.5.1 General

Icing on a structure at sea requires a combination of water or moisture and surfaces above sea level at sub-freezing temperatures. There are two major types of icing: atmospheric and sea spray.

A.6.3.5.2 Atmospheric icing

Atmospheric icing is related to precipitation, humidity and fog. Dry snow does not usually adhere to a surface and, by itself, it poses little hazard. The density of accumulated snow can be as low as 100 kg/m^3 , while that of ice is around 900 kg/m^3 . If sea spray or sleet dampens the snow, the wet snow freezes to the surface. The ice thus formed is porous, with low mechanical strength, and can usually be removed. In contrast, water that is super-cooled freezes solid on contact with a cold surface. Super-cooling in the atmosphere occurs when the liquid phase reaches temperatures below the freezing point. Super-cooled droplets exist in the form of frost smoke, super-cooled fog, or freezing rain and drizzle. These are the most common sources of atmospheric icing.

Opinions on the seriousness of atmospheric icing differ. Atmospheric icing can produce a uniform layer of ice on all surfaces over the height of the structure starting from a few metres above the waterline. Freezing rain can potentially cover only the upward or windward surfaces; for tubular members, it can be assumed that it covers half the circumference. By itself, atmospheric icing does not necessarily cause major structural consequences, though its operational consequences are severe. If atmospheric icing occurs at the same time as sea-spray icing, it can accelerate the build-up of icing. The last phenomenon is called mixed icing.

Further guidance on atmospheric icing is provided in ISO 12494^[5] and in ISO 35106.

Ice accretion from freezing rain can be estimated by using theoretical models such as those described in Reference [50].

A.6.3.5.3 Sea-spray icing

Icing caused by sea spray is the most frequent and most important form of icing in the sea. Another cause of sea-spray icing is shipped water, which enters the deck of a vessel over the bow or sides. The latent heat content of this water, even if its temperature is near the freezing point, is sufficient to avoid freezing if it flows off the vessel quickly. This water, in addition, contributes to the melting and flushing away of ice that has already formed on deck. If the scuppers freeze over and become blocked or the railings are covered with ice, the water can be trapped and frozen. The probability of sea-spray icing at height on a structure is dependent on extreme crest heights and sub-zero air temperatures. The severity of sea-spray

icing is also strongly dependent on structural size and shape and how the structure is operated (e.g. stationkeeping, vaning, etc.).

Sea spray is formed in two ways. The most important with regard to icing is sea spray generated by the vessel or structure itself as it interacts with waves. The second form is created when the wind blows droplets of water off wave crests, and depends on the form and steepness of the waves and wind speed. Sea-spray icing begins to occur at wind speeds of 8 m/s to 10 m/s. The stronger the wind, the higher the spray is lifted. While the height of sea-spray icing is usually limited to 15 m to 20 m above the sea surface, there have been reports of sea-spray icing at up to 60 m above the sea surface.

Certain ranges of air temperature, water temperature and wind speed are required to cause a significant accumulation of superstructure icing. These conditions are:

- an air temperature less than the freezing point of seawater (which depends on the salinity of the water);
- a wind speed of 10 m/s or more;
- a seawater temperature colder than 8 °C.

A strong wind, cold air and cold seawater all contribute to greater accumulations of ice. In arctic and cold region seas, icing can occur throughout the year. Icing is most likely at the end of autumn or in winter when air temperatures are below zero and there is no ice cover on the sea surface. Icing can be classed by its intensity as slow, fast, or very fast. Broadly speaking:

- a) slow icing (ice accumulation of less than 10 mm/h) occurs with air temperature between 0 °C and –3 °C and any wind speed, or with air temperature of –3 °C or lower and wind speed of less than 7 m/s;
- b) fast icing (ice accumulation between 10 mm/h and 30 mm/h) occurs with air temperature between –3 °C and –8 °C and wind speed of 7 m/s to 15 m/s;
- c) very fast icing (ice accumulation greater than 30 mm/h) occurs with air temperature at or below –8 °C and wind speed of more than 15 m/s.

The rate of ice thickness accumulation also depends on the structure and the height above water. Icing events last for more than 12 h in approximately three-quarters of reported cases and can last for up to several days. Icing can also accumulate through a series of independent icing events. Much depends on the degree of melt and loss of adhesion between events, as well as possible countermeasures.

Further guidance on assessment of icing severity is found in ISO 35106 and Reference [51].

A.6.3.6 Visibility

No additional guidance is offered.

A.6.3.7 Polar lows

A polar low is a small and often intense low pressure phenomenon that is formed over open water in arctic regions. Polar lows are typically a few hundred kilometers in diameter, about one-tenth the size of a normal low pressure system, which makes them difficult to detect and track. Polar lows typically last from 1 h to 6 h at a particular location and can be associated with winds in excess of 30 m/s. Polar lows are usually associated with heavy precipitation, often in the form of snow. The association of polar lows with the presence of open water has led to increased frequency at northern latitudes as a result of sea ice retreat. Further details can be found in ISO 35106.

A.6.4 Oceanography

A.6.4.1 Water depth

Bathymetric limitations can prevent the drift of deeper draft ice features into certain areas and thereby influence ice grounding and ice gouging potential.

A.6.4.2 Waves

A.6.4.2.1 General

Wave generation in ice-covered seas is reduced relative to that in open water, since the ice cover limits the available fetch. Locations of ice edges and ice concentration and any impact of climate change should be considered when performing a wave hindcast study or wave forecasting. A practical approach to wave generation is to cut off further wave growth when the ice cover concentration exceeds a certain value, such as 50 %.

Wave propagation is reduced when waves travel into ice-covered regions. In addition, waves are attenuated as they move through an ice-covered region. The amount of attenuation depends on wavelength, ice concentration, ice floe size and distance travelled through the ice. Studies have been performed to investigate wave propagation in ice-covered channels^[52]. Actual measurements of wave propagation through an ice field^{[53] to [57]} have shown that, after travelling through thin and medium FY ice for over 300 km, waves with amplitudes greater than 1 m can still be observed, although the average amplitudes are much less. In sea ice, internal waves have caused surface waves with periods up to 30 min and a phase velocity of 2 m/s^[58].

Theoretical models for wave attenuation in ice covered seas are provided in References [59] and [60]. Recent reviews^{[61][62]} update the information known about wave interaction in sea ice.

A.6.4.2.2 Wave-induced break-up of ice

The global geophysical role of wave-ice interaction has two aspects: the physical effects of waves on the ice cover and the use of waves as a diagnostic tool in ice mechanics. The physical effects include the ability of waves to break up ice sheets into floes and to herd these floes into patterns that determine the morphology of the marginal ice zone (MIZ), the break-up of tabular icebergs, the calving of ice tongues, and the generation of ambient noise. The diagnostic role stems from the long-range propagation of wave

energy in the form of flexural-gravity waves through ice sheets, and the information that the dispersion relation and attenuation rates provide about ice properties and mechanics.

As waves move into the MIZ, they cause drifting ice sheets to experience an increasing degree of flexure. Eventually the flexure causes the ice to break up into fragments, which themselves break again until a distribution of floe sizes is established, with the smallest floes in the steepest wave field at the extreme ice edge. The floes thus created act as a shield for the interior pack, selectively damping out the shorter-period waves. If the ice field is an open one, so that the floes do not collide, the wave attenuation process can best be described by a scattering model^{[54][62][63]}. As soon as the pack tightens up, floe collisions occur and the pack begins to behave hydrodynamically either as a collection of very large floes or as a single entity. Since the floes can no longer surge in response to the waves, energy attenuation can occur more significantly in the form of viscous losses from the boundary layer under the ice.

Once the waves have crossed the MIZ and reached the interior of the pack ice or a landfast ice boundary, further propagation can be considered as a flexural-gravity wave with altered dispersion, which can then be effective in breaking up the interior ice sheets.

The most extensive measurements of wave decay across floe fields in the MIZ have been described in References [54] and [55]. The main conclusions from the observations are as follows.

- a) The attenuation of waves with distance into the pack takes a negative exponential form, with an attenuation coefficient that decreases with increasing wave period over most of the spectral range. In heavy compact ice (e.g. East Greenland) the energy attenuation coefficient typically varies from $2 \times 10^{-4} \text{ m}^{-1}$ for the longest swell to $8 \times 10^{-4} \text{ m}^{-1}$ for 8 s to 9 s waves, corresponding to e-folding distances of 5 km to 1,2 km (distances over which attenuation is 1/e).
- b) There is some evidence of a “roll-over” at the shortest periods (less than 6 s to 8 s), where the decay rate can actually start to diminish as the wave period shortens.
- c) The directional spectrum spreads inside the ice field until it is essentially isotropic within a few kilometres of the edge.
- d) Some waves are reflected from the outer edge of the ice field by only a few percent, even when the edge is compact.

The general problem of ice break-up by waves is addressed in References [64] and [65], and the theory has also been applied to the break-up of tabular icebergs^[66]. Reference [67] describes a mathematical model for the evolution of floe size distribution with time, given a specified break-up rate.

A number of mechanisms have been proposed for the way in which very large floes are broken up by waves. The simplest approach is to consider standing waves^{[68][69]}. A second mechanism, wind-induced tilt^[70], occurs when a wind blowing over a large ice sheet causes the downwind end of the sheet to tilt downwards. Periodic cracking of the ice can relieve bending stresses due to the tilt. Break-up can also be influenced by the gradual weakening of the sea ice that occurs through the process of fatigue induced by the unremitting action of the ocean waves^[71].

A phenomenon that can affect coastal facilities, man-made islands and structures with low freeboard is called an “ice storm”. The event, which occurs when high onshore winds coincide with low ice

concentrations offshore, causes ice pieces to be thrown onto the shore. Such events have been reported in Norton Sound, Beaufort Sea and along the Russian Northern Sea Route.

A.6.4.3 Ocean currents

Ocean current information plays an important role in the prediction of ice movement and pressure. In regions of high tidal currents with dominant directions, the period when the tide changes from one direction to another can cause significant pressure within an ice field with a concentration of 9/10 to 10/10 as it tries to respond to the direction change.

NOTE The concentration represents the number of tenths of the total area under consideration that is covered by ice; e.g. 9/10 indicates that ice covers nine-tenths of the area considered; see A.6.5.2.2.

For lower ice concentrations, this effect is minimized. For offshore operations in the Okhotsk Sea, this resulting pressure is sufficient to cause icebreakers with propulsion in the range of 10 MW to 12 MW to become “stuck” until the ice field pressure relaxes after its direction has changed.

Ocean currents affect not only the speed with which ice interacts with a structure but also the encounter frequency associated with various ice features. Accurate estimates of the anticipated current speed are, therefore, important.

A.6.4.4 Other oceanographic factors

A.6.4.4.1 Marine growth

Ice interactions with structures remove marine growth. Complete cleaning to a depth equal to the tidal range plus the average ice floe thickness can be assumed, with partial cleaning down to a depth equal to the tidal range plus the average ridge keel.

A.6.4.4.2 Tsunamis

In regions affected by the possibility of a tsunami, the potential for ice cover to reduce the tsunami wave height as it comes to shore can be taken into account.

A.6.4.4.3 Dissolved oxygen

No additional guidance is offered.

A.6.4.4.4 Water temperature and salinity

Representative values for EL minimum water temperatures can be generated by using monthly sea water temperature data, either from recorded temperature profiles or from good quality hindcast data. For each month, average water temperature and standard deviation is calculated. The monthly minimum temperatures can be estimated as the mean temperature minus 3,5 times the standard deviation. The representative EL minimum water temperature is the lowest of the 12 monthly minimum temperatures. If any of the monthly minimum temperatures are less than the freezing temperature for water, the

representative EL minimum water temperature can be taken as the lower of $-1,9^{\circ}\text{C}$ or the actual local freezing temperature.

Due to the lower variability of water temperatures, LAST in water can be taken as equal to the EL minimum temperature.

Water temperature varies with water depth. Representative EL minimum temperatures can be calculated for different depths by using data measured at known water depths. Care should be taken in the surface layer where the water can freeze. For structure likely to be exposed to sea ice, the low temperatures in air can be used for estimating the low temperatures in surface ice at these positions.

International organizations encourage the determination of salinity from the mass fraction of dissolved salt in seawater, expressed as g/kg. Seawater salinity has typically been determined by measuring the conductivity of seawater and its temperature. Many sources report salinity as parts per thousand (‰ or ppt) when measured using conductivity as a determination of salinity. For clarity, g/kg should be used instead. Note that the conductivity measurement is not a direct measurement of the weight of salt per kg water.

A.6.5 Sea ice and icebergs

A.6.5.1 General

A.6.5.1.1 Nomenclature and modelling

The World Meteorological Organization (WMO) sea ice nomenclature^[47] should be used when possible for describing sea ice and icebergs.

Statistical modelling from limited site-specific data sets is generally performed by Monte Carlo simulations where theoretical probability distributions are fitted to the data and then randomly sampled; see, for example, References [72] and [73].

Additional information for this subclause can be found in ISO 35106.

A.6.5.1.2 Ice growth

Sea ice is a complex material that is composed of solid ice, brine, gasses (mostly air) and, depending upon the temperature, solid salts. Ice growth mechanisms can produce several different grain structures (ice textures), depending on the prevailing conditions. The most common grain structures include granular, frazil, columnar and discontinuous columnar. The details of the ice microstructure significantly influence the mechanical and physical properties of the ice.

When the ice grows, it traps some of the salt that is present in the seawater. By the end of the ice season, FY sea ice has a salinity in the range of 4 g/kg to 6 g/kg. Ice found in brackish waters, such as the Caspian Sea and Baltic Sea, has a salinity closer to zero. MY ice also has a salinity typically of 1 g/kg to 2 g/kg. The brine, gasses and solid salts are usually trapped at sub-grain boundaries between a mostly pure ice lattice. Because there are a number of salts within the ice, the phase relationship with temperature is multifarious; see, for example, Reference [74].

When the sea surface layer cools to the freezing temperature, ice crystals form, firstly as frazil and then as a solid cover. Its thickness increases due to the difference between the heat fluxes to the atmosphere from ice and to ice from the sea. The main factors are the air temperature, the snow cover thickness and the water temperature. The heat balance equation characterizing the ratio between these fluxes at the ice-water boundary is given in References [75], [76] and [77]. Once an ice cover is formed, its growth and thickness depend on the amount of heat that is conducted upward from the ice/water interface. This is a function of the properties of ice and water, and the temperature gradient in the ice. The ice (or snow) surface temperature depends on the thermal properties of the ice (or snow and ice) and the air temperature, which is usually expressed in terms of Freezing Degree Days — the cumulative sum of freezing temperatures, C_{FDD} , as given in Formula (A.6-1).

$$C_{FDD} = \left| \sum (T_a - T_f) \right| \quad \text{for } T_a < T_f \quad (\text{A.6-1})$$

where

T_a is the daily average air temperature;

T_f is the freezing temperature of the underlying water.

in which the sum is made only over the days for which the air temperature is less than the freezing temperature of the water. The freezing temperature of the sea water surface depends on the water salinity. Although salinity can vary over the course of the year, geographical differences are more important. The freezing temperature of water, T_f , is usually taken to be $-1,8\text{ }^{\circ}\text{C}$, but a value closer to $0\text{ }^{\circ}\text{C}$ is recommended in low-salinity regions such as the Baltic Sea and the Caspian Sea.

A number of theoretical and empirical formulae to predict ice thickness and growth have been developed, e.g. References [78], [79], [80] and [77]. Most of these have the form given in Formula (A.6-2), which follows directly from the assumptions of Reference [78]:

$$h^2 - h_0^2 + m(h - h_0) = \alpha C_{FDD} \quad (\text{A.6-2})$$

where

h is the current ice thickness, expressed in metres;

h_0 is the initial ice thickness, expressed in metres.

The parameter α is given by Formula (A.6-3):

$$\alpha = \omega \frac{2k_i}{\rho_i l} \quad (\text{A.6-3})$$

where

k_i is the thermal conductivity of ice ($2,3\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$);

ρ is the ice density (approximately 900 kg m^{-3});

l is the latent heat of fusion for ice ($334 \times 10^3\text{ J kg}^{-1}$);

ω is an empirically-derived coefficient.

If the parameter, α , is calculated in SI units, i.e. in $\text{m}^2 \text{s}^{-1} \text{°C}^{-1}$ in Formula (A.6-3), it should be converted to $\text{m}^2 \text{day}^{-1} \text{°C}^{-1}$ before use in Formula (A.6-2).

The parameter, m , in Formula (A.6-2), which is expressed in metres and accounts explicitly for conduction through a snow layer on top of the ice, is

$$m = \frac{2h_s k_i}{k_s} \quad (\text{A.6-4})$$

where

h_s is the snow thickness, expressed in metres, assumed constant over the growth period;

k_s is the thermal conductivity of snow; for dry snow with a density of 300 kg m^{-3} , a value of approximately $0,3 \text{ W m}^{-1} \text{°C}^{-1}$ can be used.

The simplest application of Formula (A.6-2) is to ignore the term involving the snow layer, such that $m = 0$ is assumed. In this case, the coefficient ω is less than unity to account for the insulating properties of the snow. The coefficient ω can be as low as $0,2^{[81]}$ but is typically between $0,3$ and $0,7^{[77]}$. When preliminary estimates of ice thickness for actions applied to structures are calculated, see Clause 8, ω values in the top of this range can be used. For preliminary estimates of load-bearing capacity, see Clause 16, values in the lower part of the range can be used. In the absence of snow or if C_{FDD} is calculated from ice surface temperatures, one can assume a value of unity for the coefficient ω .

Formula (A.6-4) assumes a constant snow thickness over the growth period, which is not always realistic. When the snow thickness changes over time, Formulae (A.6-2) to (A.6-4) can be applied incrementally over a series of steps in which a constant snow thickness is assumed. A limitation of Formula (A.6-4) is that it does not account for flooding of water over the surface of the ice.

Because of the many variables that can influence ice growth, the parameters, ω (or α) and m , should be estimated using local ice thickness and air temperature data whenever possible. When the parameter m is non-zero, a non-linear fitting technique can be used to estimate the two coefficients.

Formula (A.6-2) was applied to data for 1935-1937 from several stations in the Russian Arctic^[79], from which the parameter values $m=0,5$ and $\omega=0,6$ were estimated for zero initial ice thickness, h_0 .

When applying any formula based on Freezing Degree Days, a starting date needs to be selected. Ice formation starts when the surface water reaches the freezing point, which happens some time after negative air temperatures occur. This delay can range from a few days in shallow and protected waters to months, depending on water depth, currents, winds, and the presence of islands and other anchoring points. For sea water (water salinity above $2,5 \%$), the upper boundary layer (tens to hundreds of metres) of the water column needs to be cooled down. In exposed coastal areas without the protection of islands, newly formed ice can drift repeatedly into warmer offshore areas and melt before a stable ice cover is formed. One approach for estimating the starting date for which Freezing Degree Days are summed in Formula (A.6-1) is to perform a running mean of degree days over some averaging period (e.g. 30 days) and to select the date when this changes from positive to negative. Whatever approach is used for the starting date for accumulating Freezing Degree Days, it should be based on local ice and air temperature data.

The maximum thermally grown level sea ice thickness is in the range of 2 m for arctic regions. For values in different regions, see Annex B. For thick ice, the heat flux driving the ice growth becomes small and the heat flux from the water (oceanic flux) has a significant influence the growth. The ice growth stops when the heat flux through the water is equal to the flux through the ice. Increasing the convection layer thickness entrains underlying water that is typically warmer, thereby decreasing the ice growth rate. Increasing the salinity of the sub-ice water layer decreases the freezing temperature and, consequently, the growth rate. Spatial differences in the water density stratification and the resultant differences in the heat fluxes during the period of ice growth can contribute to spatial non-uniformity of ice thickness^[82].

Freezing degree models have been shown to provide reasonable estimates of ice growth in a variety of regions, if the appropriate coefficients can be determined. But information on local ice thickness in the region of interest is necessary to obtain the coefficients for the region. Freezing degree models do not perform well in regions where ice rafting is significant, where snow flooding and refreezing is an important ice growth mechanism, or where there is large annual and spatial variability in snow thickness. Also, they do not provide information of the thickness variability within a region. If ice thickness is a critical parameter, or if the probability density of ice thickness is required (as opposed to a mean or maximum value), then it is necessary to obtain measurements of the local ice thickness throughout the winter and in several different locations in the region of interest. With this information, more sophisticated theoretical approaches could be considered and validated against the on-ice observations.

A.6.5.1.3 Sea ice salinity

For level FY sea ice the salinity, S , is usually expressed as a fraction by mass of the salts contained in a unit mass. In this document, it is expressed as a ratio of grams of salt per kilogram of sea ice or its melt (g/kg), although it has been expressed traditionally in parts per thousand (‰, also psu — ‘practical salinity unit’, more or less equivalent to ‰). In sea ice there is usually some salinity variation with depth in the ice sheet. This depth dependency of the salinity changes throughout the winter as the salt within the ice migrates downward through the ice. While there can be marked salinity variations even within a small sample, the average salinity of a cold growing FY sea ice sheet is related to the ice thickness^[83] and can be expressed as in Formula (A.6-5):

$$S_i = 4,61 + \frac{0,916}{h} \quad (\text{A.6-5})$$

where

S_i is ice salinity, expressed as a mass fraction in g/kg;

h is ice thickness, expressed in metres.

For decaying ice (see A.6.5.1.5), much of the brine has drained and the salinity can typically range from close to zero up to 4 g/kg^[84].

A.6.5.1.4 Brine volume and total porosity

Sea ice contains pure ice, brine and gasses — the latter is essentially air. The amount of brine and gasses are usually given as their volume fractions to the total volume. So that the brine fraction, v_b , is the ratio of

the volume of brine to a unit volume and the gas fraction, ν_g , is the ratio of the volume of gasses to a unit volume. The total porosity is defined as the sum of the brine and gas fractions and is an important property of sea ice, notably because this parameter affects the ice's mechanical response, see A.8.2.8. Knowing the salinity, temperature and density of sea ice, the brine and gas fractions can be calculated as given in Reference [85] for temperatures less than $-2\text{ }^{\circ}\text{C}$ and in Reference [86] for warmer ice.

However, the density is often not well known (namely because it is more difficult to determine in the field), so when only ice temperature and salinity are known, the gas content cannot be determined. A simpler empirical formula can then be used^[87], which assumes a constant bulk ice density of about 920 kg/m^3 :

$$\nu_b = S_i \left(\frac{49,2}{|T_i|} + 0,532 \right) \quad (\text{A.6-6})$$

where

- ν_b is the brine fraction (or total porosity, neglecting gas fraction), expressed as a volume fraction;
- S_i is the ice salinity, expressed as a mass fraction in grams per kilogram (g/kg);
- T_i is the ice temperature, expressed in degrees Celsius.

In growing cold FY sea ice, the gas fraction is often around 0,02 to 0,05, but in melting FY ice and old ice much of the brine is replaced by air and the gas fraction can be substantially higher, up to at least 0,2.

Knowledge of the brine volume and/or total porosity of the ice is important, since the strength decreases with increasing brine volume and porosity.

A.6.5.1.5 Ice decay and melting

Increasing air temperatures and solar radiation are the primary reasons for sea ice decay. When the ambient air temperature warms to approximately $-10\text{ }^{\circ}\text{C}$, most of the salt within the ice has been converted from a solid to a liquid phase. For air temperatures above $-10\text{ }^{\circ}\text{C}$, the brine pockets rapidly increase in size and interconnect to form brine drainage channels that promote desalination of the ice. The decrease in ice strength has been directly linked to the decay of sea ice^[88].

The change in ice thickness during the warm period of the year occurs not only due to melting from the top, but also as a result of ice melting from the lower surface. This usually takes place at the edge of a floe or at a fracture where heated water forms. Empirical formulae also exist for the calculation of the rate of melting from the bottom and top ice surfaces^[82].

The melting of ice floes by wave action can play a major role in their decay near the ice edge and for grounded ice features in open water. Ice drift into warmer water also plays a role in the removal of ice in the summer.

A.6.5.2 Ice types

A.6.5.2.1 Stage of development

Ice types can be characterized as first-year (FY), second-year, and multi-year (MY) sea ice, shelf ice and glacial ice. The term “old ice” includes second-year and MY ice, see Reference [89].

The surface appearance of FY sea ice changes as the ice gets thicker, going from black-grey for new and young ice to white when thicker. The stages of development of FY ice are categorized by the WMO as follows^{[47][41]}:

- a) new (<1 cm thick): sea ice found in small platelets or lumps, usually subdivided into frazil, grease ice, slush or shuga;
- b) nilas (1 cm to 10 cm thick): a thin crust of floating ice that easily bends with the waves and swells and has a matt surface appearance;
- c) young ice (10 cm to 30 cm thick), subdivided into
 - grey (10 cm to 15 cm thick), which often breaks under wave action,
 - grey-white (15 cm to 30 cm thick);
- d) thin FY ice (30 cm to 70 cm thick), is separated into
 - stage 1 (30 cm to 50 cm thick),
 - stage 2 (50 cm to 70 cm thick);
- e) medium FY ice (70 cm to 120 cm thick);
- f) thick FY ice (>120 cm thick).

In some arctic regions, ice persists all summer and the freezing process restarts in the autumn. Ice that has survived one (summer) melt season is termed second-year ice. Generally, over the next winter, it becomes thicker than FY ice. The WMO states that second-year ice normally does not exceed a thickness of 2,5 m. Second-year ice has a smooth undulating surface. In summer and early autumn, it often has numerous bluish-green puddles of water on the surface.

Ice that has survived one (summer) melt season is termed second-year ice, and ice that has survived more than one (summer) melt season is termed MY ice. Second-year and MY ice have low salinity, are thicker and are considerably stronger than FY sea ice.

A.6.5.2.2 Concentration and form

Ice is also characterized according to its concentration. The concentration describes the amount of the water surface covered by ice as a fraction of the entire area, and is expressed in tenths. The actual area in the denominator varies depending upon the viewpoint of the observer, i.e. from a ship, from an aircraft or viewing a satellite image.

Ice can also be characterized by its form; the WMO code uses ten categories to describe the horizontal dimension. The categories consist of the smallest forms (pancake, brash and ice cakes), floes (small, medium, big and vast), landfast ice, icebergs and uncertain.

Acceptable concentration definitions include the following:

- a) ice-free: no ice is present;
- b) open water: a large area of freely navigable water in which ice is present in concentrations less than 1/10;
- c) drift ice/pack ice: term used in a wide sense to include any area of ice, other than landfast ice, no matter what form it takes, or how it is disposed; when concentrations are high, i.e. 7/10 or more, the term drift ice can be replaced by the term pack ice;
- d) very open drift: ice whose concentration is 1/10 to 3/10 and water predominates over ice;
- e) open drift: ice whose concentration is 4/10 to 6/10, with many leads and polynyas; floes are generally not in contact with one another;
- f) close pack: ice whose concentration is 7/10 to 8/10, composed of floes mostly in contact with one another;
- g) very close pack: ice whose concentration is 9/10 to less than 10/10;
- h) compact ice: ice whose concentration is 10/10 and no water is visible;
- i) consolidated ice: ice whose concentration is 10/10 and the floes are frozen together.

The following terms are used in ice messages and forecasts to describe the distribution of ice in a given area:

- ice cake: any relatively flat piece of ice less than 20 m across;
- ice openings: includes all forms of fractures and cracks;
- crack: any fracture of landfast ice, consolidated ice, or a single floe, which is followed by separation ranging from a few centimetres to several metres;
- strips: long, narrow area of drift ice, about 1 km or less in width, usually composed of small fragments detached from the main mass of ice, which run together under the influence of wind, swell or current; and
- ice edge: demarcation at any given time between the open water and sea, lake or river ice, whether landfast or drifting, which can be classified as either compacted or diffuse.

A.6.5.2.3 Icebergs

Glaciers and ice caps with access to open water can be found in many regions. As they are formed by snow falling and gradually being compressed into ice over many hundreds of years, they consist of freshwater ice. The extremely large (several tens of million tonnes) ice pieces that calve from a glacier are called

icebergs. Smaller pieces are termed bergy bits and growlers. Iceberg sizes are classified according to waterline length as growlers (0 m to 5 m), bergy bits (5 m to 15 m), small (15 m to 60 m), medium (60 m to 120 m), large (120 m to 200 m) and very large (>200 m). The average density of icebergs is generally in the range 850 kg/m³ to 910 kg/m³[90].

Icebergs can survive in the ocean for many years, either floating or grounded. Reference [47] provides an accepted iceberg-shape terminology. Unfortunately, this shape terminology is not really useful for dealing with icebergs in offshore operations. An alternative shape terminology^[63] has been modelled after Reference [91]. The distinction between tabular and non-tabular icebergs is useful from design and operational perspectives. Some wedge- or dome-shaped icebergs can be more difficult to tow.

Additional information can be found in ISO 35106.

A.6.5.3 Ice morphology

A.6.5.3.1 General concepts

The density of ice is less than that of water; thus, ice is generally found floating. Some forms of non-floating ice such as anchor ice, ice foot, stranded ice and grounded ice can also be found.

Anchor ice is submerged ice attached or anchored to the seabed. It is found in shallow sub- or intertidal zones when the air temperature is below the freezing point of water.

An ice foot is a narrow strip of ice that is frozen to the shore of an island or beach. In the context used here, it is formed when crushed ice remains frozen against an island or structure after an ice floe impact event has occurred.

Stranded ice is floating ice that is aground in shallow water.

Grounded ice refers to ice that is attached to or in contact with the seabed.

A.6.5.3.2 Level and pack (broken) ice

Level ice can be defined as sea ice with un-deformed upper and lower surfaces. Level ice normally has a granular top layer, a transition zone and then columnar grains through most of the remainder of the thickness of the ice sheet.

A subset of level ice (termed S2 and S3 in scientific terminology)^[92] is classified according to the orientation of the *c*-axis (the axis of symmetry of the hexagonal lattice). The mechanical properties (flexural strength, compressive strength, Young's modulus, etc.) are influenced by the crystal structure of the ice and its *c*-axis orientation. If the ice cover has been rafted at an early stage of growth and then continues to grow, it is difficult to distinguish it from pure level ice without ice texture analysis. If the rafted layers are thin, <10 cm, the rafted ice behaves for most practical purposes as pure level ice.

While the WMO does not recognize the term “broken ice”, it has gained acceptance within the industry as meaning pack ice or ice floes. Ice floes originate due to ice dynamics (i.e. the movement of ice caused by stresses resulting from thermal expansion, wind and currents), waves moving into an ice sheet, ice sheet interactions and ice sheets interacting with objects such as structures, ships, etc. Temperature variation

can induce internal stresses in the ice cover and crack propagation can occur, breaking a sheet ice into ice floes.

A.6.5.3.3 Ridged and rafted ice (deformed ice)

The ice cover can deform when subjected to movement caused by external stresses on the ice sheet/floe and interactions with another ice sheet/floe. Two common deformation mechanisms are ridging (the interaction of two ice sheets/floes at their edges) and rafting (the submersion of one ice sheet/floe beneath another). In both cases, deformations are localized where ridging and rafting processes take place.

Ridges are often categorized into pressure (compression) ridges and shear ridges. Pressure ridges are in general curvilinear features, but they can sometimes be linear. They are caused by one ice sheet/floe moving into another. They can exist as single features, with a triangular or trapezoidal keel and sail, but they are often found in larger ridge fields. Shear ridges tend to be straight features caused by one ice sheet/floe sliding along another's edge. A common feature of a shear ridge is a vertical side, both above and below the water, where the interaction took place. Shear ridges are often found at the boundary between landfast ice and the moving ice pack.

In general, ridges show a wide range of shapes and sizes. Keel depths up to 50 m and sail heights up to 12,8 m have been measured, but ridge keels deeper than 30 m are rare^[93].

FY ice ridges are porous features that consist of ice, water, air and snow. The above-water part, called the sail, has pores filled with air and snow. The underwater part, called the keel, has pores filled with water and in some cases air pockets can exist. Second-year and MY ridges are generally composed of ice with a very low porosity ^{[94][95]}. The keel depth to sail height ratio is an important parameter, and is usually between 4 and 5 for FY ridges and around 3 to 3,5 for second-year and MY ridges^{[96][97][98]}.

A ridge keel is further separated into an upper refrozen layer, called the consolidated layer, and a lower unconsolidated part. The consolidated layer grows through the ridge lifetime as a function of the surrounding meteorological and oceanographic conditions, air and water temperature, snow depth and the velocity of the wind; surrounding currents are of principal importance. There is no clear indication whether the mechanical properties are similar to or weaker than those of level ice. References on this topic include [99] to [108]. For FY ridges, the ratio of the thickness of the consolidated layer to the level ice thickness that has grown in open water under the same temperatures to which the ridge was exposed is an important factor, and is generally between 1,5 and 2. A consolidated layer thickness of 8,5 m has been measured in FY ice in the Okhotsk Sea^[109]. The distinction between the consolidated and unconsolidated parts of a keel is less clear for MY ridges, as it is possible that some can be consolidated all the way through the keel^[110].

Rafting generally occurs with thinner ice, typically less than 0,4 m. Several layers can raft and consolidate, producing a thick consolidated ice feature^[111]. Sometimes rafting will result in an interlaced finger appearance (finger rafting). Rafted ice is generally smooth so it is difficult to distinguish from level FY ice. Thickness measurements are necessary to distinguish between them.

A.6.5.3.4 Rubble fields and stamukhi

Rubble fields and stamukhi are areal features formed from piles of broken ice. Oval, rectangular or square in shape in the plane of the ice surface, these features can range in lateral extent from tens of metres to kilometres and can be found in a range of water depths.

Use of the terms “rubble fields”, “stamukhi/stamukha” and “hummocks/hummock fields” varies by region and individual preference. The WMO^[47] defines a hummock as “a hillock of broken ice which has been forced upwards by pressure” but does not include the areal aspect. Further differentiations include descriptions of hummock field as “an area of sea ice that has essentially all been deformed into a series of hummocks”, rubble field as “An area of sea ice that has essentially all been deformed. Unlike the expression hummock field, it does not imply any specific form of the upper or lower surface of the deformed ice” and stamukha as “The Russian expression for a large hummocky pile of ice grounded in water depths of more than 20 m...”^[234]. The use of the term, stamukhi, is sometimes restricted to piles that are grounded or to describe the sail portion of these features.

A feature distinguishing hummocks from ridges is their degree of consolidation. As such, the term “hummock” is most applicable to MY ice, although the term can be used to describe deformed FY ice that has consolidated over the course of the winter season. While the term “hummock” is only used with reference to MY ice features in this document, it can be used to describe different features elsewhere.

Statistics on the physical dimensions of rubble/stamukhi type features (both FY and MY) exist for the US Chukchi Sea^[113], for regions offshore Russia^{[114][115]}, for offshore Sakhalin Island^[116], and for the Canadian Beaufort Sea^[96].

A.6.5.3.5 Landfast ice

Landfast ice is a continuous, stable ice cover that is frozen to the shore or a grounded feature. The extent of landfast ice from shore depends upon the water depth, the local geography (i.e. islands, bays, shoals, etc.), and wind and water current speeds, and can be from a few metres to several hundreds of kilometres. Landfast ice is normally composed of FY ice, but second-year and MY landfast sea ice does exist in the northern Canadian arctic islands and off Northeast Greenland.

The boundary between landfast ice and pack ice is called the shear zone, or transition zone. This zone consists of substantial ice deformation and consequently a high ridge density (defined as the number of ridges per unit length; e.g. per kilometre). When the ice within the shear zone moves, it is part of the pack ice, but when it freezes it becomes part of the landfast ice cover.

Pack ice is any ice cover that is not landfast. The parameters used to characterize it are ice concentration, the floe size distribution, ice velocity and the thickness distribution. One can also characterize ridge dimensions and frequency.

A.6.5.3.6 Icebergs

Where required for the specification of design criteria, quantitative representations for iceberg shape should be established. Typically, these involve interrelationships between easily measurable index dimensions (maximum waterline length, waterline width perpendicular to the length, maximum height

and maximum draught), and their relationship with other parameters, such as metacentric height, waterline area, radii of gyration and block coefficient.

NOTE The block coefficient is the ratio of iceberg volume to the volume of a rectangular prism formed from the index dimensions.

Significant additional information on icebergs can be found ISO 35106.

A.6.5.4 Ice movement

A.6.5.4.1 Processes

Wind, waves, current and the thermal expansion of ice affect ice movement and pack ice pressure. Ice movement rates and the proximity to shore affect the number of ice features encountered, ice actions, and operations. Ice pressure can affect vessel traffic, IM and evacuation procedures.

Ice can be very dynamic under the influence of wind and current. Although ice drift speeds are generally less than 1 m/s, speeds of over 3 m/s have been observed in regions of high tidal currents, such as Cook Inlet, Alaska. Numerous publications are available that describe the factors that influence ice drift speed, i.e. surface and keel drag coefficients, horizontal areas, wind speed, current speed, etc. If actual measured ice drift data are not available, ice drift speed can be estimated by the use of algorithms adopted in computer simulation models, determination of ice-feature encounter frequency, speed of ice impact, etc.

An important phenomenon that results from ice dynamics is ice pressure. Ice pressure is common in coastal regions when onshore winds cause ice to build up along a coast or when the wind or current direction changes rapidly. Changes due to tidal currents can be quite important in this respect. In either case, the ice cannot respond by changing its direction, and internal stresses within the ice cover build up, causing ice pressure. The effect of ice pressure is to reduce the capability of a vessel to transit through the ice. In extreme cases, it has been known to cause ice floes to penetrate a vessel hull, causing it to sink. Offshore platforms are generally designed to higher local actions than those caused by ice pressure, but a check should be performed.

Wind, waves, currents and sea ice, when present, govern the drift of icebergs. Since most of the iceberg mass is under water, ocean currents have a greater effect than sea ice on iceberg speed and direction^[63].

A.6.5.4.2 Marginal ice zone

The region of the ice cover adjacent to the open ocean boundary is called the marginal ice zone (MIZ), which is created when waves and swell from the open sea penetrate into the ice cover, see 6.4.2.

If the wind is blowing towards the ice edge from the open sea, it compresses the MIZ and produces a compact ice field with a sharp outer boundary of small cakes and brash ice (fragments of broken floes). Atmospherically, an on-ice wind is often associated with warm moist air from the open sea being cooled over the ice so that compact ice margins are often difficult to observe from the air or from visible-range satellite; their structure is best revealed by synthetic aperture radar.

When the wind is blowing away from the edge, most of the MIZ becomes diffuse. The outermost edge, instead of just becoming an open ice field fading away into the open sea, takes on a new organization of

its own, with a series of compact ice edge bands forming, separated by completely open water and lying with their long axes roughly perpendicular to the wind. In winter this opening up of the ice edge permits new ice to form in the open water areas, leading to enhanced brine rejection in the MIZ.

In northern oceans, a wind parallel to the ice edge can create forcing for water and/or air temperatures. This can create forcing away from the ice edge, in the case of water temperature, which can be of relevance in the event of scenarios that involve oil spills. Similarly, the interaction can produce a surface front outside the ice edge; an example is a front with a temperature jump of 6 °C in 25 km, observed 100 km off the ice edge in the Barents Sea^[117].

A.6.5.5 Ice properties

Guidance with respect to the mechanical properties of ice is provided in A.8.2.8.

A.6.5.6 Ice monitoring

ISO 35106 provides information on ice monitoring.

A.6.6 Seabed considerations

A.6.6.1 Earthquakes

Examples of arctic and cold regions that are known to be seismically active are indicated on maps in ISO 19901-2, and include:

- Cook Inlet;
- Okhotsk Sea and Tatar Strait;
- Sea of Japan;
- Bohai Sea; and
- certain regions of offshore Canada.

A.6.6.2 Permafrost

Reference should be made to A.9, as well as ISO 19901-8 for marine soil investigations and ISO 35106 for data requirements.

A.6.6.3 Ice gouge

Ice gouging or scouring (terms used synonymously in the literature) occurs when an ice keel moves while in contact with the sea floor. Ice features associated with gouging include:

- FY ridges or stamukhi within ice floes driven by pack ice;
- fully consolidated (or nearly so) second-year and MY ridges within ice floes;

- stamukhi being moved or destroyed by movements of the surrounding ice;
- icebergs or ice islands.

Ice gouge depths can range from a few centimetres to several metres, depending on the type of ice feature creating the ice gouge and the seabed soil type. Depths can vary significantly within the footprint area of the ice gouge itself and also along the length of the ice gouge.

Ice gouges are generally linear features that can extend for a kilometre or more in length. In the following discussion, the term ice gouge is used for furrows or linear features, while the term pit is used for areal features. Pits are distinguished from ice gouges in that they have limited lateral extent, in the range of a few metres to tens of metres.

Generally, it is thought that ice gouges are created by upslope movements of ice keels in contact with the seabed. Downslope ice gouging has also been observed for ridge keels^[118] and for icebergs, where pitch motions can occur during the gouging process. The significance of iceberg motions is also illustrated by the presence of chains of pits that have been seen in the seabed off Canada's Labrador coast^[119]. Isolated pits in the seabed have been observed in various locations such as Canada's east coast^[120] and the Caspian Sea.

Specific detailed knowledge regarding the gouging process is not generally available, and the number of direct observations that have been made in the field is quite limited. Knowledge of the gouging process is derived primarily from the impressions in existing seabeds or in ancient seabeds that are now exposed.

It is generally recognized that the ice-soil interaction process depends on the ice feature and type of interaction. In the Canadian Beaufort Sea, the available literature suggests that ice gouges are long, linear features with relatively consistent dimensions over their length and width, and perhaps some rise-up of the base of the ice gouge track. It is generally thought that these features were created by MY ridge keels^[121]. Recent information obtained with a multi-beam echo-sounder, which provides a more complete record of the ice gouge, shows that local variations do occur in the ice gouge track. Reference [118] describes cases where the number of furrows within a multi-keeled ice gouge produced by an MY ridge keel varies along the ice gouge track. They attribute this to changes in ice drift direction, which can alter the orientation of the gouging keels, potentially causing them to be “shadowed” by one another.

Surveys along ice gouge lengths of several kilometres in the Canadian Beaufort Sea have shown that the track can be divided into well-defined phases (increasing ice gouge depth without rise-up, increasing ice gouge depth with rise-up and constant ice gouge depth with rise-up), and that the base of the ice gouge can rise by several metres over the length of the feature^{[122][118][123]}. This can indicate that the ice keel is being uplifted along the ice gouge track or, alternatively, that the ice keel is being abraded or failing mechanically along the track or perhaps a combination of the two.

Off Canada's east coast and off Greenland, where icebergs are the main ice gouging feature, other characteristic marks have been observed. Deep pits have been observed in the seabed at the end of ice gouge tracks, where icebergs have ground themselves into the seabed, broken up or melted in place. Pits can also form due to rotation of a gouging ice feature resulting in an increase in draft. The same features have been observed for stamukhi. Isolated iceberg pits that are probably due to melting, calving or break-up and subsequent impact with the seabed have also been observed. The depth of pits formed by icebergs can reach 10 m, with horizontal dimensions several times greater. Linear ice gouge tracks are

occasionally found with periodic impressions in the seabed, likely the result of wave-excited pitch motions of marginally stable icebergs.

Consideration should be given to rocky seabeds, infill effects and subsequent gouging when estimating ice gouge frequency from seabed records. Corrections can potentially be made using appropriate models.

Data requirements for ice gouges are found in ISO 35106. Actions due to ice gouges are addressed in Clause 14 of this document.

A.6.6.4 Strudel scours

Rivers that discharge into arctic coastal waters can thaw well in advance of the bottomfast sea ice along the coast during the spring melt season. The river water flows onto the ice and spreads offshore, flooding substantial portions of the nearshore zone. Drainage occurs through discontinuities in the ice, which typically consist of tidal cracks, thermal cracks and seal breathing holes. The downward flow is not simply due to drainage. It is driven by buoyancy of the submerged ice, resulting in a jet-like downward stream^[124] which can create strudel scours. The extent of scouring depends on drainage rate and water depth (typically less than 7 m). Scour depth can reach several metres.

Two types of strudel scours have been observed: circular and linear. Circular scours form beneath either circular drainage features or enlarged segments of crack drains. Linear scours form beneath crack drains.

In general, the distribution and severity of strudel scours are controlled by river discharge and the propagation and drainage of the flood water through discontinuities in the ice canopy.

Data requirements for strudel scours are found in ISO 35106. Actions due to strudel scours are addressed in Clause 14 of this document.

A.7 Reliability and limit states design

A.7.1 Design philosophy

A.7.1.1 Governing principles

This document builds on and extends the general provisions of ISO 19900. This document aims to ensure the performance of arctic offshore structures through a design approach in which underlying reliability targets are reflected in the partial action factors associated with the various limit states. The ULS and ALS are more clearly differentiated in terms of both actions and resistance, and the ALS is emphasised for abnormal environmental events.

This document allows the designer to treat individual design situations separately and thereby meet overall targets in an approximate sense by applying individual action combinations and partial action factors, and by applying limit states and factors for resistance appropriate for ULS and ALS.

Clause 7 sets out provisions, performance-based where possible, for offshore structures in arctic and cold regions. While a degree of prescription has been provided to facilitate practical design, there is also the possibility for probabilistic evaluation of environmental action combinations and factors in order to allow flexibility in the selection of safe, technically feasible and efficient design options.

It is possible that the reliability of a particular structure in some ice environments is not always consistent with the assumptions made during the calibration of the partial action factors presented in this document. Therefore significant site-specific conditions should be assessed in the context of the state of knowledge relevant to the development of this document^[125]. Also, when considering phases such as construction, transportation, installation and decommissioning, it should be noted that the reliability targets and partial action factors have been explicitly derived for in-place, in-service conditions.

It is also prudent to consider the overall reliability of a structure in addition to whether the reliability associated with individual design situations and limit states provisions has been satisfied. If parts of the structure are assessed separately, then appropriate weighted reliabilities and event probabilities should be applied to ensure that the overall reliability target for the structure is achieved.

The design verification process envisaged by this document with respect to an arctic offshore structure can be summarized as follows:

- identify all reasonably foreseeable hazards and hazardous events;
- define design situations for qualifying events (e.g. annual probability of occurrence greater than 10^{-2} for ULS), for the complete structure and for its components, including foundations, considering both local and global effects;
- for each design situation, calculate or estimate the permanent and variable actions, and the EL or AL action for the principal environmental or accidental action;
- for each design situation dominated by an ice event, calculate ice actions for various combinations of ice parameters (such as ice thickness, ice strength, drift speed, ridge geometry, iceberg mass, etc.). These define the ice events. The ice action hazard curve is thereby defined and the EL or AL ice action arising and the associated ELIE or ALIE is established;
- for each design situation characterized by a principal environmental action, add the companion actions to obtain the EL (or AL) environmental action (E_{EL} or E_{AL});
- for each relevant limit states action combination in Table 7-3, combine E_{EL} or E_{AL} with permanent and variable actions in order to obtain the design action for each action combination for that design situation;
- analyse the structure (linear/quasi-linear for ULS, non-linear/full collapse permitted for ALS) in order to determine design action effects in all structure and components including foundations;
- verify the design of the complete structure and its components, including foundations, by ensuring that design action effects from each action combination do not exceed design resistance. For ULS, design resistance is based on factored resistances. For ALS, design resistance can be a range from factored resistances, which provides a lower limit because one component is likely to fail first, up to complete loss of integrity/final collapse, which is the upper limit taking account of the ductility and reserve strength of the structure.

A.7.1.2 Life-safety categories

No additional guidance is offered.

A.7.1.3 Consequence categories

No additional guidance is offered.

A.7.1.4 Exposure levels

By analogy to the evacuation of platforms in the path of hurricanes in various parts of the world, the evacuation of an arctic offshore structure (and wells secured) can be planned in the case of a predictable extreme or abnormal ice event such as an approaching ice island. This can constitute an L2 exposure level design situation. Berms and protection structures can potentially be designed as L3 if the platforms or structures they protect retain their own integrity with respect to life-safety and other consequences after the failure of the L3 structures.

This document extends the provisions of ISO 19900 so that exposure level applies not only to a complete platform or structure, but also to parts (structural components) of a platform or structure. When a structural component or part of a platform or structure is designated with a lesser exposure level (i.e. L2 or L3) than the rest of the platform or structure, 7.1.4 should be interpreted by replacing “platform or structure” with “component” in the second paragraph. When a component of a platform or structure is designated with a lesser exposure level, the failure of the component should lead to impairment only of a part of the platform or structure with an equivalent or less restrictive exposure level, where L3 is the least restrictive.

A.7.1.5 Safety and reliability

The design process includes the need to identify all reasonably foreseeable hazardous events. This document focusses on ice events. If the annual probability of ice event occurrence permits an EL ice action or an AL ice action to be identified, ice actions are required to be calculated and the structural design needs to be verified for resulting design situations. If the annual probability of ice event occurrence is less than the probability specified for the AL ice action (10^{-4} for L1, 10^{-3} for L2), the event is not included in the design verification process, but can be significant for the risk profile of the structure with respect to the reliability targets set out in Table A.7-1.

Such very unlikely events can be caused by ice islands and large icebergs at some locations. These very unlikely events, which can have high consequences, can be subject to the owner's risk management policy as pertaining to life safety and other consequences including economic loss. This policy should consider operational measures for mitigating risks as deemed appropriate under the principle of “As Low As Reasonably Practicable” (ALARP) for all foreseeable hazardous events, both above and below the probability of the AL ice action.

Evaluation of ductility and reserve strength arising from robustness can often demonstrate a risk of structural failure or collapse significantly lower than the reliability targets.

Operational measures to reduce ice actions (see 8.2.7) can reduce the probability of occurrence of ice events. The consequences of such events can be reduced by planning for appropriate emergency response measures, such as production shutdown and evacuation of personnel, see 18.2.

A.7.1.6 Limit states

This document adopts ALS as the Abnormal Limit State to emphasise the importance, and potential predominance of, abnormal ice events and actions for an arctic offshore structure. Design verification of structural strength, other than fatigue strength, is performed for both ULS and for ALS action combinations.

The ULS provides the limit states verification for EL events and actions. The analysis method for ULS is normally based on elastic/quasi-elastic analysis. The ULS will generally limit inelastic behaviour and large deformations in order to meet the criterion for no significant damage under EL action effects. Significant damage would involve a reduction in the resistance capacity of the structure or its components, such as a reduction in resistance capacity or stationkeeping ability, with respect to after-damage design situations.

The ALS provides limit states verification for AL events and actions. The analysis method for ALS can take into consideration system ductility and reserve capacity, i.e., robustness. Non-linear or progressive collapse analysis of a robust structure or component results in a larger design resistance due to considerations of system ductility, reserve capacity, and action redistribution.

In general, robustness does not mitigate loss of static equilibrium of the structure considered as a rigid body, nor in some cases foundation failure. Depending on the relationship between EL and AL action effects, either ULS or ALS can govern the structure as a whole or particular components of the structure.

This limit states design approach should ensure that a platform can resume normal operations after an EL event, whereas after an AL event, the post-damage integrity of the structure or structural components would need to be assessed as described in ISO 19900.

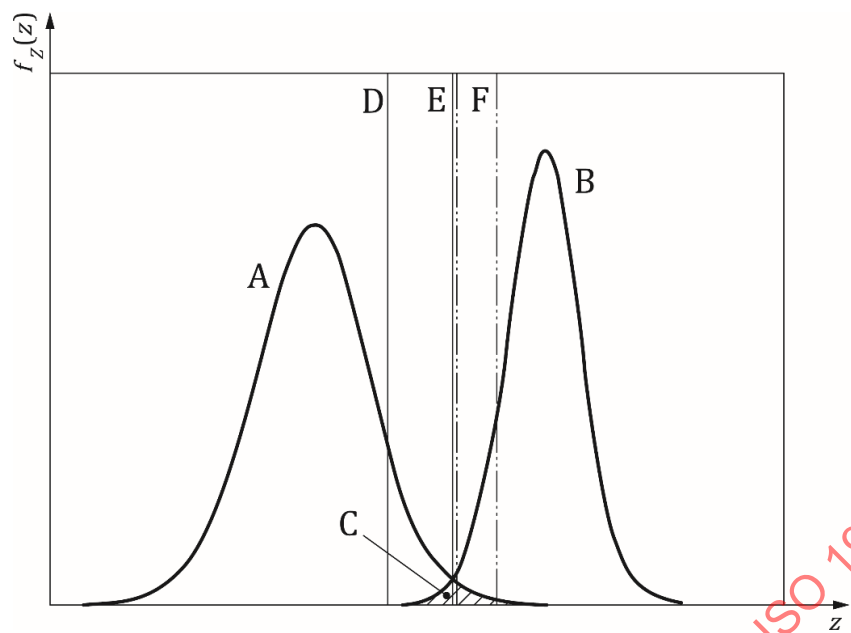
A.7.1.7 Alternative design methods

No additional guidance is offered.

A.7.2 Limit states design method

A.7.2.1 Limit states

For the limit states approach, the total design action effect in a limit state is derived from an analysis of an appropriate combination of the factored representative values of the actions. Representative values should be derived as characteristic values from a probabilistic description of the action, but otherwise can be a nominal value. "Nominal" refers to values of a basic variable determined on a non-statistical basis, typically from acquired experience or physical conditions. Similarly, the characteristic material properties or resistances are factored to obtain the design values of resistances (for ULS) or are assessed in a wider context of robustness and system ductility (for ALS). The total design action effect should not exceed the design resistance (see Figure A.7-1). This is indicated by Key item "E" in Figure A.7-1, where the value of the design action effect does not exceed the value of the design resistance.



Key	
<i>z</i>	action effect or resistance
A	pdf for action effect
B	pdf for resistance
C	domain of possible failure (a situation in which action effect exceeds resistance)
D	representative (characteristic) action effect
E	design value: factored representative action effect and factored representative resistance
F	representative (characteristic) resistance

Figure A.7-1 — Schematic showing action effect, resistance, and failure domain

Resistance, as defined in ISO 19900, implies the capacity of the component of a structure to withstand action effects without failure. In this context, failure can involve insufficient strength, stability or rigidity, or inadequate serviceability.

Many aspects of modelling actions and resistances can be uncertain, including basic assumptions, incomplete or simplified mathematical/mechanical models, idealizations and the use of insufficiently tested or calibrated variables. Typical examples include:

- the assumption of an ice pressure versus area relationship for a specific structure at a specific site, an assumption that, in principle, can only be verified by a dedicated series of full-scale ice-action measurements;
- mathematical modelling of the structure and foundations, in particular non-linear modelling and structural analysis of reserve strength and resistance for the ALS.

While it is generally agreed that these uncertainties should be accounted for in the formulation of design criteria and, by extension, in the calibration of partial action factors, good practice is for the designer-analyst to adopt a “cautious” deterministic approach using appropriately conservative assumptions.

The use of the limit states design method, with its corresponding factors, is intended to achieve an acceptable reliability level in the design, but the method itself does not allow a quantification of that level. While the achieved reliability can vary from one design situation to another, the individual factors are optimized so that deviations from the target reliabilities over a number of design situations are

minimized. A calibration makes use of a full probabilistic approach whereby the probability of non-performance in each limit state is calculated specifically. The advantage of the factored action and resistance approach is that, because of the optimization of factors achieved by weighting the results for each design situation, the achieved reliability levels are close to the intended targets and show a narrower variation among different design situations, while maintaining practical simplicity.

Once calibrated, the factors are associated with a specific range of design situations, and the design situations are normally specified in a document such as a “basis of design”. Partial factors can also be associated with the probabilistic combination of actions to calculate a combined EL or AL action which represents the reduced likelihood of the individual EL or AL value of one action combining with the EL or AL value of another (e.g. maximum ice actions occurring simultaneously with a strong earthquake). The factored action and resistance approach is also known by alternative names: load and resistance factor design method (LRFD) or partial factor design method (PFD).

Non-linear methods of analysis can be used, in which structural components can behave inelastically (i.e. individual design resistances are exceeded and/or action effects are redistributed to other components), if there is sufficient ductility and if the overall structural design is adequately robust. Robustness represents the ability of a structure to reach the ALS without complete loss of integrity even in the event of component failures. Procedures and further provisions for floating systems are described in 13.4 and 13.5.

A.7.2.2 Actions

The concepts of “frequent environmental processes” and “rare environmental events” were introduced in other codes^[26] to emphasize the distinction between frequent events (wind, storms, etc.) that have several peak values each year, and relatively rare events such as iceberg collisions that occur only once every several years but nevertheless can be expected during the design service life. The design action values for such iceberg collisions can be calculated for annual exceedance probabilities of 10^{-2} and 10^{-4} per year for L1 structures.

In this document, the concepts of EL and AL environmental events replace the concepts of “frequent process” and “rare events”. Note that these two sets of concepts are not equivalent, in that EL and AL are descriptors associated with defined probabilities, whereas the previous concepts were general descriptors.

Hazardous events arise from hazards. The general term “event” includes all types and probabilities of hazardous event. Ice events can be either or both of the following:

- a) the occurrence of an ice feature that results in ice-structure interaction;
- b) a peak value in the ice action applied to the structure within a specified time or distance travelled by the ice.

Ice events can be described in terms of the dimensions, mass or geometry of the ice feature, ice thickness, ice strength, drift speed, and any other ice-related factors influencing the magnitude of ice actions during interaction with the structure. Local ice actions are generally described according to b), while events

leading to global actions can involve both a) and b). A typical approach to calculating EL or AL ice action for a design situation defined by a particular ice feature includes:

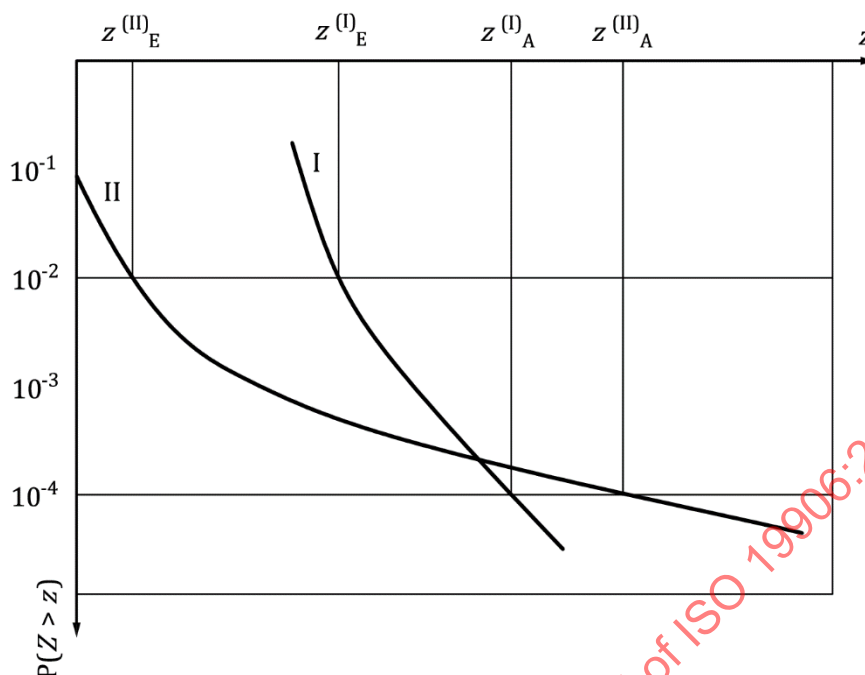
- defining the action hazard curve by ranking ice actions by their magnitude;
- determining EL and AL ice actions, as the values of actions where the action hazard curve crosses the relevant probability axis, see Figure A.7-2;
- estimating EL and AL ice actions from all the listed ice actions from all ice events using information about estimated number of ice events per year and specified annual probability of exceedance for EL and AL ice action

Calculated EL and AL ice actions can then be related back to specific ice events as described in Clause 8. The calculation of representative values for ice actions is detailed in A.8.2.2, and the Monte Carlo approach is illustrated in A.8.2.2.4.

If an ice event occurs with an annual probability less than that specified for design verification, a design situation is not defined and the ice actions do not need to be calculated.

The EL and AL ice actions should be calculated and the associated ELIE and ALIE should be established for all applicable design situations. The circumstances involved with the ELIE and ALIE can include operational measures such as IM, disconnection and move-off. This approach removes the previous somewhat arbitrary distinction between the frequencies associated with frequent processes and rare events.

As required in 7.2.2.3 and 7.2.2.4, the 10^{-2} EL ice action and 10^{-4} (for L1) or 10^{-3} (for L2) AL ice action characteristic values should be calculated for all ice events, and applied as the representative values. If characteristic values cannot be calculated, as in the case of insufficient data, nominal values should be estimated based on expert judgment and used as the representative values. Depending on the shape of the hazard curve, the EL ice action can dominate, or can be close to zero such that the AL ice action can dominate, as shown in Figure A.7-2. Conversely, for very rare ice events with an annual probability of occurrence less than 10^{-2} , the EL ice action does not occur and only an AL ice action can be calculated. Companion actions should be considered when comparing the relative significance of EL and AL actions.

**Key**

z, Z	action	z_E	EL ice action
$P(Z > z)$	annual probability that action Z exceeds specified value z (annual probability of exceedance)	z_A	AL ice action
I	action hazard curve for frequent events		
II	action hazard curve for rare events		

Figure A.7-2 — Schematic illustration of EL and AL ice action, for different hazard curves

Potential examples of events for which only AL ice actions apply include iceberg and ice island events. If such ice events occur with an annual probability greater than 10^{-4} (for L1 structures), the AL ice action with an annual probability of exceedance of 10^{-4} can be estimated using the approach outlined in 8.2 and A.8.2.

Temperature gradients arising from functional requirements or environmental conditions can be an important action in the design of arctic offshore structures. These can be considered variable actions (Q) when determining partial action factors and action combinations.

A.7.2.3 Principal and companion environmental actions

Table 7-1 provides guidance on stochastically dependent, stochastically independent and mutually exclusive environmental processes. The first column in Table 7-1 indicates the type of the principal EL or AL environmental action in a particular combination of environmental actions. The second column shows the types of environmental actions that are likely to have high or possibly EL values at the same time as the principal actions in the first column. The third column indicates types of environmental actions that are stochastically independent of the principal actions, and are therefore not likely to occur or to have high values at the same time. The types in the second and third columns should both be included in the environmental action combination under consideration. The fourth column lists environmental actions

that should normally be excluded from the environmental action combination with the principal action under consideration.

If a deterministic analysis is performed, then the representative extreme value of each relevant companion action should be factored by the relevant factor provided in Table 7-2 and then combined with the representative EL or AL value of the principal action. The resulting combined environmental action is then used in the relevant action combinations specified in Table 7-3.

If a probabilistic analysis is performed, joint probability distributions of the principal and appropriate companion values should be defined and analysed so that the resulting combined environmental action for each design situation has the annual probability of exceedance relevant to the limit state for that design situation. It can be expected that the principal action itself at the “design point” will have an effective value less than its individual EL or AL value, because the resulting EL or AL value is determined by the probabilistic analysis of all relevant actions. The resulting environmental action is then used in the relevant action combinations specified in Table 7-3.

The values specified in Table 7-2 are derived from a calibration analysis (see A.7.2.4) so as to be conservative to account for a wide variety of possibilities. For the design of arctic offshore structures, a full probabilistic calculation for companion actions is preferred.

A.7.2.4 Combinations of actions and partial action factors

The partial action factors for permanent and variable actions presented in Table 7-3 are based on ISO 19902 for fixed steel structures. For fixed concrete structures and for floating systems, ISO 19903 and ISO 19904-1 present different and sometimes lower values of these partial action factors. Therefore, if using ISO 19902, ISO 19903 and ISO 19904-1 for the respective structure types, the use of their partial action factors for permanent and variable, but not for environmental, actions is permitted. The calibration analysis for this document demonstrates that the partial action factor required for environmental actions for arctic offshore structures is not sensitive to small changes in the gravity partial action factors^[125].

The partial action factors are specified to be not less than the values in Table 7-3 (or in the structure-specific documents, if used) because larger factors can be used if greater reliability is required. In the case of partial action factors less than unity in Table 7-3 for overturning, uplift and action reversal, lower partial action factors can provide greater reliability. For action combination 1, in order to ensure a robust “still water” design in the case that the environmental action effect could reduce the action effects due to permanent and variable actions in a component, the structure is to be analysed for each design situation both with and without the environmental action. The latter (without the environmental action) is consistent with the “permanent and variable actions only” design situation specified in ISO 19902.

Thermal contraction and gravity combinations are defined in ISO 19900. Moving actions can be considered as variable actions.

A partial action factor of 1,2 for permanent hydrostatic pressure and for physically limited variable actions can be used, because of the very low uncertainty in the maximum values of these actions. An example of a physically limited variable action is the contents of a tank for which the variable mass cannot exceed that determined by the maximum volume of the tank.

Partial action factors have not been included for the L3 exposure level in Table 7-3. Although their specification is usually at the discretion of the owner and subject to national approval processes, some guidance on general values is provided in Reference [125].

This document allows the user to perform a calibration of partial action factors for use in place of the partial action factors presented in Table 7-3, to the reliability targets presented in Table A.7-1, for all exposure levels. This can be necessary due to particular aspects of the physical environment, the structure type, the ice-structure interaction scenarios and other factors such as IM if these are an integral part of the system design. A methodology for such a calibration is presented in Reference [125]. The results of such a calibration can be values of partial action factors that are less than or are greater than the values in Table 7-3. In such a calibration, due account should be taken of the relevant resistance, including definition of the ULS and ALS limits for failure, and partial factors on materials and resistance as specified in ISO 19902 and ISO 19903 as well as in other documents for offshore structures.

The targets in Table A.7-1 are for single causes, i.e. for each action combination under ULS and ALS, and apply to both global effects such as overturning and local effects.

Table A.7-1 — Reliability targets for each limit states action combination

Exposure level	Reliability target
L1	$1 - 10^{-5}$
L2	$1 - 10^{-4}$
L3	$1 - 10^{-3}$

The partial action factors in this document were calibrated according to Reference [125]. The calibration accounts for weighted combinations of all action effects over all design formulae and action combinations, for different resistance models, for different levels of action effect model uncertainties, for different levels of statistical uncertainty, and for different mean action event occurrence rates. The methodology involves a weighted optimization process with the objective function minimizing the deviation from L1, L2 and L3 targets, with checks that upper bound failure probability constraints are not violated. For L1 structures, a target annual failure probability of 10^{-5} was applied (target reliability of $1 - 10^{-5}$, see Table A.7-1), and a constraint was applied to ensure that no limit state annual failure probability exceeded 10^{-4} .

The reliability targets in Table A.7-1 take cognizance of both human safety and environmental protection through the exposure levels L1, L2 and L3, as explained in ISO 19900. It is emphasized that the targets in Table A.7-1 are for single causes, intended to be the governing one or ones. It should be noted that the reliability targets do not include operational risks such as transportation to and from the structure, platform or facility. Seismic risk is addressed separately, by reference to ISO 19901-2.

For exposure level L1, a manned platform for which evacuation or shutdown is not planned in the face of extreme or abnormal design situations for which the design is verified, as distinct from being disconnected in the face of situations for which it is not designed, the reliability target can be considered as being approximately associated with the worst case individual risk to life-safety for each person on the platform, as well as significant environmental damage, for one specific limit state or failure cause. Background to the value of the reliability target associated with exposure level L1 is provided in Reference [126].

Values of reliability targets have been quantified in CAN/CSA S471 for arctic and other offshore structures, Reference [26], since its initial publication in 1992. The “annual reliability target level” of $1 - 10^{-5}$ for CAN/CSA S471 “Safety Class 1”, equivalent to ISO 19906 “exposure level L1”, served as a basis for the $1 - 10^{-5}$ annual reliability target used for calibrating the L1 partial action factors in this document. CAN/CSA S471, now withdrawn, has been applied successfully in offshore projects subject to ice actions, such as Terra Nova and White Rose on the Grand Banks off Canada's east coast.

For the lower exposure levels L2 and L3, the annual reliability target is reduced to compensate for the reduced exposure of personnel and the environment. The value for “exposure level L3” in this document is consistent with the “annual reliability target level” of $1 - 10^{-3}$ for CAN/CSA S471 “Safety Class 2”.

In view of the track record of successful application of these reliability targets for actual designs, an attempt at greater accuracy has been avoided, since an overly precise definition involving smaller subdivisions of orders of magnitude of the probabilities is not considered justifiable. The resulting calibrated partial action factors are consistent with other documents for offshore structures.

A.8 Events and actions

A.8.1 General

No additional guidance is offered.

A.8.2 Ice events and actions

A.8.2.1 General principles for calculating ice actions

The ice design process is illustrated in Figure A.8-1. A key issue is the identification of plausible ice scenarios and ice events for defining design situations based on the structural design, the local ice conditions and the metocean environment. The results are representative values of EL and AL ice actions, as relevant for each design situation.

The design situations for a structure include global and local ice actions. Global actions represent the total action applied to the structure, whereas the local actions are those applied to a specified area within the nominal contact area. The imprint of the ice feature on the structure at a given penetration, without any reduction for spalls involving pieces of ice that break off, is termed the global or nominal contact area (see Figure A.8-2). The imprint of the ice feature can extend to the full width of the structure. The actual contact area can be much smaller than the nominal contact area. For most structures subjected to ice interactions, the design should consider both global and local ice actions.

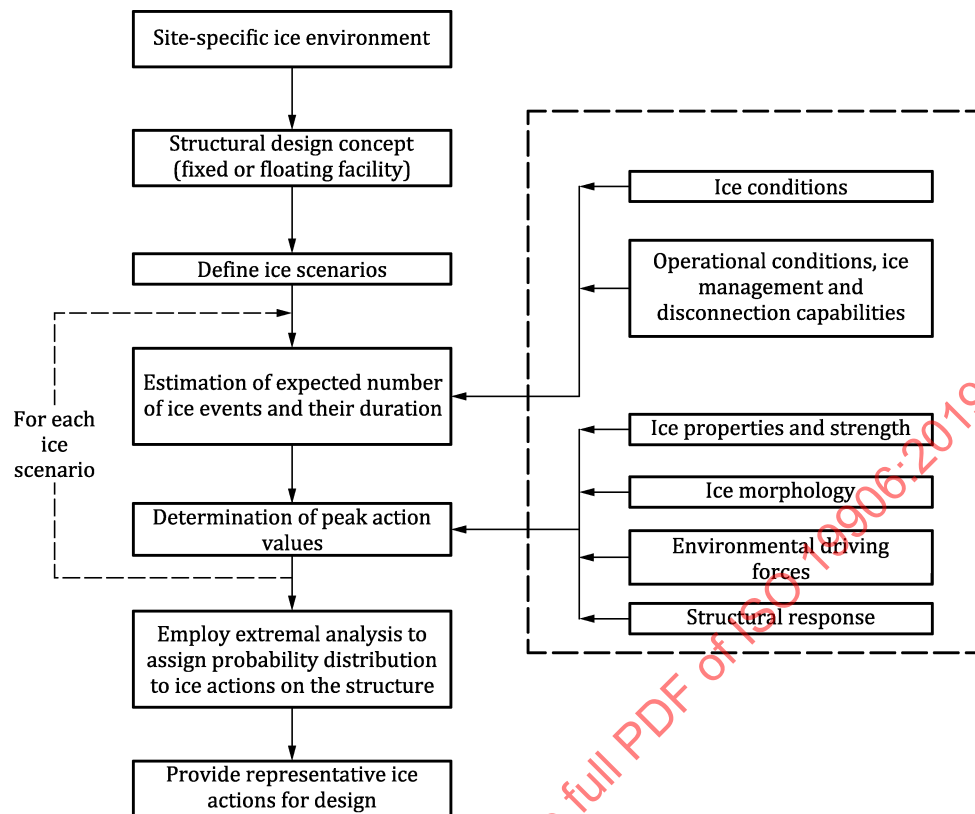
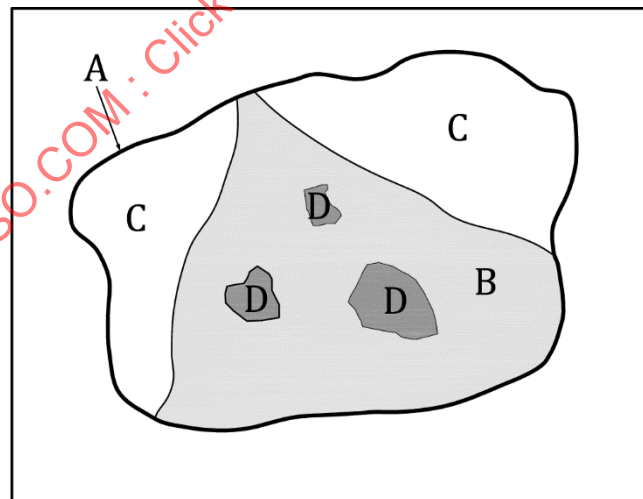


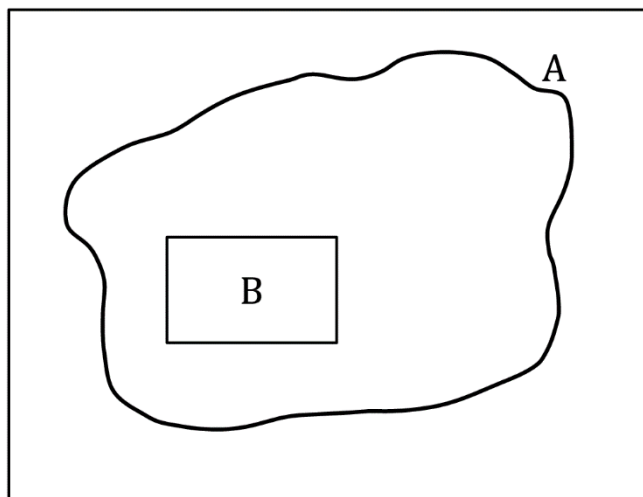
Figure A.8-1 — Flowchart of overall approach for calculating ice actions

**Key**

- A global interaction area or nominal area
 B actual contact area

- C large spall
 D high pressure zone (HPZ)

Figure A.8-2 — Illustration of nominal contact area for glacial or massive ice feature interactions

**Key**

- A nominal contact area for global actions
 B design area for local ice actions

Figure A.8-3 — Illustration of local pressure design area

The global ice pressure is usually defined as the global action divided by the nominal contact area. Both laboratory tests and field measurements show that ice pressure distributions within the global (nominal) interaction area are highly non-uniform and rapidly changing with time during the ice-structure interaction.

Global design is concerned with the global action exerted on a structure and corresponding global action effects under the limit states described in this document, see 7.2.1.1, and in ISO 19900:2013, subclause 7.1. For massive ice features, the contact area and the global action will tend to increase with penetration distance of the structure into the ice.

It has been found necessary to develop two separate ice pressure relationships, one for global design and the other for local design. Smaller areas within the global interaction area can be subjected to local pressures that are considerably higher than the global average pressure. This is addressed by assessing local design separately using local pressure relationships.

For local design, the maximum ice pressure and action that can develop on a smaller subarea within the nominal contact area is required (see Figure A.8-3). A range of local design areas and corresponding local pressures should be evaluated to determine the critical local action for the structure considered. The highest pressure on a subarea can occur anytime during the interaction and anywhere within the nominal contact area.

Detailed procedures for determining global ice actions and local ice actions are presented in A.8.2.4 and A.8.2.5.

A.8.2.2 Representative values of ice actions

A.8.2.2.1 Representative values

In this document, representative ice actions are determined at the extreme level and at the abnormal level, with relevant annual exceedance probability levels, for each ice scenario under consideration and for all design situations.

Representative ice actions can be estimated using:

- probabilistic methods, in which the joint probability distribution of the most important parameters is used to calculate characteristic values for EL and AL actions — the characteristic value is the main representative value;
- deterministic methods, in which extreme (e.g. thickness, for sea ice) or abnormal (e.g. mass or kinetic energy, for icebergs) and nominal values (e.g. pressure) of ice parameters are combined to construct ELIE and ALIE for which corresponding actions are calculated.

Note that several different combinations of ice parameters can result in ELIE or ALIE (e.g. extremely large iceberg moving at average speed or an average size iceberg moving at extreme speed).

For definitions, reference should be made to Clauses 3, A.3, 7.2.2.3 and 7.2.2.4. “Nominal” refers to values of a basic variable determined on a non-statistical basis, typically from acquired experience or physical conditions.

Regardless of the method, the objective is to estimate appropriate EL and AL actions. More effort is required for probabilistic methods, with the potential benefit of increased reliability and efficiency in the design. Where insufficient site-specific data are available for a particular interaction scenario, nominal values of the parameters can be used.

For each ice scenario under consideration, the annual ice action, Z , is the maximum of the individual actions V_j in a year, as given in Formula (A.8-1):

$$Z = \max(V_1, V_2, \dots, V_j, \dots) \quad (\text{A.8-1})$$

If no events take place in a particular year, Z should be set to zero. Each V_j and, consequently, Z is a function of n , generally random, contributing parameters, X_i , as given in Formula (A.8-2), which is called an action equation:

$$V = V(X_1, X_2, \dots, X_i, \dots, X_n) \quad (\text{A.8-2})$$

The relationship between the individual action, V , and the contributing parameters, X_i , can be analytical or numerical, and a single expression or involving multiple expressions, such as the minimum of more than one mechanism acting simultaneously against the structure and within the ice cover.

While Z is typically the global horizontal action, it can be an overturning moment, a vertical action or a local action. For sea ice events, the parameters X_i can include ice thickness, floe sizes, drift velocity, interaction width, ice crushing pressure, and others. The parameters with the most significant effect on extreme values of the action, Z , are generally the ice thickness and ice strength, whether for level ice, rafted ice or the consolidated layer of a ridge.

A.8.2.2.2 Probabilistic approach

A.8.2.2.2.1 Analysis of ice events

In the probabilistic approach, the representative actions $z_{r,E}$ and $z_{r,A}$ are obtained from Formulae (A.8-3) and (A.8-4):

$$P(Z > z_{r,E}) = 10^{-2} \quad (\text{A.8-3})$$

$$\begin{aligned} P(Z > z_{r,A}) &= 10^{-4} \text{ (for L1 structures)} \\ &= 10^{-3} \text{ (for L2 structures)} \end{aligned} \quad (\text{A.8-4})$$

where P is a probability, subscript E refers to EL and subscript A refers to AL .

These can be rewritten equivalently as given in Formulae (A.8-5) and (A.8-6):

$$F_Z(z_{r,E}) = 0,99 \quad (\text{A.8-5})$$

$$\begin{aligned} F_Z(z_{r,A}) &= 0,9999 \text{ (for L1 structures)} \\ &= 0,999 \text{ (for L2 structures)} \end{aligned} \quad (\text{A.8-6})$$

where $F_Z(z)$ is the cumulative distribution function of the annual maximum, Z .

In many situations, the annual maxima can be used directly to form the distribution of ice actions. If events such as ridge or iceberg impacts are used to define ice actions, then it is reasonable to connect the distribution of the annual maxima $F_Z(z)$ with the cumulative distribution function of the ice action, $F_V(v)$, reached during *one* event. The relationship between $F_Z(z)$ and $F_V(v)$ depends on the frequency of events and the characteristics of the ice interaction process. Using this relationship and the function $F_V(v)$, one can calculate the desired values $z_{r,E}$ and $z_{r,A}$ by solving Formulae (A.8-5) and (A.8-6) analytically or numerically. Further discussion on the relationship between individual events, annual maxima and extremes is provided in Reference [127].

The number of ice events within a given period can often be considered as a Poisson process. For the distribution of annual maxima, the Poisson distribution with arrival rate $\eta[1 - F_V(z)]$ and Poisson parameter $n=0$ (corresponding to an absence of events in the reference period)^[127] yields the relationship between $F_Z(z)$ and $F_V(v)$ as given in Formula (A.8-7):

$$F_Z(z) = \exp\{-\eta[1 - F_V(z)]\} \quad (\text{A.8-7})$$

where η is the average annual encounter frequency (see A.8.2.2.5). Formula (A.8-7) is valid for arbitrary values of η , whether large (e.g. of order of thousands for ridges) or small (e.g. of order of 10^{-3} for icebergs).

Due to small values of exceedance levels involved in Formulae (A.8-3) and (A.8-4), Formula (A.8-7) yields the approximate relationship given in Formula (A.8-8):

$$F_V(z_{r,\alpha}) \approx 1 - \frac{\alpha}{\eta} \quad (\text{A.8-8})$$

where $z_{r,\alpha}$ is the representative ice action corresponding to α , the annual probability of exceedance associated with EL or AL actions.

The approximation in Formula (A.8-8) is valid for $\alpha \leq 10^{-2}$.

NOTE Formula (A.8-8) does not apply for $\alpha/\eta > 1$, when ice events are very rare and η is small. In this case, the representative ice action corresponding to the exceedance level α is equal to zero. For instance, if the interaction frequency of icebergs is $\eta = 10^{-3}$, then one can determine the representative value for the AL ice action ($\alpha = 10^{-4}$, L1 structures), while the representative value of the EL ice action ($\alpha = 10^{-2}$) is zero.

Ice events can be associated with discrete iceberg, ridge or floe scenarios, they can be associated with a particular mechanism or ice regime, or they can reflect monthly or seasonal maxima.

The distribution of ice actions, $F_V(v)$, should reflect the joint distribution of the parameters X_i . In most circumstances, distributions for all of the parameters are not necessary for calculating representative values of ice actions. Some parameters have a small variability and do not have a significant influence on the representative actions, or do not have a large influence in the functional relationships associated with the ice action. This gives rise to widely used semi-probabilistic approaches, in which a probabilistic treatment of actions is performed on a reduced set of parameters by expressing the load Formula (A.8-2) as given in Formula (A.8-9):

$$V = V(X_1, X_2, \dots, X_j, X_{j+1,N}, \dots, X_{n,N}) \quad (\text{A.8-9})$$

where the joint distribution of the main contributing parameters 1, ..., j is considered, while single nominal values for $j + 1, \dots, n$ are used for the remaining ones.

Generally, the main parameters should be characterized such that their combination does not lead to overly conservative or unconservative estimates of representative ice actions. Proper attention should be drawn to the tails of the distributions in question since they have a strong effect on ice actions at small exceedance levels.

When nominal values are used to develop the ELIE or ALIE, care should be exercised to ensure that the resulting ice action approximates the EL or AL level, as required. To ensure this, nominal values should represent the most likely ones associated with the representative actions. For example, if the ice geometry and interaction scenario are modelled probabilistically, a nominal value for ice pressure should reflect the contact areas, aspect ratios and interaction velocities associated with the representative actions.

A.8.2.2.2.2 Combining different events

For m ice action events in a given time period, say a year, it is necessary to consider a set of actions corresponding to the m events, say $Y_1, Y_2, \dots, Y_m$. The designer is concerned with the maximum of these as given in Formula (A.8-10):

$$Z = \max(Y_1, Y_2, \dots, Y_i, \dots, Y_m) \quad (\text{A.8-10})$$

If the individual cumulative distributions are $F_1, F_2, \dots, F_m$, and if it is judged that the actions are stochastically independent^[127], then Formula (A.8-11) applies:

$$\begin{aligned} F_Z(z) &= P(\text{all } Y_i \leq z) \\ &= F_1(z) \cdot F_2(z) \cdot \dots \cdot F_m(z) \end{aligned} \quad (\text{A.8-11})$$

A.8.2.2.3 Deterministic approach

Deterministic approaches differ from probabilistic methods in that they deal not with distributions of actions, but only with distributions of selected parameters. Such approaches can be used for preliminary design of L1 and L2 structures and for the final design of L3 structures in arctic and cold regions. In deterministic approaches, the representative ice action is generally estimated based on the ELIE or the ALIE where EL or AL parameter values $X_{1,E}$ and $X_{1,A}$, respectively, are selected for the most important parameter (such as ice pressure or thickness) and nominal parameter values, $X_{j,N}$, for the remaining parameters. Representative action values for relevant interaction events Y_i are obtained from Formula (A.8-12):

$$y_{ri,E} \text{ or } y_{ri,A} = Y_i(X_{1,E} \text{ or } X_{1,A}, X_{2,N}, \dots, X_{j,N}, \dots, X_{n,N}) \quad (\text{A.8-12})$$

and the representative values of the ice action are approximated by $z_{r,E}$ or $z_{r,A}$ which is equal to $\max\{y_{r1,E}, y_{r2,E}, \dots, y_{rm,E}\}$, or $\max\{y_{r1,A}, y_{r2,A}, \dots, y_{rm,A}\}$, where E refers to ELIE (i.e. $X_{1,E}$) and A refers to ALIE (i.e. $X_{1,A}$).

Nominal values of the parameters, $X_{j,N}$, should generally be selected to result in conservative values of the actions. To ensure this, the nominal value of each parameter should be a conservative upper bound where it contributes to increase the ice action and a lower bound where it decreases the action.

A commonly employed deterministic approach involves the use of the EL sea ice thickness combined with a nominal global pressure for ice crushing to establish the ELIE. In this case, the ice pressure is not necessarily specified at the extreme-level, since this can result in overly conservative actions or be impractical to determine with any accuracy. For many level ice interactions annually, the maximum global ice pressure expected in a year is an appropriate nominal value. If only a few interactions occur annually, a lower value can be used. The combination of all parameters at the extreme or abnormal level can produce conservative estimates of actions.

In A.8.2.4.3, A.8.2.4.4 and A.8.2.4.5, the parameters related to ice properties recommended in the text are intended to be used in conjunction with the 10^{-2} annual probability of exceedance (100-year) ice thickness for the ELIE unless stated otherwise.

A.8.2.2.4 Monte Carlo simulation

Because of the complexity of ice action calculations, Monte Carlo simulation methods are generally used in practice. It is appropriate to use different input parameters or distributions for different times within the ice season when sufficient data exist. Allowances for correlations between the different input quantities should be used if they can be established. Sampling can be carried out directly from the distributions or by discretizing the distribution into bins. When using bins, one should ensure that the tails of the distributions are modelled accurately. Specialized methods such as importance sampling can be used.

The combination of parameters from each Monte Carlo realization, whether from a single ice scenario or multiple ice scenarios, is used to calculate an ice action. The maximum ice actions from all the realizations in each year are ranked and plotted against a cumulative probability or probability of exceedance scale. An example is given in Figure A.8-4. Serviceability level, EL and AL ice actions can be determined from the plot. While a single value of an ice action is determined for each limit state, there are numerous combinations of parameters that yield very similar ice action magnitudes. Examining the values of the parameters that contribute to the EL or AL ice action, by means of the ELIE or ALIE, provides a basis for checking the physics of the ice interaction scenario and the input parameters.

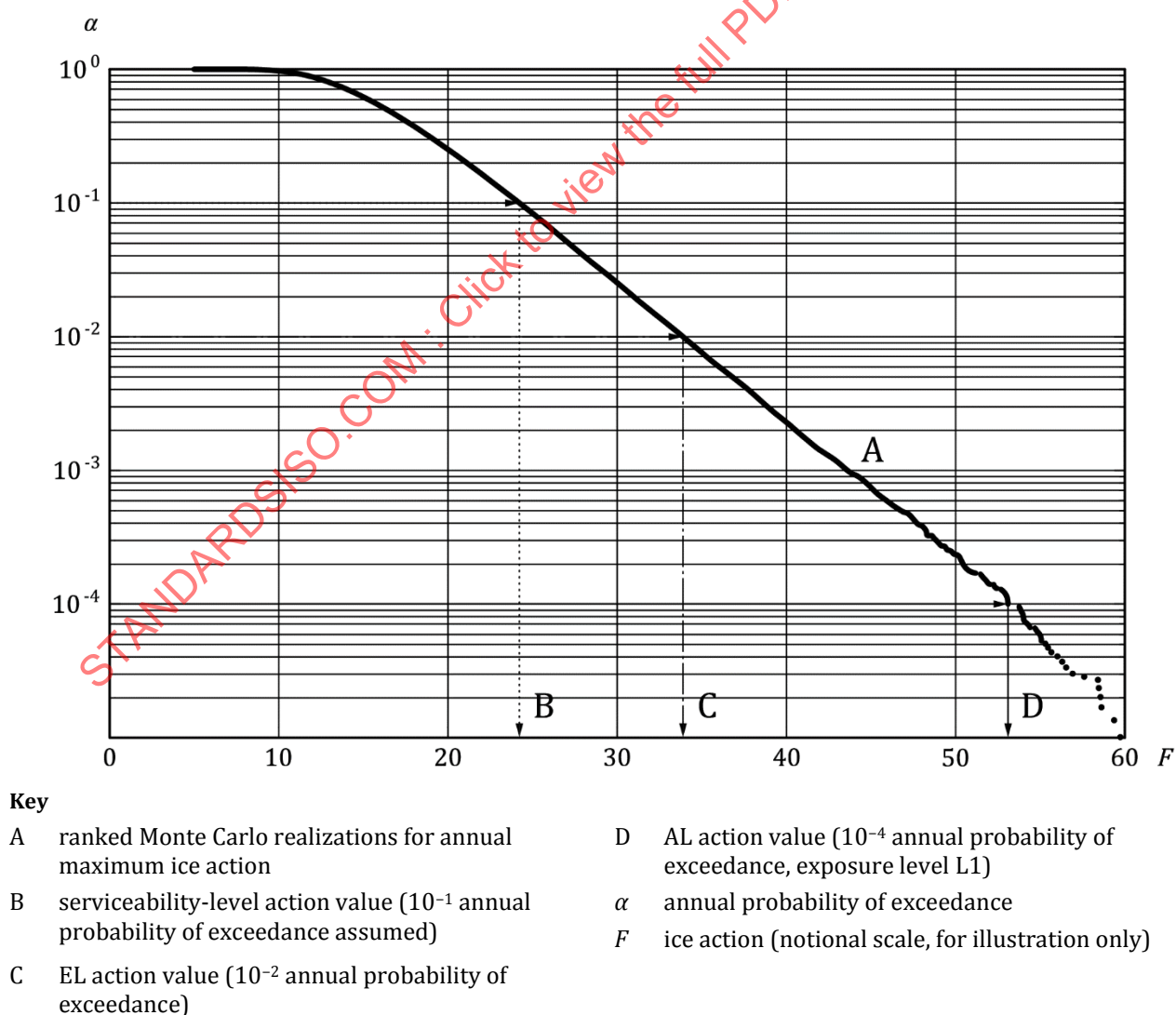


Figure A.8-4 — Example showing estimation of characteristic ice actions based on Monte Carlo simulation

The number of realizations required for a Monte Carlo simulation depends on the rate at which the event occurs (η , in A.8.2.2.5), the number of parameters in the model for ice actions, Formula (A.8-2), the correlation between the parameters and the annual probability level required. The number of realizations can be estimated from Formula (A.8-13):

$$n_r = q(n_p) \frac{\eta}{\alpha} \quad (\text{A.8-13})$$

where

- $q(n_p)$ is a function of the number of parameters for which distributions are specified in the calculation;
- η is the annual frequency or rate of events;
- α is the annual probability of exceedance (10^{-2} for EL action and 10^{-4} for AL action with L1 structures);
- n_p is the number of parameters in the model.

The function $q(n_p)$ should be determined and the reliability of the estimate for the EL action or AL action value should be demonstrated. Experience shows that a value of $q(n_p)$ between 10 and 100 provides consistent estimates of EL or AL actions as long as the number of parameters in the model for ice actions is not large.

A study is generally performed to investigate the sensitivity of the resulting ice action distribution to the input parameters or to bias in the physical models used. The sensitivity study should include varying the shape of the tail of the probability distribution for the most important parameters.

A.8.2.2.5 Encounter frequency

A particular ice scenario can consist of a succession of discrete interactions, for example a series of interactions with ice ridges, areas of rafted ice, thick ice floes or icebergs. Scenarios that can be considered in terms of discrete events frequently represent the design situation for arctic offshore structures. The rate of interaction, η , can be determined by comparing the area of possible interaction swept out by the ice feature, taking into account the structure width, with the area of the region under consideration, as shown in Figure A.8-5. The rate of interactions per unit time can be calculated as given in Formula (A.8-14):

$$\eta = \rho_A (\bar{D} + w) \bar{v} \quad (\text{A.8-14})$$

where

- ρ_A is the areal density (number per unit area) of the ice features;
- w is the width of the structure, or the average width if it is not circular;
- $\bar{D}$ is the average width of the ice features expected in the region;
- $\bar{v}$ is the average drift velocity (speed) over the region.

For iceberg interactions with structures having a cross-section that varies with depth, the average sum of the structure and ice feature width at the point of contact should be used.

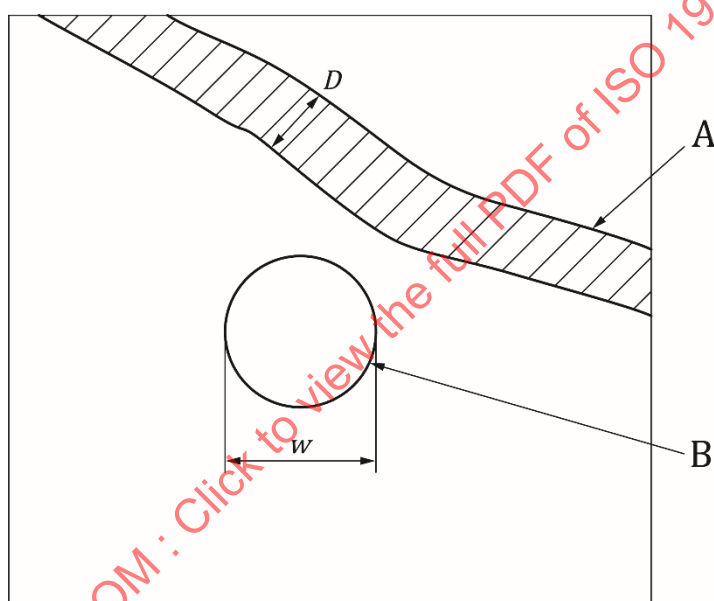
For ice floes, where coverage is known, the areal density can be determined as given in Formula (A.8-15):

$$\rho_A = \frac{C_N}{\bar{A}} \quad (\text{A.8-15})$$

where

$\bar{A}$ is the mean floe area;

C_N is the fraction of the sea surface area that is covered by the ice floes.



Key

A area swept out by ice feature
B structure

D width or diameter of the ice feature
 w width of the structure

Figure A.8-5 — Geometric definitions for determining collision probability

If the mean and standard deviation of the floe diameter are known, the mean floe area can be calculated as given in Formula (A.8-16):

$$\bar{A} = \frac{\pi}{4} \left(\bar{D}^2 + \sigma_D^2 \right) \quad (\text{A.8-16})$$

where

$\bar{D}$ is the mean floe diameter;

σ_D is the standard deviation of the floe diameter.

For discrete ice features, the areal density is the mean annual (or seasonal, as required) number of features per unit area. Measured areal densities should be corrected to remove spatial and temporal sampling biases where appropriate.

Average values of areal density and drift speed are used to obtain average interaction rates, for example in a month, a season or a year. IM and avoidance can be used to modify the interaction rates.

The drift speed is generally determined from measurements of ice movement. It is emphasized that the value used for the calculation of interaction rate should be the average over the region in which the structure is located. It should not be updated in accordance with A.8.2.2.6.

A.8.2.2.6 Updating distributions for encounter

Generic distributions of ice feature size and velocity are those inferred from snapshots of a region over time. The region should be chosen to ensure that the size and velocity distributions are representative of the structure location.

For ice features with a given residence time, the larger ones and those moving faster are more likely to encounter a structure. The velocity distributions used for the encounter are updated from the generic distributions using Bayes' theorem by amending the probability density of velocity f_V to $f_{V|e}$ as given in Formula (A.8-17)^[128]:

$$f_{V|e}(v) = \frac{vf_V(v)}{\int_{\text{all } u} uf_V(u)du} \quad (\text{A.8-17})$$

where

- e is the encounter or event;
- v, V is the ice drift speed;
- u is an integration parameter representing drift speed.

Formula (A.8-17) is simply a weighting of the velocity distribution (or histogram) by the velocity, in which larger weights are applied to higher velocities. The denominator is the average drift speed and scales the integral of the probability density function of drift speed to unity.

Regardless of the velocity field, the distribution of the horizontal dimension of the ice features in the region should be updated from f_D to $f_{D|e}$ using the analogous expression as given in Formula (A.8-18):

$$f_{D|e}(d) = \frac{(d+w)f_D(d)}{\int_{\text{all } u} (u+w)f_D(u)du} \quad (\text{A.8-18})$$

where

- e is the encounter or event;
- w is the width of the structure;
- d, D is the width of the ice feature;
- u is an integration parameter representing the width of the ice feature.

For certain data collection and analysis techniques, the distributions of drift speed and ice feature dimensions are updated, in which case they should not be modified. An example is where impact parameters are obtained from drift simulations.

Distributions of drift speeds and ice feature dimensions should be updated only for the consideration of impact or interaction conditions. They should not be updated for the interaction rate calculations in Formulae (A.8-14), (A.8-15) and (A.8-16).

A.8.2.2.7 Determination of probability distributions

The choice of parameter distributions is important, particularly when the distribution has a marked influence on extreme values for ice actions. The following should be considered.

The choice of distribution should reflect the nature of the process, e.g. the draught of ice features should not exceed the water depth, while ice speeds and physical dimensions are strictly positive.

Field data should be used, and best estimates should be made for defining probability distributions of the random parameters.

The simplest forms for distributions are often best, particularly where the quantity of data is limited.

Sampling bias should be corrected, e.g. if small features are not sampled, a truncation limit should be specified for the distribution.

The distributions should reflect uncertainties in the data. Special attention should be made for the tails of parameter distributions that are responsible for higher ice actions. Extrapolation to extreme or abnormal values from limited datasets can result in significant errors in ice actions and potentially lead to unsafe or overly conservative designs. Where direct measurements are insufficient, sound and defensible physical and mathematical reasoning should be made in the application of data from other geographical regions, when merging available datasets and establishing correlations with other local parameters. The use of conservative deterministic values in such cases is a viable alternative.

Average parameter values and distributions associated with the representative actions should be verified to ensure they are realistic physically and make sense in combination.

Seasonal variations should be considered for parameters influencing ice actions.

A.8.2.2.8 Ice action data

The guidelines that are provided in A.8.2.3 to A.8.2.6 are based on a large amount of full-scale data and observations that have been compiled between 1965 and 2007. Most expressions that are proposed in A.8.2 for ice action determination have been calibrated by using such data. Further full-scale data can be used to specify methods of determining ice actions, provided that the data are used for conditions that are similar to the conditions under which the data were collected.

A.8.2.3 Ice events and design situations

Ice events occur when ice interacts with the structure. The shape and size of the structure, the motion of the structure, and the ice scenario including ice conditions and the environmental driving actions can influence the nature of the interaction, failure modes and resulting ice actions. The factors associated with the ice features and ice conditions that can influence the ice events are illustrated in Figure A.8-6. Note that Figure A.8-6 does not include issues related to the response of the structure to ice actions.

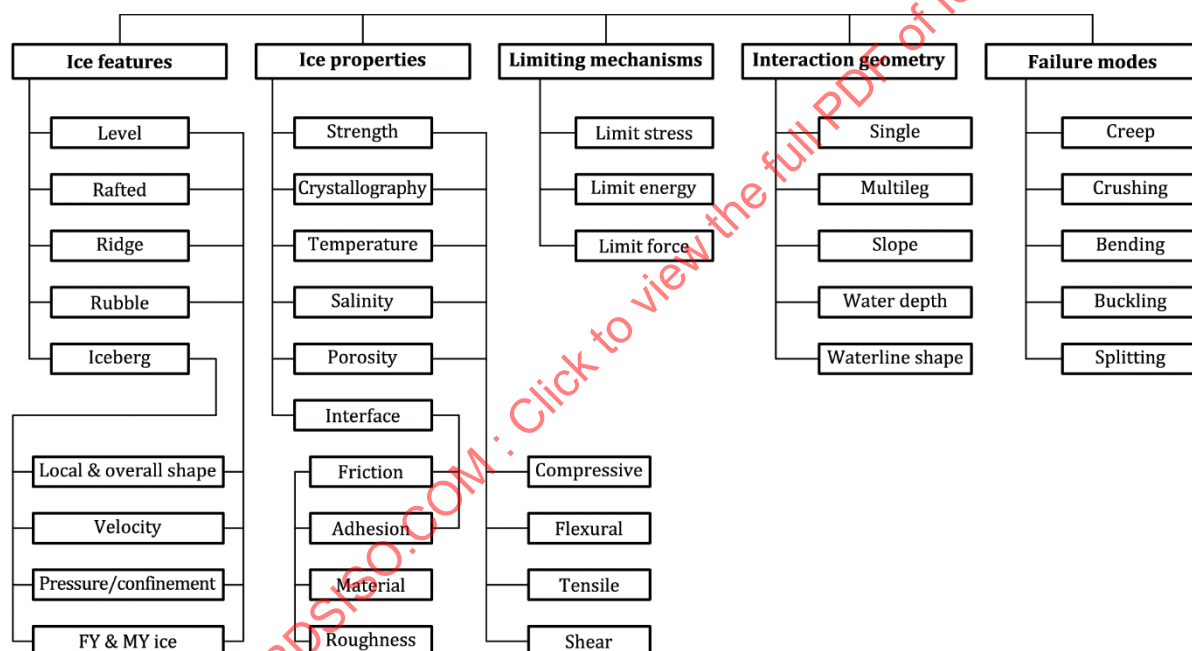


Figure A.8-6 — Factors associated with ice features and ice conditions influencing ice actions

The main physical parameters used to characterize various types of ice interactions are given in Table A.8-1. Level ice is found wherever sea ice is present. FY ice ridges are found in most areas where the sea ice is mobile. Rafted ice is often found adjacent to ridges. Old ice, which can comprise second-year and MY ice, is found in areas exposed to the arctic ice pack; it is typically colder than FY ice and has a higher strength due to the lower brine content.

Table A.8-1 — Common physical parameters used to describe ice events

Ice type	Parameter	Ice type	Parameter
Level ice	ice thickness	FY ridges	thickness of the consolidated or refrozen rafted ice
	drift speed		keel draught
	floe size		keel geometry
	floe spacing or frequency		surrounding level ice thickness
Rafted ice	total thickness		lateral extent of consolidated layer
	drift speed		ridge orientation relative to structure
	consolidation time or degree of bonding		ridge length
	extent of rafted ice areas		ridge spacing or frequency
	number of layers of ice rafted		drift orientation relative to the structure
	spacing or frequency		drift speed
Thick ice floes	floe thickness	Icebergs	mass
	floe speed		drift speed
	floe size		waterline length
	floe edge thickness		local shape
	floe drift orientation relative to the structure		drift orientation to structure
	ridge spacing or frequency		depth of first contact with structure
MY ridges	ridge keel draught		iceberg frequency
	drift speed		height above waterline
	ridge keel geometry		draught
	ridge orientation relative to structure		waterline width perpendicular to length
	ridge length		
	surrounding level ice thickness		
	ridge sail height		
	ridge spacing or frequency		

The development of ice events can be assisted through reference to descriptions of the physical environment found in Annex B. Final designs generally require site-specific data collection.

Ice actions for different ice events can be calculated from information provided in the subclauses listed in Table A.8-2. The calculations for actions due to MY ice features can be applied to second-year features, with corresponding consolidated dimensions.

Table A.8-2 — Subclause references for various ice events

Ice scenario ^a _{,b}	Fixed structures					Floating systems			Man-made islands	
	Vertical		Conical or sloping		Multi-leg	Ship-shaped	Spar/ buoy vertical	Spar/ buoy conical	Vertical	Sloped
	Wide	Narrow	Wide	Narrow						
FY ^c level	A.8.2.4.3 A.8.2.4.10		A.8.2.4.4 A.8.2.4.10		A.8.2.4.3 A.8.2.4.4 A.8.2.4.9 A.8.2.4.10	A.8.2.4.3 A.8.2.4.4 A.8.2.4.8	A.8.2.4.3 A.8.2.4.8	A.8.2.4.4 A.8.2.4.8	A.8.2.4.3 A.8.2.4.10	A.8.2.4.4 A.8.2.4.10
FY ridges and rubble fields	A.8.2.4.5, A.8.2.4.6				A.8.2.4.5 A.8.2.4.9 A.8.2.4.6 A.8.2.4.10	A.8.2.4.5, A.8.2.4.6, A.8.2.4.8			A.8.2.4.5, A.8.2.4.6	
FY discrete floes	A.8.2.4.7				A.8.2.4.7 A.8.2.4.9	A.8.2.4.7, A.8.2.4.8			A.8.2.4.7	
Old level ice	A.8.2.4.3		A.8.2.4.4		A.8.2.4.3 A.8.2.4.9	A.8.2.4.3 A.8.2.4.4 A.8.2.4.8	A.8.2.4.3 A.8.2.4.8	A.8.2.4.4 A.8.2.4.8	A.8.2.4.3	A.8.2.4.4
MY ridges and hummock fields	A.8.2.4.5, A.8.2.4.6				A.8.2.4.5 A.8.2.4.9 A.8.2.4.6	A.8.2.4.5, A.8.2.4.6, A.8.2.4.8			A.8.2.4.5, A.8.2.4.6	
Old discrete ice floes, icebergs and ice islands	A.8.2.4.7, A.8.2.4.6				A.8.2.4.7 A.8.2.4.6 A.8.2.4.9	A.8.2.4.6, A.8.2.4.7, A.8.2.4.8			A.8.2.4.6, A.8.2.4.7	
^a A.8.2.2, A.8.2.4.3, A.8.2.5, A.8.2.7 and A.8.2.8 can apply for all ice events.										
^b A.8.2.4.11 can apply for fixed structures and man-made islands in FY level ice.										
^c FY refers to first-year ice.										

The ELIE/ALIE is an event involving a combination of circumstances and parameters that results in the EL/AL ice action or action effect on the structure. Potential uses of ELIE, ALIE include:

- defining the parameters having the most significant effects on the EL and AL actions;
- where quality data are only available for a subset of parameters related to ice actions, these can be used with nominal values of other parameters to define the ELIE and ALIE from which approximate or conservative estimates of EL and AL ice actions can be calculated.

For a), sampling strategies for data collection programs and sensitivity analyses can benefit significantly from the ELIE and ALIE, as can the verification of Monte Carlo calculations.

For b), a key aspect is to ensure that accurate and realistic joint probability distributions are developed. The concept of ELIE and ALIE can be useful when only some parameters are well defined. The nominal values used in combination should provide reasonable or potentially conservative estimates of EL and AL ice actions. Examples include:

- EL ice thickness with a nominal pressure;

- EL ridge thickness and other geometric parameters with nominal strength values;
- EL or AL combinations of the mass, velocity and potentially shape for massive ice features with nominal values for strength and other parameters.

A.8.2.4 Global ice actions

A.8.2.4.1 Limiting processes

For many ice events, it is useful to consider limit stress, limit energy and limit force processes, each of which should be investigated in the assessment of representative values of ice actions.

The limit stress process is when ice failure adjacent to the structure (compressive, shear, tensile, flexure, buckling, splitting) governs the ice action. For limit stress conditions, the ice feature has sufficient driving force to fail the ice and typically envelops the structure. In many circumstances, limit stress processes are associated with the representative values of ice actions. Ice floe splitting is a limit stress mechanism that can come into play prior to full envelopment of the structure.

The limit energy process, sometimes called the limit momentum process, occurs when the kinetic energy (or momentum) of the ice feature limits the ice action. Examples include large isolated floe (e.g. old ice in summer), ice island or iceberg impacts.

The limit force process occurs when actions from winds, currents and the surrounding pack ice on an ice feature in contact with the structure are insufficient to fail the ice against the structure.

For some ice events, one can consider a combination of the above processes. Whenever limit force processes are considered, it should be verified that the action is less than that calculated according to the limit stress process. Ice features can split (limit stress process) in a limit force or limit energy situation. When floes contain ridges, limit stress conditions should be checked at the structure interface. Other failure processes should be verified for the ridges and at the interface between the ridge and the level ice behind it, and limit force actions associated with ridge building should be assessed for the edge of the floe. The ice action on the structure can be the minimum arising from each of these processes. Generally, if more than one limiting process can occur simultaneously, the one that gives the lowest ice action should govern. These issues are discussed further in A.8.2.4.2.

A.8.2.4.2 Ice failure modes

A.8.2.4.2.1 Overview of failure modes

The mode of ice failure against the structure has a significant effect on the magnitude of the ice action. The failure mode for sea ice (e.g. crushing, shear, flexure, creep) depends on parameters such as ice thickness, presence of ridges, ice velocity, ice temperature and structure shape. Conditions that induce ice failure by flexure generally result in smaller ice actions than for crushing. Different modes of ice failure can occur on the same structure type depending on ice conditions and interaction velocity, even during the same event. Dynamic structural response is generally associated with ice crushing failure.

Structure geometry is an important factor in determining ice actions. Key design features include the structure type (multi-leg, monopod or caisson), vertical or sloping waterline geometry (see Figure A.8-7), the plan shape of the structure and the plan dimensions. Bracing and appendages should not be exposed to ice actions unless designed specifically to resist them.

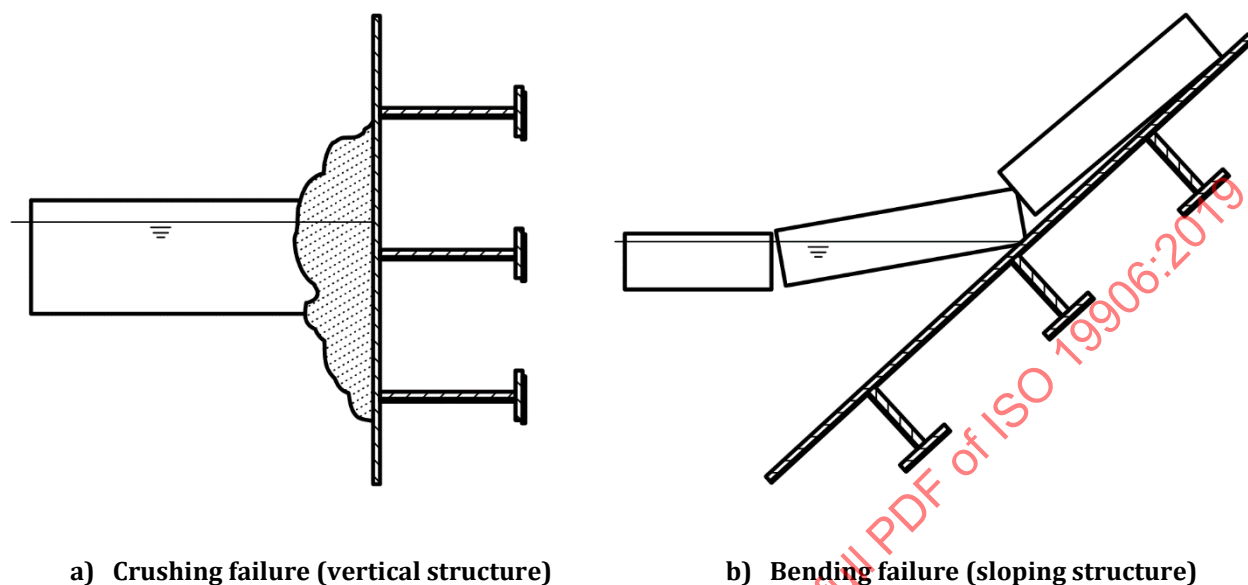


Figure A.8-7 — Vertical profile showing ice failure modes

The profile of the structure is a key issue. Structures with vertical walls in the waterline region generally experience larger ice actions than sloping ones for similar waterline dimensions. Ice actions are generally less for sloping structures, except in situations where large amounts of ice rubble accumulate on the sloping surface. If this occurs, flexural failure can be impeded and different modes or mixed modes of failure can occur with potentially larger actions.

The waterplane form can also influence the magnitude of the global ice action, but to a much lesser extent than the slope. Actions are reduced for a rectangular structure with a corner facing the preferred ice motion direction.

The plan dimensions of the structure influence the magnitude of ice actions. Many experiments and observations demonstrate the existence of a size effect, whereby the global or effective pressure (total action divided by the nominal contact area) for a narrow structure is higher than for a wide one.

Break-out of an ice feature frozen around a structure can potentially generate large ice actions. Such behaviour is more likely in areas of very small tidal range. While experience has shown that this situation is not generally critical for the design of large offshore structures, the issue should be addressed.

A.8.2.4.2.2 Level ice failure

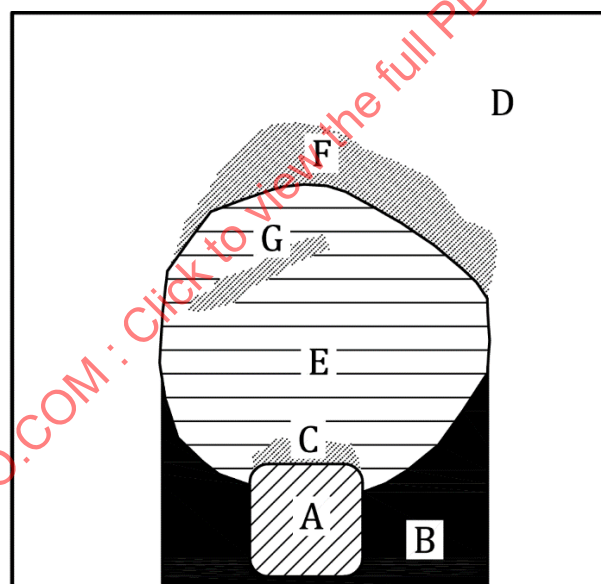
When a sheet of level ice or rafted ice acts on a vertical structure, the ice can fail in different modes. These include flexural failure modes such as bending and buckling, vertical (radial) splitting and crushing. Crushing failure usually dominates ice actions for vertical structures. If the structure has a sloping face, the ice often fails in flexure as it rides up or down the face.

In shallow water, rubble accumulations on the face of the structure can alter the mode of failure from crushing or flexural to a mixed mode or rubbing failure. Large rubble accumulations interacting with the seabed can buffer the ice action and potentially reduce the transfer of actions to the structure.

A.8.2.4.2.3 Ice failure processes for floes

When a thick FY floe or an old ice floe comes to rest against the structure, ridge-building behind the ice floe and ice-failing locally at the structure can take place, as shown in Figure A.8-8. When these occur simultaneously, the minimum of the actions resulting from the two processes is used for design.

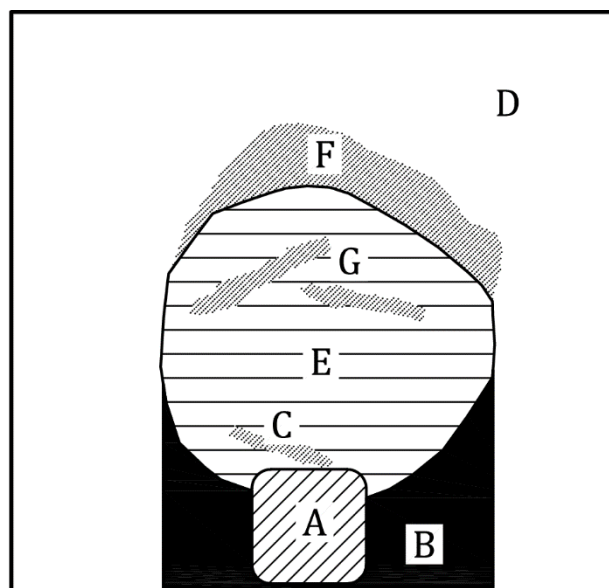
When a ridge within a floe makes contact with the structure, as shown in Figure A.8-9, a number of failure processes can take place within and adjacent to the ridge, in addition to crushing or flexure against the structure. Potential failure processes, such as shear failure of the ridge, ridge break-out from the surrounding ice sheet with rubble-building behind the ridge, in-plane failure of the ridge, and out-of-plane failure of the ridge, are shown in Figure A.8-10. Out-of-plane ridge failure can be the result of ridge-grounding on the seabed or on a berm adjacent to the structure. As long as the failure processes can take place simultaneously, the minimum action from the various processes should be considered.



Key

A	structure	E	old ice floe or thick FY ice floe
B	open water in wake of ice floe	F	ridge building
C	local ice failure adjacent to structure	G	ridge embedded in ice floe
D	FY ice		

Figure A.8-8 — Ridge-building and local ice failure processes

**Key**

A	structure	E	old ice floe or thick FY ice floe
B	open water in wake of ice floe	F	ridge building
C	ridge failure	G	ridges embedded in ice floe
D	FY ice		

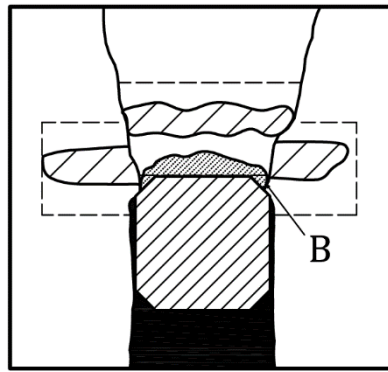
Figure A.8-9 — Ridge-building and ridge failure adjacent to the structure

A.8.2.4.3 Vertical structures

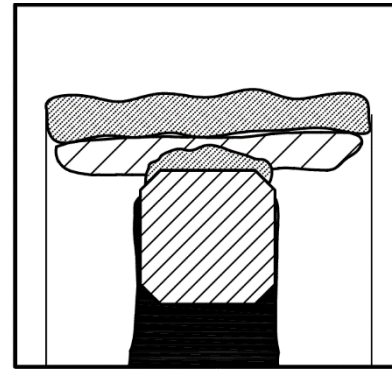
A.8.2.4.3.1 Compression failure of an ice sheet

Ice crushing is a complex compressive failure process, involving the development of a damaged layer as well as sequential development of flakes or spalls, and potentially horizontal splits or cleavage cracks, see Figure A.8-11.

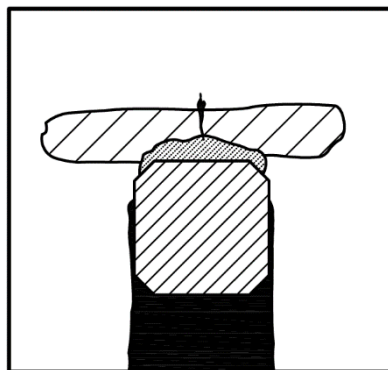
Observations on ice-structure interactions at full scale and medium scale show that the response of ice to higher indentation rates in these interactions is profoundly irregular. Fractures and spalls occur, some running to free surfaces at the top and bottom of the ice sheet, others into the ice sheet. The result is that small patches or narrow line-like areas, i.e. high pressure zones (HPZs), can form at the ice-structure interface, while other areas on the interface experience little or no pressure. These HPZs have an important effect on local ice actions, as discussed in A.8.2.5.



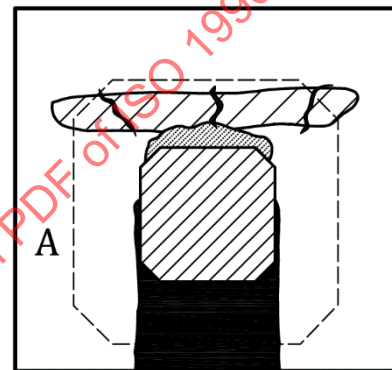
a) Ridge shear failure (dashed line shows displacement of ridge)



b) Ridge break-out



c) In-plane ridge failure



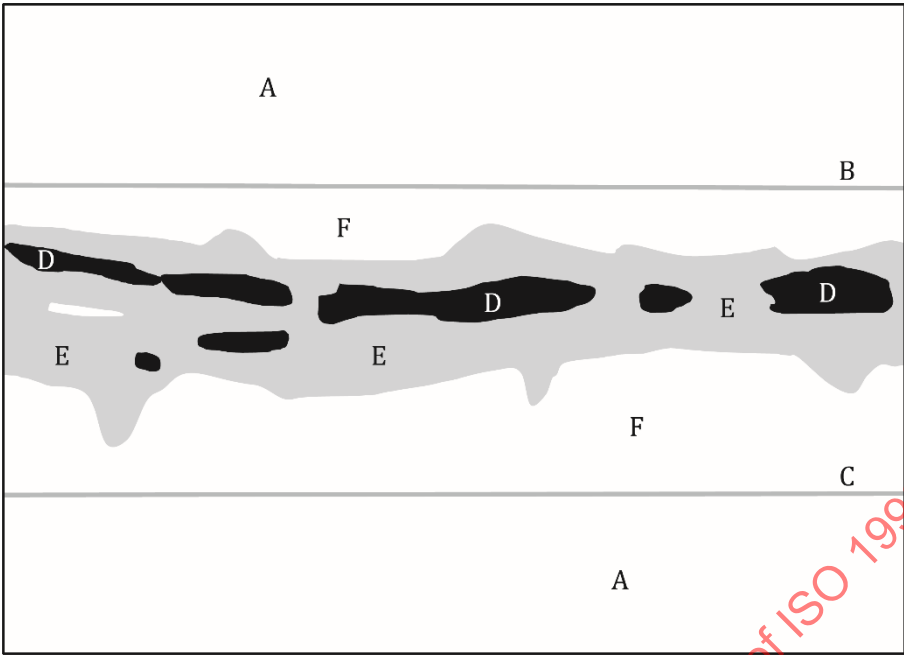
d) Out-of-plane ridge failure

Key

- A sea floor footprint of sloping structure
B ice rubble lodged against structure

Figure A.8-10 — Ridge failure processes

Figure A.8-11 shows the structure of an HPZ, and the appearance of these within a plane of interaction. Within the HPZs, the state of stress in the ice is triaxial, varying from low confinement near the edges to high values of contact pressure near the centre.



Key

A	face of structure	D	high pressure zone (HPZ)
B	top surface of ice	E	low pressure zone
C	bottom surface of ice	F	cracked or spalled areas

Figure A.8-11 — Schematic showing localization of action in sea ice interaction with a vertical structure

The pressures within the areas where compressive actions are transmitted from the structure to the ice fluctuate considerably both in space and in time, with most of the contact pressure concentrated intensely in the HPZs. These entities produce crushed ice consisting of large quantities of quite small pieces. While HPZs tend to occur in the most confined regions, away from the free surfaces, the random nature of the fracture processes results in HPZs sometimes being away from their “most likely” locations. Field data on this failure process are used in A.8.2.5.2 to define formulae for local pressures due to level ice actions.

For low-speed laterally confined interactions of level FY ice with a vertical structure, horizontal splits or cleavage cracks can develop as a result of vertical strain in the ice cover. Starting at the HPZs, the horizontal extension of the cracks can reach several times the ice thickness and contribute to the compression failure of the ice sheet.

The failure process just described means that local ice pressures are much more variable than those on global areas. Over the larger global areas, the local pressures average out so that global pressures averaged over the nominal contact areas are lower.

The effect of the relative speed between the ice and the structure has been observed in global and local ice pressures measurements. It is recognized that there is a range of ice speeds in nature that influence ice-structure interactions. As a result, the relationships for global ice pressure in A.8.2.4.3 do not consider speed effects. Formula (A.8-21) for ice pressures is intended to include speeds resulting in the highest pressure. In Formula (A.8-25), the probability distributions for the parameters include the effect of speed.

A.8.2.4.3.2 Global actions due to ice crushing

When ice crushing occurs against a structure, the global ice action normal to the surface, F_G , can be expressed as given in Formula (A.8-19) regardless of the limiting mechanism:

$$F_G = p_G \cdot A_N \quad (\text{A.8-19})$$

where

p_G is the ice pressure averaged over the nominal contact area associated with the global action;

A_N is the nominal contact area.

The nominal contact area is the projection of the intact ice feature onto the structure without any reduction for spalls or fracture.

Because the nominal contact area, A_N , for level ice, rafted ice or the consolidated layer of a ridge, is the product of the ice thickness, h , and the width, w , Formula (A.8-19) for the global ice action can be rewritten as Formula (A.8-20):

$$F_G = p_G \cdot h \cdot w \quad (\text{A.8-20})$$

For glacial ice or massive feature interactions, the nominal contact area is the projected contact area of the ice feature on the surface of the structure for a given penetration into the ice (see Figure A.8-2).

When limit stress or limit driving force processes govern, the nominal contact area can be constant through the interaction or can assume some maximum value. For limit energy and limit force situations, the nominal contact area typically increases during the course of the interaction according to the shapes of the ice feature and the structure.

Ice pressure, p_G , is often the most important parameter when designing structures against ice actions. The pressure associated with the global action is influenced by the ice temperature, the nominal contact area, the shape or aspect ratio of the contact area, the nature of the contact, the relative speed and displacements between ice and structure, as well as the compliance of the structure. Since ice pressure can vary significantly in time, peak values typically depend on the recording frequency.

A.8.2.4.3.3 Global pressure for sea ice

Data obtained from full-scale measurements in Cook Inlet, the Beaufort Sea, Baltic Sea and Bohai Sea have been used to determine upper bound ice pressure values for ice events where FY ice or old ice (second-year or multi-year) acts against a vertical structure. The data have also been used to analyse how the ice thickness and the width of the structure influence the global ice action. Based on these studies, the global ice pressure can be determined as given in Formula (A.8-21):

$$p_G = C_R \left[\left(\frac{h}{h_1} \right)^n \left(\frac{w}{h} \right)^m + f_{AR} \right] \quad (\text{A.8-21})$$

where

- p_G is the global average ice pressure, expressed in megapascals;
- w is the projected width of the structure, expressed in metres;
- h is the thickness of the ice sheet, expressed in metres;
- h_1 is a reference thickness of 1 m;
- m is an empirical coefficient equal to $-0,16$;
- n is an empirical coefficient, equal to $-0,50 + h/5$ for $h < 1,0$ m, and to $-0,30$ for $h \geq 1,0$ m;
- C_R is the ice strength coefficient, expressed in megapascals;
- f_{AR} is an empirical term given by

$$f_{AR} = e^{\frac{-w}{3h}} \sqrt{1 + 5 \frac{h}{w}} \quad (\text{A.8-22})$$

Formulas (A.8-21) and (A.8-22) apply for rigid structures with aspect ratios w/h greater than 1, where the structure displacement at the waterline, obtained as a static response to the representative ice action, is typically less than 10 mm. For aspect ratios w/h greater than about 5, the f_{AR} term given in Formula (A.8-21) can be disregarded. Formula (A.8-21) does not explicitly include temperature effects^[129].

NOTE Observations of ice interactions on relatively narrow lighthouse structures (structure width $< \sim 2$ m, ice thickness $< \sim 1$ m) in the northern Baltic Sea^[130] support the inclusion of the f_{AR} term in Formula (A.8-21). Data on narrow structures in thicker ice are not available so, in the absence of other information, the f_{AR} term should be included in global ice pressure calculations.

For deterministic analysis, three regional values for C_R are specified in Table A.8-3.

Table A.8-3 — Regional values for ice strength coefficient

C_R MPa	Region
2,8	Arctic FY and MY ice (e.g. Beaufort)
2,4	Subarctic (e.g. Okhotsk Sea — off northeast Sakhalin Island)
1,8	Temperate (e.g. Okhotsk Sea — Aniva Bay, North Caspian Sea, Cook Inlet, Baltic Sea, Bohai Sea)

The C_R value recommended for the Arctic can be conservative, as it potentially includes some magnification due to the compliance of the structure in the referenced data from the Beaufort Sea^[131].

According to another data series from a stiff structure in the Baltic Sea, the ice strength parameter associated with the ELIE has been obtained as $C_R = 1,8$ ^[132] in conditions where the ice speed was higher than 0,1 m/s and the maximum waterline displacements in the direction of ice action of the structure were about 0,4 % of the ice thickness. Under these conditions, the strength value C_R obtained does not exhibit magnification due to the compliance of the structure.

Caution should be exercised when using Formula (A.8-21). Recent analyses^[133] provide additional insight on its application to wide structures. The values of C_R suggested for different regions are for undeformed ice sheets. If these are used to estimate ice actions from re-consolidated layers of FY and MY ridges, which

can be weaker than undeformed ice, upper bound estimates can be expected. The value of C_R can potentially be modified for this scenario based on available data. While the recommended values of C_R , based on regional observations, are suggested as ELIE values for estimation of EL ice actions, it is noted that the number of annual events can vary from region to region.

Formulae (A.8-20), (A.8-21) and (A.8-22) can be used in a probabilistic analysis by first estimating probability distributions for the ice thickness and the strength parameter C_R based on regional data. These probability distributions should represent parent distributions rather than distributions of extreme values. The global EL ice action can then be determined by following A.8.2.2. Consideration should be given to the annual exposure in terms of the frequency of events, or the length or extent of ice interacting with the structure.

Table A.8-4 illustrates, based on Baltic Sea data, variability in C_R for exposure to different numbers of events per year, n , and to different return periods. The column identified by $F_P(p)$ is the cumulative probability corresponding to the return period. Based on the amount of exposure associated with the data, a 135 km distance travelled by the ice annually, the C_R value at the 10^{-2} annual exceedance probability level is 1,8. This corresponds to the $n = 24$ annual ice events shown in Table A.8-4, see Reference [134]. The annual maximum value for C_R is 1,3. The maximum EL action associated with the following two ELIE scenarios should be considered for design:

- a) annual maximum (i.e. $F_P(p) = 0,50$) C_R with a 1/100 year ice thickness; and
- b) 1/100 year C_R with the annual maximum thickness. The specification of ice thickness should consider the number of events expected in a year which can vary from region to region.

Table A.8-4 — Examples of ice strength coefficient C_R dependence on exposure to ice events

n	Total distance km	Return period	$F_P(p)$	C_R MPa
1	6	1 year	0,5	0,99
1	6	100 years	0,99	1,45
24	135	1 year	0,5	1,34
24	135	100 years	0,99	1,80
24	135	10,000 years	0,9999	2,30
100	563	1 year	0,5	1,49
100	563	100 years	0,99	1,96

In Reference [135], a probabilistic method is proposed for including the effect of exposure on C_R using temperate data from the Baltic Sea. Exposure was represented in terms of the distance moved by the ice past the structure. Using this approach, C_R values can potentially be scaled based on exposure and applied to different regions of interest.

Guidelines provided in A.8.2.6 should be used to check whether the static analysis should be supplemented by a dynamic analysis.

A.8.2.4.3.4 Influence of local ice conditions on ice pressures

Different geographical areas have different ice conditions due to climatic conditions, and due to the mobility and morphology of the ice. Some areas, such as the Beaufort Sea, have old ice while others, such as the Okhotsk Sea, Cook Inlet, Baltic Sea or Bohai Sea, have no old ice. As a guide to action calculations and to defining regions of different climate and relative ice strengths, one can consider the following divisions:

- arctic, having about 4 000 Freezing Degree Days per winter season (e.g. Beaufort Sea);
- sub-arctic, having about 2 000 Freezing Degree Days per winter season (e.g. Okhotsk Sea — off northeast Sakhalin Island);
- temperate, having about 1 000 Freezing Degree Days per winter season (e.g. Okhotsk Sea — Aniva Bay, North Caspian Sea, Cook Inlet, Baltic Sea, Bohai Sea).

NOTE The method for calculating Freezing Degree Days is given in A.6.5.1.

The freezing index (Freezing Degree Days; see A.6.5.1) is an important parameter in assessing the thickness of refrozen rafted ice and of the consolidated ice thickness of pressure ridges. While FY ice can raft to similar thicknesses in areas with differing Freezing Degree Days, the thickness of solid, continuous ice or the consolidated layer differs due to the varying ability of the atmosphere to remove heat from the ice.

As described above, the ice strength parameter C_R has been estimated as 2,8 MPa for arctic areas and 1,8 MPa for temperate areas. When evidence indicates that the ice strength is different in the area of interest, three possible approaches that can be used to specify the ice strength parameter C_R are described below.

In the first approach, the value of $C_R = 2,4$ can be used for sub-arctic regions in the absence of any other evidence. For the second approach, the ice strength parameter for sub-arctic or intermediate regions can be expressed as given in Formula (A.8-23):

$$C_R = C_{R0} \cdot \frac{\sigma}{\sigma_0} \quad (\text{A.8-23})$$

where

C_R is the strength parameter for the area of interest;

C_{R0} is the strength parameter for the reference area, e.g. 2,8 MPa for arctic areas and 1,8 MPa for the Baltic Sea;

σ is a measured or inferred strength index for the area of interest;

σ_0 is the strength index for the reference area.

The strength index can involve a variety of compressive strength measures, including borehole jack measurements, uni-axial or multi-axial strength measurements, continuous indentation experiments, and relationships between temperature, brine volume and compressive strength. It is emphasized that proper justification should be made for the use of a relationship of the form presented in Formula (A.8-23).

Considerable caution should be exercised in scaling the C_R parameter, particularly when large differences exist between ice conditions and temperatures for the area of interest and the reference area.

Scaling based on small-scale uniaxial compressive strength measurements should be done with caution. If in situ strength measurements are used, these measurements should cover a sufficiently broad geographical region to be representative. Further discussion on compressive strength is provided in A.8.2.8.2.

When scaling strength indices, it should be recognized that characteristics of the structure can influence the measured data. Ice pressures due to continuous crushing obtained on a rigid structure in one region should not be used directly for compliant structures. Pressures on compliant structures can be significantly higher than on rigid structures.

Where other data are not available, borehole jack strengths can be used to scale C_R between two regions. The borehole strengths depend on temperature and salinity in a similar manner as for uniaxial compressive strength.

The third approach proposed in Reference [46] can also be used as a practical means of estimating or scaling C_R . The strength index is evaluated by dividing the ice sheet into a number of layers, for which typical temperature and salinity profiles are obtained. In this method, a time-averaged value is first determined for the temperature at the snow-ice interface. For a constant air temperature, the maximum time for an ice temperature profile to reach equilibrium is 5 days for $h = 0,5$ m, 11 days for $h = 0,75$ m, 19 days for $h = 1,0$ m, 43 days for $h = 1,5$ m and 77 days for $h = 2,0$ m. The distribution of the brine volume, v_b , can be determined from Formula (A.6-6) by assuming a linear temperature profile within the ice sheet.

The average strength index is then obtained as given by Formula (A.8-24):

$$\sigma_0 = \left[\frac{1}{n} \sum_{i=1}^n (C_i)^2 \right]^{1/2} \quad (\text{A.8-24})$$

where

n is the number of layers ($n \geq 5$);

C_i is the strength coefficient obtained from Table A.8-5 for layer i .

Table A.8-5 — Ice strength coefficient, C , as a function of the brine volume^a

v_b	0,001	0,010	0,025	0,050	0,100	0,200
C MPa	8,4	6,0	3,4	1,6	1,0	0,8

^a See Formula (A.6-6).

Using this method, the reference value for the index strength σ_0 is 2,86 MPa for the conditions where the strength parameter has been obtained as $C_R = 2,8$. Correspondingly, the strength index is $\sigma_0 = 2,07$ MPa for temperate areas where the strength parameter has been obtained as $C_R = 1,8$.

A.8.2.4.3.5 Global ice pressures from ship ramming tests

The model proposed in this subclause is most appropriate where few interactions per year are expected (e.g. iceberg impacts on the Grand Banks). Where many interactions per year are expected, the model will yield very conservative global design pressures.

Data from ship rams into old ice indicate that the global action is random, even for seemingly identical rams. This is associated with random fracture events in the ice as it fails. Because of size effects, the average global pressure generally decreases as a function of increasing nominal contact area. The pressure-area relationship as given by Formula (A.8-25) has been developed for impact events:

$$p_G = C_P A_N^{D_P} \quad (\text{A.8-25})$$

where

A_N is the nominal contact area;

C_P, D_P are random coefficients.

The coefficients C_P and D_P have been calibrated using a large database of ship rams with old ice (Kigoriak, Polar Sea, MV Arctic, Manhattan and Oden). The projection of the original shape of the ice feature onto the structure at the appropriate penetration, and the resulting maximum actions for each simulation were then ranked and compared on a probability of exceedance basis with ship-ram trial data. A goodness-of-fit criterion was used to decide which combination best represented the coefficients. The preferred combination was a mean and standard deviation of 3,0 MPa and 1,5 MPa, respectively, for C_P (lognormal distribution) and a mean and standard deviation of -0,4 and 0,2 respectively, for D_P (normal distribution), with the nominal contact area expressed in square metres^[136].

When extrapolated to large contact areas, the pressure-area Formula (A.8-25) can yield unrealistically low pressures for the instantaneous ice pressure. A lower bound cut-off for the pressure-area curve should be considered in such cases. Guidance can be obtained from Formula (A.8-21) for low aspect-ratio interactions.

A.8.2.4.3.6 Point of action

For sea ice actions on a vertical structure, the point of action can be taken as the mid-depth of the ice. For structures with some deviation from the vertical, the point of action can be taken as the mid-point of the ice in contact with the structure at maximum penetration.

For the interaction of icebergs or other massive features, the point of action can be taken as the point of first contact or the mid-point of the ice in contact with the structure at maximum penetration. For certain geometries of structures, e.g. stepped structures, multiple points of contact should be verified with increasing penetration, particularly if a higher point of contact results.

Water level changes as a result of waves, tides, storm surges and long-term fluctuations should be taken into account. Where appropriate, the correlation between ice thickness, ice velocity and water level should be considered when calculating ice actions.

When torsional actions are considered, the centroid of the contact area can generally be used as the point of action. In such cases, the orientation of the action should reflect the tangential frictional action.

A.8.2.4.4 Sloping structures

A.8.2.4.4.1 Description of the failure process

Offshore structures with a sloping surface can be considered as an alternative to a vertical structure. Level ice interacting with a sloping structure is more likely to fail in a flexural failure mode. Ice actions in such failure modes can be significantly lower than in a crushing failure mode, which is typical for vertical-sided structures. Sloping icebreaking surfaces can also reduce ice actions from ice ridges. An approach for calculating ice actions for thicker MY ridges is provided in A.8.2.4.5.2.

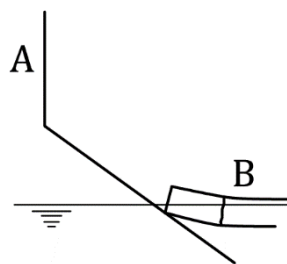
There are several possible types of sloping structures. A conical shape is often preferred for offshore structures due to its symmetrical plan shape. In addition to smooth conical structures with circular waterlines, multi-faceted cones with flat, sloping faces have also been investigated. Ice actions on conical or multi-faceted sloping structures have been extensively investigated, both theoretically and in numerous small-scale laboratory test programmes. Ice actions on sloping structures were also studied during several field programmes, including Kemi-1 lighthouse in 1983-86 in the Gulf of Bothnia, two piers of the Confederation Bridge from 1997 to the present, jacket-type production platforms in the Bohai Sea, the Kulluk downward breaking floating caisson in the Beaufort Sea, and an experimental tower at Mombetsu, Japan. These structures experienced a wide variety of FY ice conditions, including level ice, ice ridges and rubble fields. Results and observations from these field measurement programmes were used as benchmarks for verification of theoretical models^[137] and ice design criteria for newly built conical and sloping structures. Alternatively, when the full-scale data are not available, model test data can be used to verify the validity of theoretical models and design criteria, provided that the scaling is adequate in the tests (see also 16.5).

A side geometry that is formed of two sloping flat surfaces can be used in areas where the ice movement has a dominant direction. Studies have also been done on sloping flat panels to obtain fundamental understanding of the ice actions due to sheet ice. Flat sloping panels can also be used as a part of a structure.

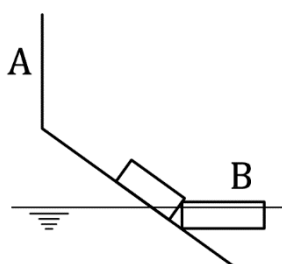
Sloping structures break the oncoming sheet ice by deflecting it either upwards or downwards. The resulting ice action has both a vertical and horizontal component. The horizontal and vertical components of ice action on a downward-breaking structure are lower relative to those acting on an upward-breaking structure of the same size and slope angle. In the case of a downward-breaking structure, the vertical component of the ice action is directed upwards, reducing the effective shear resistance at the structure-seabed interface.

Ice interaction with a sloping surface is a complicated process that includes failure of intact ice, ride-up of broken ice pieces, accumulation of ice rubble on the slope, and subsequent clearing of the rubble accumulation; see Figures A.8-12 and A.8-13.

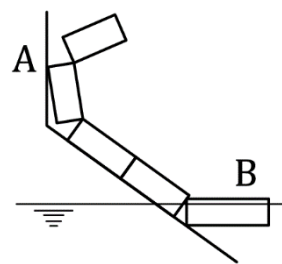
Ice rubble can also accumulate under the ice sheet, further complicating the interaction process. The maximum ice action on a sloping structure is hence a function of several different parameters, including bending, compressive and shear strengths of the ice sheet, friction coefficient between structure surface and ice, presence of snow, density of ice, and the height and geometry of ice rubble.



a) Ice sheet approaches structure



b) Ice begins to fail and ride up face of structure

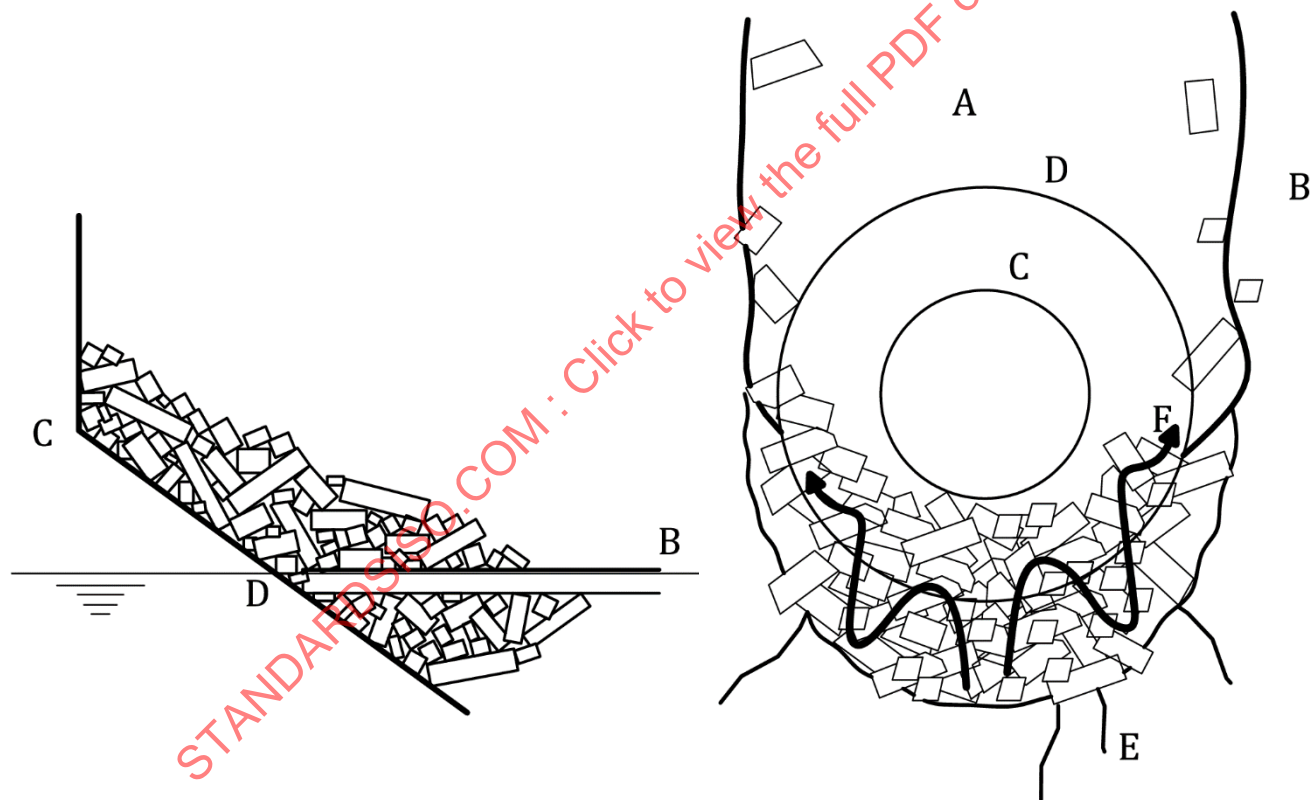


c) Ice blocks ride up face of structure and are turned back at vertical face

Key

- A sloping structure
B encroaching ice sheet

Figure A.8-12 — Processes in the interaction between a sloping structure and sheet ice



a) Ice rubble pile-up against a sloping structure

b) Ice failure and clearing of rubble around an upward-breaking conical structure

Key

A open water in wake of structure	D waterline of structure
B encroaching ice sheet	E cracks forming in encroaching ice sheet
C top of sloping face of structure	F clearing of ice rubble blocks around structure

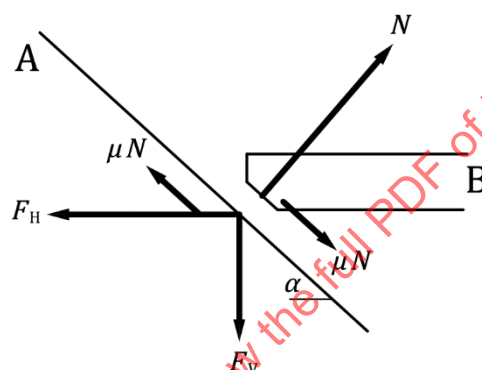
Figure A.8-13 — Ice rubble pile-up and clearing around a sloping structure

Figure A.8-14 depicts level-ice action components for a two-dimensional interaction with an upward breaking structure. The horizontal and vertical components of ice action are as given by Formula (A.8-26):

$$\begin{aligned} F_H &= N \sin \alpha + \mu N \cos \alpha \\ F_V &= N \cos \alpha - \mu N \sin \alpha \end{aligned} \quad (\text{A.8-26})$$

where

- N is the component normal to the structure surface;
- α is the inclination angle of the structure surface from the horizontal, expressed in radians;
- μ is the coefficient of kinetic friction between the ice and structure surface (for values, see A.8.2.8.7).



Key

A	sloping face of structure	α	slope of structure face from horizontal
B	encroaching ice sheet	F_H	horizontal component of ice action
N	normal component of reaction to ice action on structure	F_V	vertical component of ice action
μ	ice-structure friction coefficient		

Figure A.8-14 — Ice action components on a sloping structure for a two-dimensional condition

The relationship between the vertical and horizontal components is given by Formula (A.8-27):

$$F_V = \frac{F_H}{\xi} \quad (\text{A.8-27})$$

where $\xi = \frac{\sin \alpha + \mu \cos \alpha}{\cos \alpha - \mu \sin \alpha}$

Theoretical models developed to calculate level ice actions on sloping structures can provide reasonably accurate estimates of ice action, as long as the input data and assumptions are appropriate.

A number of methods of determining ice actions on cones and sloping structures have been developed, two of which are described below. The first, as described in A.8.2.4.4.2, is based on the theory of plasticity and the second, as described in A.8.2.4.4.3, is based on elastic beam bending.

Besides the parameters used in Formulae (A.8-26) and (A.8-27), the following parameters are used in the two models, with the various parameters expressed in consistent units:

H_B is the horizontal action on the cone due to ice breaking;

V_B is the vertical action on the cone due to ice breaking;

H_R is the horizontal action on cone due to ride-up;

V_R is the vertical action on cone due to ride-up;

σ_f is the flexural strength of the ice sheet;

h is the thickness of the ice sheet;

w is the waterline diameter of the cone or width of a sloping structure;

ρ_i is the density of ice, see A.8.2.8.10;

ρ_w is the density of water;

g is the acceleration due to gravity;

ν is the Poisson ratio for ice.

The flexural strength depends on the size of the ice specimen that is used to obtain this parameter. Therefore, the values of this parameter should be adopted from field tests where the specimen size is comparable to the design condition (see A.8.2.8.3).

A.8.2.4.4.2 Plastic method for cones

This method is based on a limit analysis solution for level ice actions on upward- and downward-breaking cones^[138]. The model considers actions due to the flexural failure of the ice sheet and the ride-up actions due to ice pieces. The derivation is for an upward-breaking cone and is also valid for a downward-breaking cone if ρ_i is replaced with $(\rho_w - \rho_i)$.

The functions as given by Formulae (A.8-28) to (A.8-31) are defined for the solution:

$$f = \sin \alpha + \mu E_1 \cos \alpha \quad (\text{A.8-28})$$

$$g_r = \frac{\sin \alpha + \frac{\alpha}{\cos \alpha}}{\frac{\pi}{2} \sin^2 \alpha + 2\mu \alpha \cos \alpha} \quad (\text{A.8-29})$$

$$h_v = \frac{f \cos \alpha - \mu E_2}{\frac{\pi}{4} \sin^2 \alpha + \mu \alpha \cos \alpha} \quad (\text{A.8-30})$$

$$W = \rho_i g h_r \frac{W^2 - W_T^2}{4 \cos \alpha} \quad (\text{A.8-31})$$

where

- α is the slope of the structure measured from the horizontal, expressed in radians;
- W_T is the top diameter of the cone;
- h_r is the ice ride-up thickness ($h_r \geq h$).

The effects of a rubble accumulation on the cone can be considered by using a value that exceeds the single sheet thickness for the ride-up thickness. The parameters E_1 and E_2 are the complete elliptical integrals of the first and second kind, defined as given by Formulae (A.8-32) and (A.8-33):

$$E_1 = \int_0^{\pi/2} \left(1 - \sin^2 \alpha \sin^2 \eta\right)^{-1/2} d\eta \quad (\text{A.8-32})$$

$$E_2 = \int_0^{\pi/2} \left(1 - \sin^2 \alpha \sin^2 \eta\right)^{1/2} d\eta \quad (\text{A.8-33})$$

where η is an angular integration parameter.

Assuming a single sheet thickness of ride-up ice, the horizontal ride-up action, H_R , and the vertical ride-up action, V_R , are obtained as given by Formulae (A.8-34) and (A.8-35):

$$H_R = W \frac{\tan \alpha + \mu E_2 - \mu f g_r \cos \alpha}{1 - \mu g_r} \quad (\text{A.8-34})$$

$$V_R = W \cos \alpha \left(\frac{\pi}{2} \cos \alpha - \mu \alpha - f h_v \right) + H_R h_v \quad (\text{A.8-35})$$

The horizontal breaking action H_B and the vertical breaking action V_B are given by Formulae (A.8-36) and (A.8-37):

$$H_B = \frac{\sigma_f h^2}{3} \frac{\tan \alpha}{1 - \mu g_r} \left[\frac{1 + Y x \ln x}{x - 1} + G(x - 1)(x + 2) \right] \quad (\text{A.8-36})$$

$$V_B = H_B h_v \quad (\text{A.8-37})$$

where

Y is equal to 2,711 for Tresca yielding or equal to 3,422 for Johansen yielding;

G is equal to $(\rho_i \cdot g \cdot w^2) / (4\sigma_f \cdot h)$;

x is given by Formula (A.8-38):

$$x = 1 + \left(3G + \frac{Y}{2} \right)^{-1/2} \quad (\text{A.8-38})$$

The total action components in the horizontal and vertical directions are given, respectively, by Formulae (A.8-39) and (A.8-40):

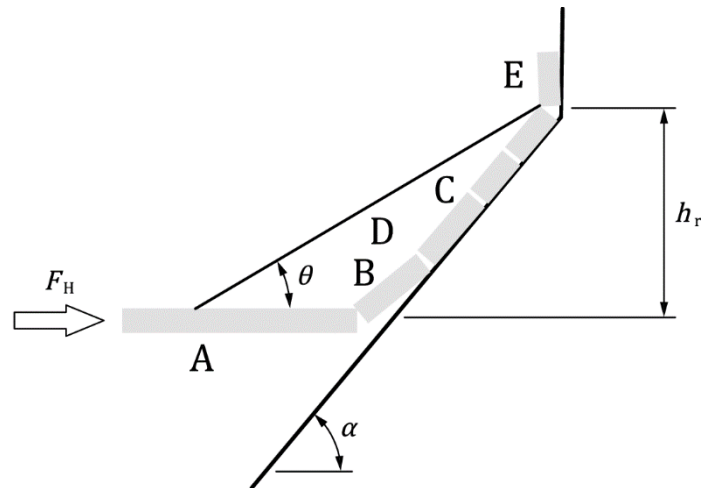
$$F_H = H_B + H_R \quad (\text{A.8-39})$$

$$F_V = V_B + V_R \quad (\text{A.8-40})$$

A.8.2.4.4.3 Model based on elastic beam bending

When an ice sheet acts on a wide slope or cone, the flexural failure component can be evaluated considering the ice sheet as an elastic beam on elastic foundation. In addition, three-dimensional effects can be considered as well as the presence of rubble on the face of the structure in the model outlined in Formulae (A.8-41) to (A.8-48)^{[139][140][141][142]}. This method can also be used for downward breaking slopes by replacing ice weight in air by ice buoyancy in water. The present model accounts approximately for axial actions in the ice sheet. There are more comprehensive approaches (see, for example, Reference [143]), which can be followed where supported by field experience.

The general configuration of ice interaction being analysed in this clause is shown in Figure A.8-15. The method incorporates secondary breaking that can lead to greater ice actions; specifies different structure widths for breaking, ride-up and block clearing; and calculates a limit to ride-up height.

**Key**

A	advancing ice	F_H	horizontal ice action
B	ice is lifted and failed in bending on slope	α	slope of face of structure from horizontal
C	ice pushed up slope through rubble	θ	rubble angle from horizontal
D	ice rubble	h_r	ride-up height
E	blocks turned at top of slope		

Figure A.8-15 — General configuration of ice action on a sloping structure

The horizontal action component is determined as given by Formula (A.8-41):

$$F_H = [H_B + H_R + H_P + H_L + H_T] I_p \quad (\text{A.8-41})$$

where

H_B is the horizontal component of the action to break the ice;

H_R is the horizontal component of the action to push the broken ice blocks up the slope through the ice rubble;

H_P is the action component required to push the sheet ice through the ice rubble;

H_L is the horizontal component of the action required to lift the ice rubble on top of the advancing ice sheet prior to breaking it;

H_T is the horizontal component of the action to turn the ice block at the top of the slope as they meet the vertical shaft;

I_p is the correction for the effect of in-plane compression in the ice sheet due to F_H . This increases the effective flexural strength.

The action component, H_B , is obtained as given by Formula (A.8-42):

$$H_B = \xi V_B \quad (\text{A.8-42})$$

in which

$$\xi = \frac{\sin \alpha + \mu \cos \alpha}{\cos \alpha - \mu \sin \alpha}$$

where

- V_B is the larger of vertical actions at the cone required to break the ice plate, first break V_{B1} or second break V_{B2} ;
- α is the inclination angle of the structure surface from the horizontal, expressed in radians;
- μ is the coefficient of kinetic friction between the ice and structure surface (for values, see A.8.2.8.7).

The vertical action at the cone required for the first break of the semi-infinite beam on elastic foundation (which is equivalent to a 3-D ice plate when the appropriate value of w_B is used, as specified further below) is

$$V_{B1} = 0,68\sigma_f(w_B)(\rho_w \cdot g \cdot h^5/E)^{0,25}$$

where

$$w_B = \left(\frac{\pi^2}{4}\right) L_c \quad \text{if } 2R > D$$

or

$$w_B = D + \left(\frac{\pi^2}{4}\right) L_c \quad \text{if } 2R < D$$

with the conditions

$$L_c = \left(\frac{Eh^3}{12\rho_w g(1-\nu^2)}\right)^{1/4}$$

and where the distance, R , to the first break for a beam on an elastic foundation is

$$R = \left(\frac{\pi}{4}\right) L_c$$

In the above, the following definitions apply:

- w_B is the effective width for breaking;
- D is the water line diameter or width of the structure;
- E is the modulus of elasticity of the ice;
- h is the level ice thickness;
- L_c is the characteristic length of an ice plate (i.e. sheet) on an elastic foundation;
- R is the distance to the first circumferential crack.

There can be a discontinuity in action as w_B switches from $2R$ being greater than D to less than D , as ice thickness increases. Engineering judgement is required in smoothing out this discontinuity in the value of w_B when the design condition is close to the discontinuity.

The action to create the second break (V_{B2}) is based on the theory developed in Reference [142]. The deflection at the end of the beam which causes the second crack is given by

$$y_{\text{crit}} = \sigma_f h^2 / 0,385 \rho_w g R^2$$

and the action to produce the crack is given by

$$V_{B2} = R w_B \rho_w g y_{\text{crit}} / 3$$

For the second break with $w_B = D$,

$$V_{B2} = 1,11 D \sigma_f h^2 / L_c$$

This action results in a new distance to the break (or piece length) given by

$$R_2 = 0,43 R$$

where R_2 is the distance to the second circumferential crack.

The action associated with the second break, V_{B2} , will usually be higher than the action for the first break, V_{B1} ; however both should be carried until the in-plane compression correction is made because this will be different for each.

The action component H_R is given by Formula (A.8-43):

$$H_R = w_R P \frac{1}{\cos \alpha - \mu \sin \alpha} \quad (\text{A.8-43})$$

in which

$$P = 0,5 (\mu_i + \mu) \rho_i g (1 - e) h_r^2 \cos \alpha \cot \alpha (1 - \tan \theta / \tan \alpha) + h_r h \rho_i g (1 + \mu \cot \alpha)$$

where

w_R is the average of waterline width, D , and the width at the top of the slope;

μ_i is the ice coefficient of friction (ice to ice);

h_r is the ride-up height;

e is the porosity of the ice rubble;

θ is the angle the ice rubble makes with the horizontal, which can be taken as the angle of repose of the rubble.

NOTE θ needs to be less than α .

For further guidance on w_r and h_r to be used in this term, see Reference [142].

The action component, H_p , is expressed as given by Formula (A.8-44):

$$H_p = w h_r^2 \mu_i \rho_i g (1-e) \left(1 - \frac{\tan \theta}{\tan \alpha}\right)^2 \frac{1}{2 \tan \theta} \quad (\text{A.8-44})$$

where w use D for this parameter, which is an approximation of the average width of the rubble on the cone or slope.

The action component, H_L , is given by Formula (A.8-45):

$$H_L = 0,5 w h_r^2 \rho_i g (1-e) \xi \left(\frac{1}{\tan \theta} - \frac{1}{\tan \alpha} \right) \left(1 - \frac{\tan \theta}{\tan \alpha} \right) + \dots \quad (\text{A.8-45})$$

$$\dots + 0,5 w h_r^2 \rho_i g (1-e) \xi \tan \phi \left(1 - \frac{\tan \theta}{\tan \alpha} \right)^2 + \xi c w h_r \left(1 - \frac{\tan \theta}{\tan \alpha} \right)$$

where

- w use D for this parameter, which is an approximation of the average width of the rubble on the cone or slope;
- c is the cohesion of the ice rubble;
- ϕ is the friction angle of the ice rubble.

The final action component, H_T , that is required for Formula (A.8-41) is given by Formula (A.8-46):

$$H_T = \frac{n}{2} h^2 \rho_i g w_T \frac{\cos \alpha}{\sin \alpha - \mu \cos \alpha} \quad (\text{A.8-46})$$

where

- w_T is the effective width for turning the ice blocks at the top of the slope (this will be the larger of the shaft width at the top of the slope or the block width);
- $n = R_2 / h$;

in which, n is the ratio of the ice piece length to its thickness.

Formula (A.8-41) has been modified from the original formula^[140] to account for compressive stress in ice sheet as a result of the applied horizontal action.

The in-plane compression correction factor (I_p) in relation to H_{B1} is given as

$$I_p = 1 / [1 - H_{B1} / (l_c h \sigma_i)] \quad (\text{A.8-47})$$

where l_c is the length of the circumferential crack, equivalent to the effective width of the break, w_B .

The in-plane compression correction factor (I_p) in relation to H_{B2} is given as

$$I_p = 1 / [1 - H_{B2} / (D h \sigma_f)] \quad (\text{A.8-48})$$

In calculating the total ice actions, the two breaking terms (H_{B1} and H_{B2}) are both calculated, as are all the other terms (H_p , H_R , H_L , H_T), and the corresponding in plane corrections are applied to Formula (A.8-41). Whichever action is the highest, is the governing total action (usually the one based on H_{B2}).

The formulae presented are for upward-breaking structures. They can easily be adapted for downward slopes by substituting buoyant density ($\rho_w - \rho_i$) in all formulae where ice density (ρ_i) is used. The breaking terms can be assumed to not change although a different flexural strength might be considered appropriate. Note that the breaking terms can be less accurate if the end deflections are greater than the ice freeboard, in which case the current formulae will be slightly conservative.

A.8.2.4.4.4 Effect of ice rubble

It should be noted that the predictions obtained from the two models provided in A.8.2.4.4.2 and in A.8.2.4.4.3 depend significantly on the amount of rubble on the slope. Depending on slope angle and the width of the cone, the volume of ice rubble can vary in different situations. Frictional effects due to snow or the roughness of the ice sheets also influence the height of the rubble pile. The frictional effects can vary in different ice regimes. Field measurements in the Bohai Sea have shown that the clearing process of the ice rubble can be very effective on narrow cones, especially in the absence of snow cover. In such conditions, the horizontal component of the ice action consists mainly of the icebreaking component.

In the model described in A.8.2.4.4.3, the actions are also very sensitive to the angle of repose chosen for the rubble pile. Combined with the rubble height, the angle of repose determines the volume of ice rubble on the slope of the structure. The force to drive the oncoming ice through this rubble pile and up the slope increases rapidly with this volume. This force is then transmitted to the structure and is a component of the total ice action. The choice of angle of repose should be based on experience and observations from actual structures. Model tests can also provide guidance. In general, the angle of repose should not be less than the structure slope angle minus 10° . For very high rubble piles, as can occur on a wide structure, an angle of about 5° less than the slope angle gives a realistic volume of rubble on the slope. It should be recognized that an angle of repose equal to the slope angle ($\theta = \alpha$) implies a single layer of ice riding up the slope. Angles of repose steeper than the slope angle cannot be accounted for in this model because this leads to a negative volume of ice rubble on the slope.

It is recognized that, in nature, an idealized uniform angle of repose for the rubble on the slope does not necessarily occur. In fact, investigators of ice action on the Kemi-1 cone in Finland and the Confederation Bridge in Canada have observed a variety of bilinear, curved or straight rubble slope angles^{[144][137]}. The geometry of the rubble formation seems to depend on ice strength, velocity, thickness, friction (snow on top of the ice) as well as on the cone angle and waterline diameter. When using the model described in A.8.2.4.4.3, the selection of the rubble angle of repose should approximate the correct volume of ice rubble that can occur on the slope.

A wide structure, especially with a flat face in shallow water, encourages rubble accumulation on the structure because the ice cannot clear around it. In this situation, rubble heights in the 12 m to 20 m range can occur. In fact, once sufficient rubble has accumulated on and in front of the structure, the ice action

required to continue to push oncoming ice through the rubble to the slope of the structure, and then up its slope, becomes so large that the ice failure mode eventually switches to failure of the oncoming ice against the rubble pile in front of the structure. The ice action is then determined using methods valid for ice acting against ice rubble. For wide structures, the ridge-building actions described in A.8.2.4.5 can be applied. If the ice rubble in front of the structure is grounded and has time to consolidate, then the crushing formulae given in A.8.2.4.3.2 and A.8.2.4.3.3 provide a conservative estimate of global ice pressures. It should also be recognized that if the ice is acting on grounded ice rubble in front of the structure, the actual action transmitted to the structure is reduced by the sliding resistance of the grounded ice rubble. This sliding resistance can be estimated from the footprint of the ice rubble and the cohesive strength of the soil. For a granular soil, the weight of the ice rubble acting on the sea floor multiplied by the tangent of the friction angle of the soil gives a reasonable estimate.

A.8.2.4.4.5 Speed effect on actions on sloping structures

Laboratory and full-scale observations indicate that several factors influence the speed dependency of ice actions on sloping structures^[145]. The failure mode of level ice on sloping structures can change from global bending failure to local ice failure adjacent to the structure (shear, crushing) at very high interaction speeds. Particularly for narrow cones, the extent of rubble build-up is generally less at high interaction velocities, which acts to reduce the global ice action.

As a result of the above processes, ice actions on sloping structures depend on the drift velocity. The velocity effect is rather complex and its magnitude depends on the slope angle, sloping surface roughness, and the ratio between ice thickness and waterline structure width.

Whenever available, relevant full-scale data should be used to determine the degree and the sense of the velocity effect for ice actions on sloping structures. Detailed observations and measurements on the Confederation Bridge do not show clear evidence of a speed effect on the global action on bridge piers in the speed range from stationary to 1,5 m/s, see Reference [146].

A.8.2.4.5 Ice rubble and ridges

A.8.2.4.5.1 FY ridges

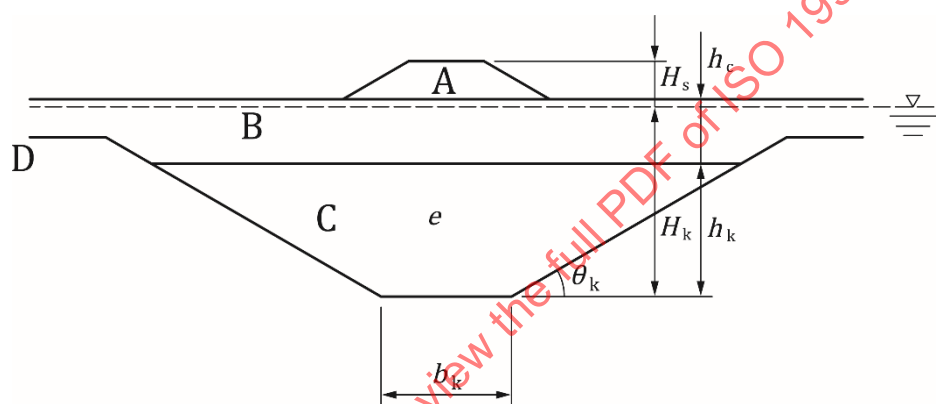
In areas where there is only FY ice, ice ridges are often the governing ice events for ice actions.

FY ridges are composed of a sail, a consolidated layer and a keel of lower strength. The keel consists of partly consolidated ice blocks or loose ice blocks with friction only between the blocks. A major part of the consolidated layer can be a rafted ice sheet where several thinner sheets of parent ice are refrozen one above the other. The geometrical forms of ice ridges vary in nature. In design, it can be assumed that the cross-section of an ice ridge is symmetric, as illustrated in Figure A.8-16.

The sail height and the level-ice thickness are often used as key parameters to define other geometrical shape parameters. For the ridge profile shown in Figure A.8-16, typical relationships are given as $h_c = 1,6h$, $H_k = 4,5H_s$ and $\theta_k = 26^\circ$. The width parameter can vary from $b_k = 0$ to $b_k = 5H_s$. The porosity of the ridge keel depends on the age of the ice ridge and varies in different sea areas. Some key indices of ridge shape are outlined in Reference [147].

The thickness parameters h_c and H_k depend on geographical location. Thicker consolidated layers and keels develop in highly dynamic sea areas due to the rafting process. Therefore, it is suggested that field data be used to specify statistical characteristics of the consolidated layer. Existing field data suggest that the parameters h_c and H_k are not correlated with each other. In the absence of field data, it can be assumed in a deterministic analysis that h_c is 2,0 times the thickness of an ice sheet that has grown in open water under the same conditions as the ice ridge.

The thickness h_c of the consolidated layer of an ice ridge is locally variable in the vicinity of the structure during an ice action. This can be considered if field data are available to create a probability distribution for the consolidated layer thickness. Using this probability distribution, an average value of the consolidated layer thickness can be determined for each event. The average value can be determined by considering the thickness variability in an area of $A = w^2$, where w is the width of the structure.



Key

A	ridge sail	h_c	consolidated layer thickness
B	ridge consolidated layer	h_k	vertical distance between the base of the consolidated layer and the base of the keel
C	ridge keel	b_k	width of the base of the keel
D	level ice	e	keel porosity
H_s	sail height	θ_k	keel angle from horizontal
H_k	keel depth		

Figure A.8-16 — Idealized geometry of a first-year ridge

If detailed data are not available, the keel porosity can be assumed to have a uniform probability distribution with a lower bound of 0,1 and an upper bound of 0,4.

An accurate, theoretical determination of the actions caused by ice ridges is difficult. An upper bound estimation of the horizontal action caused by a FY ridge, F_R , can be obtained as given by Formula (A.8-49):

$$F_R = F_c + F_k \quad (\text{A.8-49})$$

where

F_c is the action component due to the consolidated part of the ridge;

F_k is the keel action component.

Since the volume of the sail is small compared to that of the keel, the effects of the ridge sail can be neglected in the case of FY ridges. The action component, F_c , can be determined, as an estimate, using instructions given in A.8.2.4.3 for parameters of the consolidated layer of an ice ridge, or A.8.2.4.4 for sloping structures by substituting h_c for h .

Several models are available for the determination of the unconsolidated keel action component F_k . Passive failure models are generally used to determine the unconsolidated keel action component acting on vertical or inclined structures. Measurements indicate that the keel cohesion often varies from zero at the base of the keel to a maximum immediately beneath the consolidated layer. Under such conditions, the keel action can be determined for vertical structures (see Reference [148]), with suitable modification (see Reference [149]) as given by Formulae (A.8-50) and (A.8-51):

$$F_k = \mu_\phi h_k w \left(\frac{h_k \mu_\phi \gamma_e}{2} + 2c \right) \left(1 + \frac{h_k}{6w} \right) \quad (\text{A.8-50})$$

$$\mu_\phi = \tan \left(45^\circ + \frac{\phi}{2} \right) \quad (\text{A.8-51})$$

where

- μ_ϕ is the passive pressure coefficient;
- ϕ is the angle of internal friction;
- c is the apparent keel cohesion (an average value over the keel volume should be used);
- w is the width of the structure;
- γ_e is the effective buoyancy, in units consistent with c .

The effective buoyancy is given by Formula (A.8-52):

$$\gamma_e = (1 - e)(\rho_w - \rho_i)g \quad (\text{A.8-52})$$

where

- e is the keel porosity;
- ρ_w is the water density;
- ρ_i is the ice density.

Guidance for the specification of ridge keel parameters is provided in A.8.2.8.8.

Alternative formulae can be derived to obtain the unconsolidated keel action component, F_k , on a sloping structure. Measurements indicate that the keel cohesion varies from zero at the base of the keel to a maximum immediately beneath the consolidated layer. An average value over the keel depth is appropriate for use in Formula (A.8-50).

The application point for the action of a FY ridge keel can be assumed to be at one third of the keel depth below the base of the consolidated layer.

To calculate the keel action on a multi-leg structure, the sum of the keel action from each individual leg should be checked against the action on the effective width of the structure and the lower action selected. In addition, the vertical action of ice rubble should be considered if the ice acts against a submerged portion of the structure.

Formulae (A.8-50) to (A.8-52) represent a limit stress approach for actions due to ice ridges. Other failure modes, such as the ridge-building process, plug shear failure and out-of-plane ridge failure (see A.8.2.4.2), can limit the design action. The plug failure case tends to occur when the ice blocks are loose or when the cohesion is uniformly distributed in the vertical direction. The model described in References [139] and [150] can be used in such conditions.

A.8.2.4.5.2 MY ridges

1) Overview

In the Arctic, MY ridges are often the thickest solid sea ice feature to be designed for. While the size and shape of MY ridges vary considerably, there are generally more examples of near-rectangular shapes in the MY ridge population than for FY ridges. The ratio of the keel depth to sail height is approximately 3,3 for Beaufort Sea MY ridges. The keel angle is approximately 30°, and the sail angle is about 20° from the horizontal. Ridge shape parameters should be specified according to geographical location. Total ice thickness, including sail and keel, should be used when determining MY ice ridge thickness.

The dimensions of partially consolidated second-year ridges can be represented as having equivalent dimensions of fully consolidated MY ridges. The use of the full keel dimensions of second-year ridges can yield conservative estimates of ice actions.

2) Interactions with vertical structures

Conceivable failure modes for MY ridges interacting with vertical structures include crushing, shearing and in-plane bending (see A.8.2.4.2). The action exerted by the ridge is the minimum for these modes of failure.

When the structure is wide relative to the ice thickness, the crushing pressure for MY ice failing directly on the structure can be determined using Formula (A.8-21). For ice failing within the floe and behind a ridge, the same equation and parameters are used for the pressure. Some practitioners have multiplied these pressures by 1,5 to account for the frozen-in condition.

When shear failure modes are considered for MY ridges, an average bulk shear strength value of 0,25 MPa with a range of 0,15 MPa to 0,4 MPa has been used by some practitioners. Correspondingly, the flexural strength of a MY ice feature can be taken as 0,40 MPa.

3) Interactions with conical structures

Multi-year ridge actions against conical structures can be estimated using a variety of methods^{[139][151][152]}. Scale effects are not considered in these models. If scale effects on flexural strength are considered, potentially lower actions values can be calculated for extreme-level ice actions. An example is provided in Annex C of Reference [125].

The approach outlined in this subclause is based on References [153], [154] and [155], and also recognizes earlier work by others.

A MY ridge is treated as a solid beam of ice surrounded by relatively thinner ice. Prior work (e.g. Reference [156]) has shown that the force to break out the ridge from the surrounding ice occurs before the peak ridge breaking action and therefore does not need to be estimated. The ridge is assumed to be of rectangular cross section. If actual ridge cross sections are known, it is suggested that the rectangular equivalent be based on the same thickness and bending capacity. A formula is given for converting a trapezoidal ridge profile to an equivalent rectangle is presented at the end of this subclause. The method which follows is for a ridge with the length axis oriented normal to the direction of motion. Physical model tests have shown that obliquely oriented ridges do not give higher actions^[157].

4) Mechanisms

The approach is based on bounding the mechanisms observed in physical tests as well as theoretical reasoning. The mechanisms are:

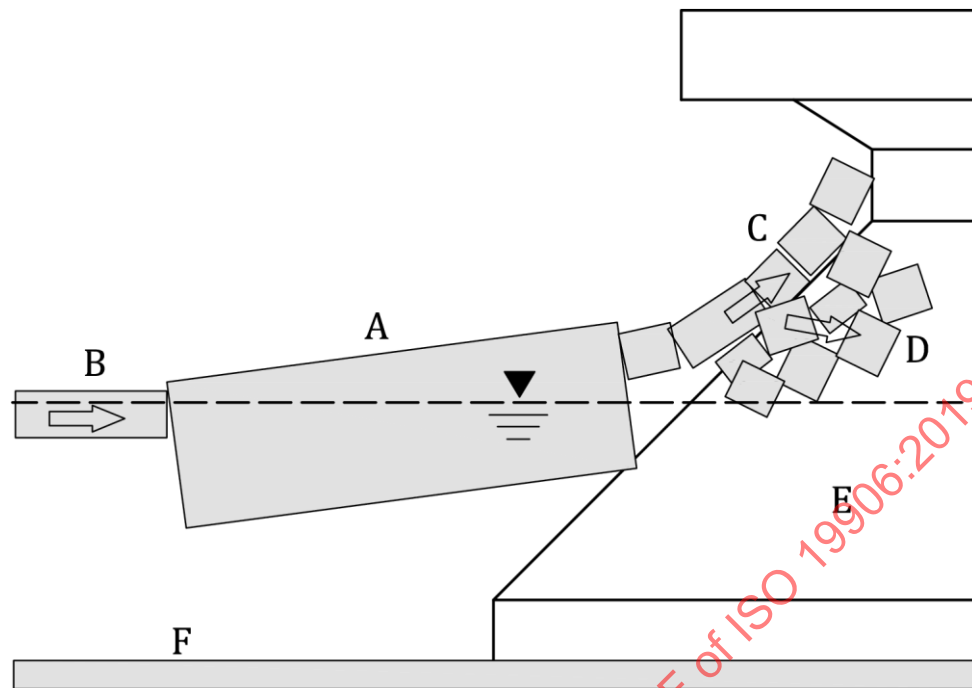
- a) Clearing the debris on the slope from level ice ahead of the ridge (this has to be added to the ridge breaking action, see Figure A.8-17.
- b) The creation of successive hinge cracks to a length which after the final break will rotate around the structure with no further breaking (this length is specified as $n_R h_R$). Based on observations in physical tests and comparison with References [158] and [159], a value of $n_R = 4,5$ is recommended. At the lengths corresponding to the final breaks the effects of curvature on the elastic foundation modulus can be ignored leading to simplified formulae compared to those of Reference [160], as used in the past.
- c) The possibility of the final hinge pieces breaking across the width of the ridge (called z-z failure), see Figure A.8-18.
- d) Final clearing of the ice blocks with their leading edge raised to the ridge thickness.

Mechanisms a), b) and c) are shown in Figures A.8-17 and A.8-18.

In exercising the approach, it has been found that the introduction of the z-z failures reduces the final clearing action so that over a range of ridge thicknesses, widths and strengths, the controlling action is always that associated with the breaking of the final hinge pieces plus the associated level ice clearing action, see References [153] and [154]. This fact leads to a much simplified methodology, which is shown in the logic diagram shown in Figure A.8-19 and for which formulae are provided.

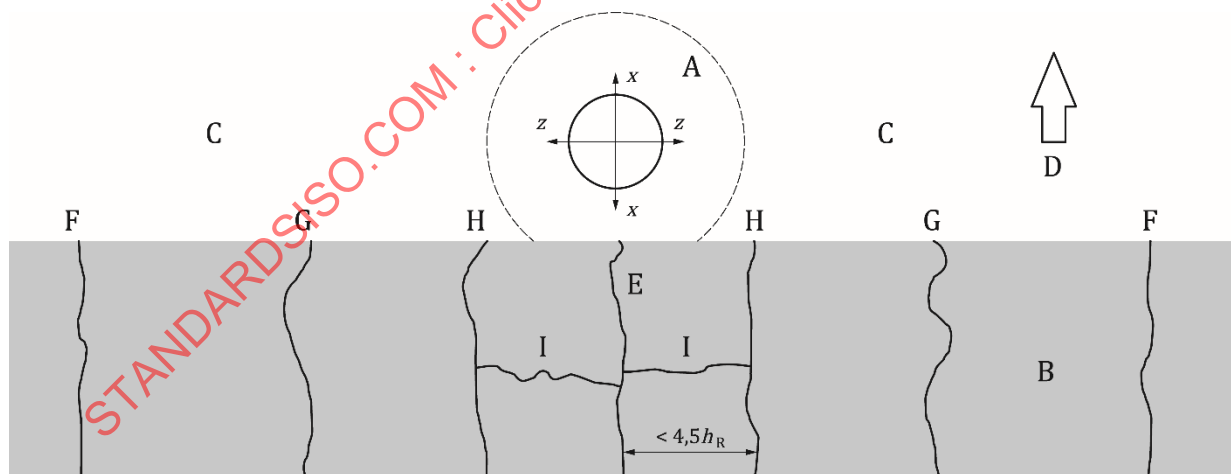
The formulae which follow are aimed at the upper bound deterministic action. This is achieved by using a penultimate hinge piece length which does not quite meet the criterion for stopping the hinge breaking calculation (in this case approximated to $4,5 h_R$). In nature, ridge length can be uncertain, this simplified approach eliminates this uncertainty by not requiring ridge length and also ensures a slightly conservative outcome. If actual ridge lengths are known these can be used in the more comprehensive deterministic approach described in Reference [154] as well as in the probabilistic approach described in Reference [161].

As in all deterministic calculations, judgement needs to be exercised to avoid inserting extreme values for all key inputs at the same time (e.g. ridge thickness, ridge width, flexural strength, etc.).

**Key**

A	MY ice ridge	D	ice rubble cleared around structure
B	direction of level ice motion	E	conical structure
C	ice rubble riding up slope		

Figure A.8-17 — Level ice clearing ahead of the ridge

**Key**

A	conical structure	F	1st hinge cracks, one each side
B	ice ridge	G	2nd hinge cracks, one each side
C	level ice	H	possible 3rd hinge cracks, one each side
D	direction of ice motion	I	z-z failures
E	centre crack, occurs first at lower action	L_{3c}	final length of broken piece ($< 4,5 h_R$)

Figure A.8-18 — Long ridge gradual breaking into smaller hinge lengths with possible final z-z failures

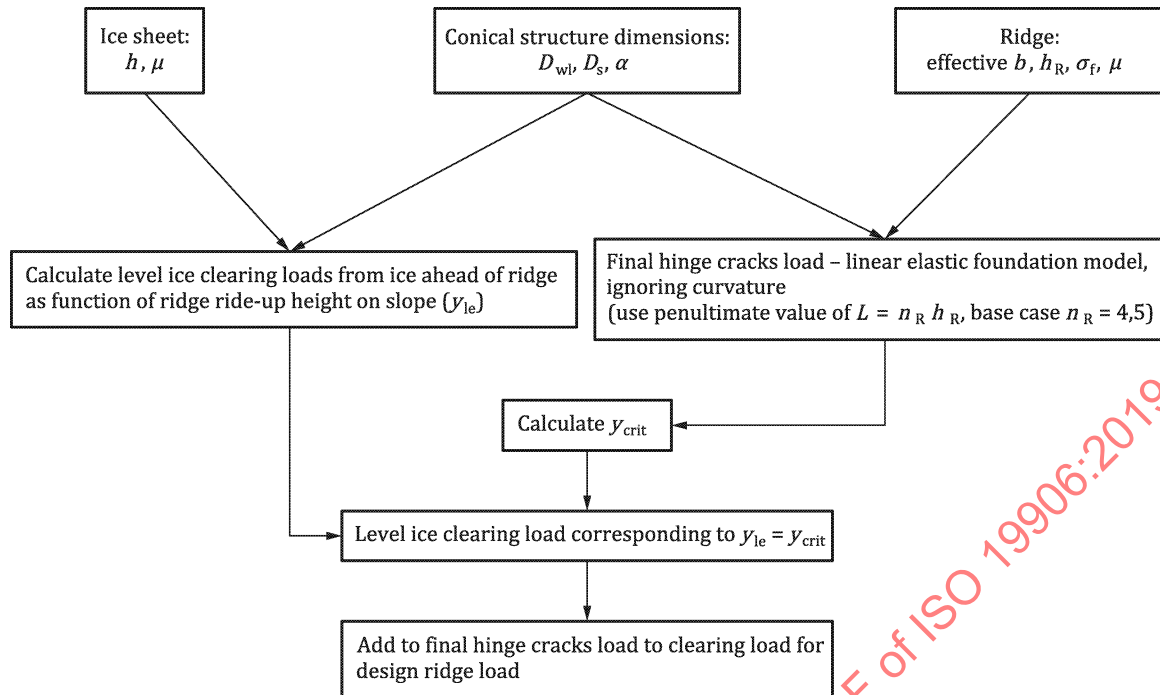


Figure A.8-19 — Logic for bounding calculations

5) Level ice clearing action

When the ridge first starts to interact with the cone, there can be a full slope height of broken ice ahead of it. The force required to clear these level ice fragments has to be added to the ridge action; as the ridge is raised higher on the cone, the value of the clearing action (H_{yc}) will diminish. It is assumed that when the leading edge of the ridge is raised to its full thickness all the level ice fragments will have cleared and H_{yc} is zero. Therefore, the formula for ice clearing action is:

$$H_{yc} = H_c (1 - y_{le} / h_R) \quad (\text{A.8-53})$$

where

y_{le} is the height to which the leading edge of the ridge is lifted;

h_R is the ridge thickness.

Note that the use of h_R is somewhat arbitrary. The height of the slope could be used instead, but some of the following formulae would be more complex as a result.

When considering the force (H_c) to clear the level MY ice ahead of a MY ridge, it is assumed that thick MY ice will ride up as a single layer and therefore:

$$H_c = H_R + H_T \quad (\text{A.8-54})$$

where

H_R is the horizontal component of the force to push the broken ice blocks up the slope;

H_T is the horizontal component of the force to turn the ice blocks at the top of the slope as they meet the vertical shaft.

The action to push the blocks up the slope is given by

$$H_R = \frac{w_R P}{\cos \alpha - \mu \sin \alpha} \quad (\text{A.8-55})$$

where

w_R is the ride-up width, calculated as the average of the waterline and shaft widths, i.e. $(D_{wl} + D_s)/2$;

D_{wl} is the waterline diameter or width of the structure;

D_s is the diameter or width at the top of the slope;

α is the slope angle of the cone at the waterline;

μ is the coefficient of friction between the ice and the structure.

For single layer ride-up, the ice action per unit width, P , is given by

$$P = h_r h \rho_i g (1 + \mu \cot \alpha) \quad (\text{A.8-56})$$

where

h_r is the ride-up height;

h is the ice thickness ahead of the ridge;

ρ_i is the ice density;

g is the gravitational constant.

The horizontal component of force to turn ice blocks at the top of a slope as they interact with the vertical shaft is of the form,

$$H_T = \frac{n}{2} h^2 \rho_i g D_s \frac{\cos \alpha}{\sin \alpha - \mu \cos \alpha} \quad (\text{A.8-57})$$

where n is the ratio of block length to thickness.

A value for n of 3,0 can be assumed. In Reference [154], it is calculated from the breaking process.

6) Final hinge crack action

For the simplified upper bound calculation,

$$L = 4,5 h_R \quad (\text{A.8-58})$$

The critical lift to fail this hinge piece length is,

$$y_{\text{crit}} = \sigma_f h_R^2 / (0,385 \rho_w g L^2) \quad (\text{A.8-59})$$

where

σ_f is the flexural strength of the ice;

ρ_w is the density of water.

The associated vertical force on the cone from one hinge piece is

$$V_c = L b \rho_w g y_{\text{crit}} / 3 \quad (\text{A.8-60})$$

where b is the ridge width.

The associated total horizontal action for ridge failure is

$$H_F = 2 \xi V_c \quad (\text{A.8-61})$$

where ξ is the transformation factor relating horizontal and vertical actions on slopes (see A.8.2.4.4.1).

The level-ice clearing action corresponding to y_{crit} can now be added to get the total cone action, H , i.e.

$$H = H_F + H_c (1 - y_{\text{crit}} / h_R) \quad (\text{A.8-62})$$

7) Transposing a trapezoidal ridge cross section to rectangular

The derivation is an equivalent rectangular cross-section such that the flexural stress (in the lower surface) for a given moment is the same in both cross-sections. The ridge thickness is assumed the same in both cross-sections.

The width of an equivalent rectangle is

$$b = 0,5 (b_1^2 + 4 b_1 b_2 + b_2^2) / (2 b_1 + b_2) \quad (\text{A.8-63})$$

where

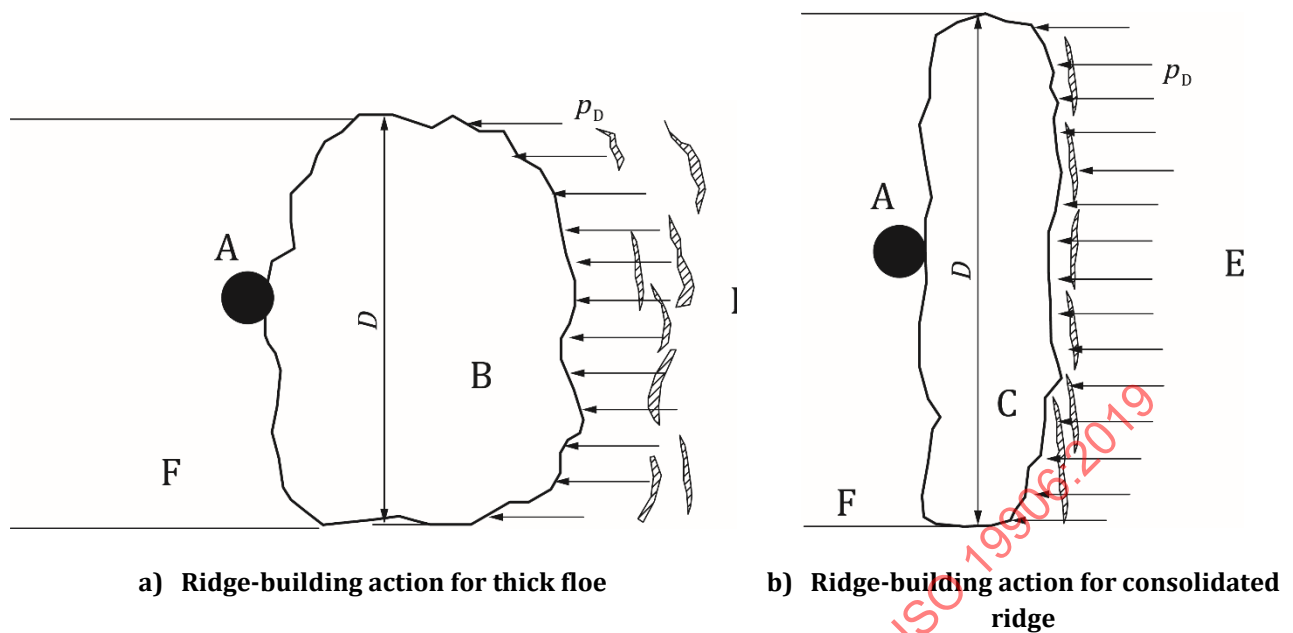
b_1 is the top width of the trapezoid;

b_2 is the bottom width of the trapezoid.

A.8.2.4.6 Limit force actions due to the ridge-building process

To calculate the ice actions due to ridge building, two key parameters are needed as inputs (Figure A.8-20). One is the ridge-building action per unit of length, p_D , on the back of the floe. The other is the ice feature width, D , over which the pack ice is acting. The limit ridge-building action is given by Formula (A.8-64):

$$F_B = p_D D \quad (\text{A.8-64})$$

**Key**

A	structure	E	surrounding ice sheet
B	thick ice floe	F	open water in wake of structure and ice feature
C	thick consolidated ice ridge	D	width of the ice feature, expressed in metres
		p_D	line action imposed on the width of the ice feature

Figure A.8-20 — Ridge-building action behind thick floe or ridge

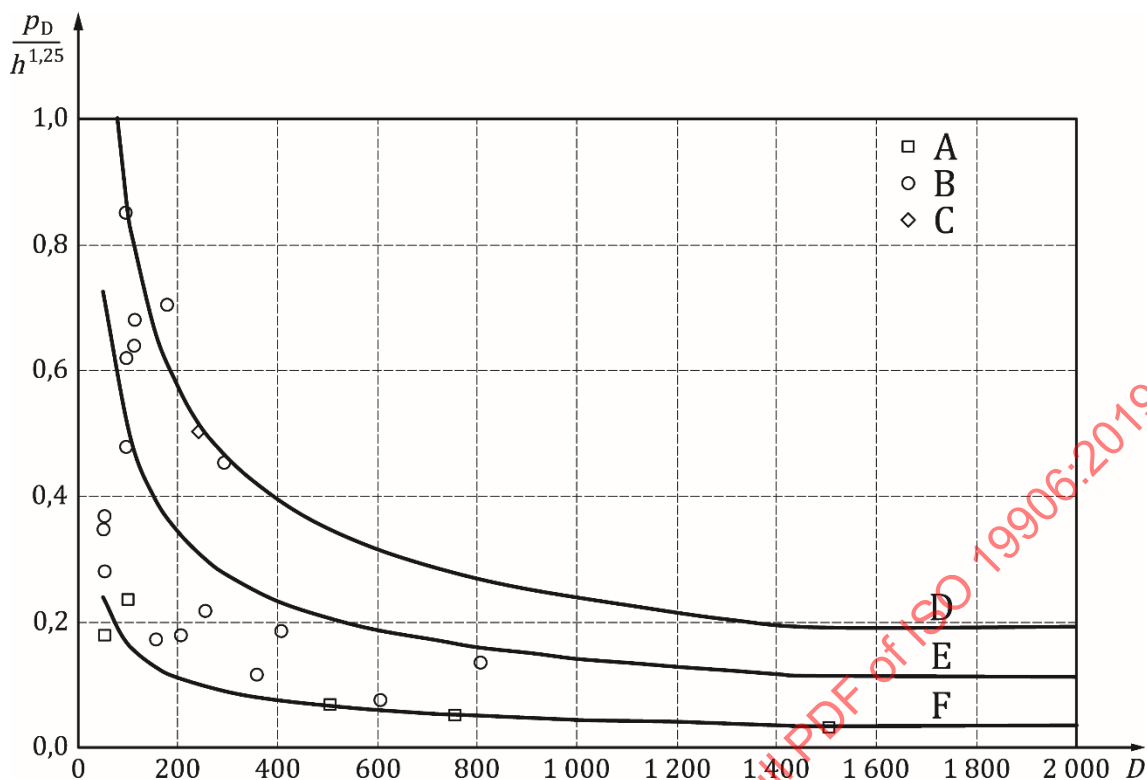
Observations of ridge building and ice rubble building in front of structures indicate that the ice fails out-of-plane in bending. The first estimates of the limit actions are based on analytical models for ridge building. Experiments were conducted in the 1980s and 1990s in the Beaufort Sea. In some test series, pressure instruments were embedded in the ice floes. The results from these tests^{[162][163]} show that the ridge-building action depends on the width, D , of the ice feature as illustrated in Figure A.8-21.

A general expression for the ridge-building action is given by Formula (A.8-65):

$$p_D = R h^{1,25} D^{-0,54} \quad (\text{A.8-65})$$

where

- p_D is the ridge-building action per unit width, expressed in meganewtons per metre;
- h is the thickness of the ice sheet acting on the thicker ice feature, expressed in metres;
- D is the width of the thicker ice feature, expressed in metres;
- R is a coefficient, see Figure A.8-21.



Key

A	data from Reference [163]	F	Formula (A.8-65), $R = 2$
B	data from Reference [164]	$p_D/h^{1.25}$	normalized ridge-building action, where p_D is expressed in meganewtons per metre
C	data from Reference [165]	D	width of thicker ice feature, expressed in metres
D	Formula (A.8-65), $R = 10$		
E	Formula (A.8-65), $R = 6$		

Figure A.8-21 — Ridge-building actions versus width (normalized to unit thickness of first year ice using h to the power of 1,25)

Figure A.8-21 shows a collection of measured data points on ridge-building actions. All data are from rubbing events where FY ice was failing against a thicker feature. These data include values from sensors embedded in ice floes^[163], values from measurements on Molikpaq, Katie’s Floeberg and Hans Island^[164] and one data point from the Molikpaq, where the thicker feature was frozen into the surrounding FY ice^[165]. Note that the pack ice sheet thickness h is raised to the power of 1,25 in order to ‘normalize’ the ridge-building line action to 1 m of ice. The normalized ridge-building line action is $p_D/h^{1.25}$, see Reference [162].

The measured data are shown in relation to the ridge building actions per unit width given by Formula (A.8-65) with R values of 2, 6 and 10. The best fit to the data collected from the embedded sensors^[163] is $R = 2$. A value of $R = 6$ is a best fit to all the data, and closely corresponds to the value developed based on theoretical considerations of three ice sheet/rubble interaction mechanisms (Reference [166], Formula 5.2.7). A value of $R = 10$ passes through the upper bound data points collected for narrower widths (<300 m) and for frozen-in floes.

Literature on ridge building actions has estimated uncertainty factors in the estimation of ridge building actions from the measured responses ranging between 1,5 and 2. For deterministic calculations, the level of conservatism is left to the judgment of the designer regarding how to combine these uncertainty factors with the values of R reported above.

If a probabilistic methodology is used, it is recommended to use a uniform distribution with values of R having an appropriate range based on interpretation of the data in Figure A.8-21 for the specific application.

Based on a review of the theories for rubble building and the measured data, it is suggested that, for widths less than 100 m and thick ice, rubbing failures cannot be relied on, and the methodology for crushing actions (see A.8.2.4.3) should be used. For thinner ice failing into ice rubble and widths less than 100 m, ridge building can still apply, see Reference [167].

The few data for widths greater than 1 500 m suggest a levelling-out of the line actions with width, and applied ridge-building line actions should not generally be less than the value corresponding to a width of 1 500 m.

A.8.2.4.7 Limit energy global ice actions

A.8.2.4.7.1 Full-scale data

Relevant full-scale measurement programmes where the kinetic energy of the ice feature has limited the ice actions include:

- Hans Island MY floe impact programme in 1980-83;
- several well-documented impacts of MY ice floes against the Molikpaq structure in the spring of 1986;
- measurements of ice floe impacts against a man-made island in the Tatar Strait in 1992;
- small iceberg impact test in Antarctica in 1990;
- bergy bit impact tests at Newman's Cove in 1992 and Grappling Island in 1995;
- bergy bit impact tests with the icebreaker Terry Fox in 2001.

Except for the MY floe impacts, most of the field data are obtained from experiments with relatively small ice features, on the order of hundreds to several thousand tonnes. Uncertainty should be considered when extrapolating these data to design situations involving features of several hundred thousand to several million tonnes.

A.8.2.4.7.2 Kinetic energy lost due to rotations of the ice feature

A large portion of the initial kinetic energy can be transferred into rotation of the ice feature during eccentric impacts, thereby mitigating the action relative to head-on impacts. If E_0 is the initial kinetic

energy of the ice feature, the reduced kinetic energy after rotation for impact with a fixed structure is given by Formula (A.8-66)^[168]:

$$E_K = \frac{E_0}{1 + \frac{\varepsilon_z^2}{r_z^2} + \frac{\varepsilon_y^2}{r_y^2}} \quad (\text{A.8-66})$$

where

$\varepsilon_z, \varepsilon_y$ are the eccentricities in the vertical and horizontal planes respectively;

r_z, r_y are the corresponding radii of gyration of the ice feature.

The eccentricities represent offset distances between the point of contact and the centre of mass of the ice feature relative to the direction of motion immediately prior to impact. The radii of gyration should reflect added inertia effects. For ice floe impacts, the ε_z^2/r_z^2 term can generally be ignored.

For probabilistic and semi-probabilistic analyses, eccentricities and radii of gyration should be random parameters reflecting the range of ice feature sizes, contact geometries and ice drift directions relative to the structure. A reduction in the impact energy due to ice feature rotation can be made for deterministic analyses when adequately substantiated or when dictated specifically by the structure and ice feature geometries.

A.8.2.4.7.3 Impact actions

The ice actions resulting from ice feature impacts can be calculated using numerical algorithms or closed-form analytical solutions. The underlying assumption in both cases is that the impact action reaches its maximum value when the penetration stops and the nominal contact area reaches its maximum.

Both analytical closed-form solutions and numerical models require that the instantaneous impact action be expressed as a function of penetration depth. Such a function can be presented as a combination of the pressure-area relationship, which describes strength properties of ice and the contact area, with the penetration depth relationship, which depends only on the structure and the ice feature geometries.

A closed-form solution^[168] can be obtained when each of these relationships is represented as a power law. The pressure-area relationship for general ice feature shapes can be expressed as given by Formula (A.8-67):

$$p = C_P A_N^{D_P} \quad (\text{A.8-67})$$

where

A_N is the nominal contact area;

C_P, D_P are coefficients.

The contact area-penetration depth relationship is given by Formula (A.8-68):

$$A_N = C_A \delta^{D_A} \quad (\text{A.8-68})$$

where

δ is the penetration depth of the structure into the ice;

C_A, D_A are coefficients.

The maximum action at the end of the interaction is given by Formula (A.8-69):

$$F_E = a \left[\frac{b+1}{a} E_K \right]^{\frac{b}{b+1}} \quad (\text{A.8-69})$$

where

E_K is the impact energy after correction for ice feature rotation;

$$a = C_p C_A^{D_p+1};$$

$$b = D_A(D_p + 1) \text{ for } b \geq 0^{[168]}.$$

For floes or ice features of relatively constant thickness, the pressure relationship can be expressed as given by Formula (A.8-70):

$$p = C_h h^{D_1} w^{D_2} \quad (\text{A.8-70})$$

where

h is the ice thickness;

w is the interaction width.

The corresponding contact area relationship is given by Formula (A.8-71):

$$A_N = h C_w \delta^{D_w} \quad (\text{A.8-71})$$

where C_w, D_w are coefficients.

In this case, the coefficients in Formula (A.8-69) are $a = C_h C_w^{D_2+1} h^{D_1+1}$ and $b = D_w(D_2 + 1)$. The coefficients C_w and D_w should be determined from the geometry of the structure and ice features. In the absence of site-specific ice feature geometry, simple geometric shapes can be used.

The contact area relationships shown above can be used to represent a variety of structure and ice feature shapes, and are not limited to small penetration depths as long as the power law forms are appropriate.

For floes, the parameters C_w and D_w should be based on measurements of the plan shape of floes in the region of interest and from the shape of the structure. For massive ice features such as icebergs, the parameters C_A and D_A should be based on measurements of the local shape of the ice features and from the shape of the structure. In the absence of site-specific data, simple geometric shapes can be used to represent the local ice shape. For circular floes and flat or circular structure faces, the power law is a good approximation for small penetrations relative to the floe and structure radii.

For deterministic solutions, the pressure, contact area and contact width coefficients are constant. As a first approximation for sea ice floe interactions, the parameter C_h can be assumed to be equal to C_R in Formula (A.8-21). For certain parameter combinations, values less than C_R can potentially yield larger actions and it is recommended that a range of values up to and including C_R be verified. In the absence of measured data, a correspondence can be made between exponents D_1 and D_2 and the parameters of Formula (A.8-21) as $D_1 = n - m$ and $D_2 = m$.

For probabilistic solutions, the contributing parameters can be random, and the contact areas or widths should reflect the distributions of measured ice feature shapes and ice impact orientations with respect to the structure. The distribution of pressures should reflect the average impact pressure over each interaction. For impact situations, random values of the pressure coefficients, C_P and D_P , can be used; see Formula (A.8-25).

A.8.2.4.7.4 Hydrodynamic effects

Hydrodynamic effects associated with ice feature motions in the vicinity of the structure can be considerable, especially in conditions where the ice concentration is low and relatively small ice features are impacting wide structures. Due to hydrodynamic effects, smaller ice features can slow down as they approach and tend to move around the structure. Consideration should be given to added mass of the impacting ice feature, with due account for the presence of the seabed and the structure^[169]. When the structure moves sufficiently during the course of the interaction, its added mass should also be considered.

A.8.2.4.7.5 Structural compliance

Structural compliance has a complex effect on the impact action. The maximum impact action is smaller for a compliant structure because part of the kinetic energy of the impacting ice feature is spent in structural deformation or displacement. On the other hand, actions on the mooring system or the structure foundation can increase due to the inertial effects if the duration of the impact is comparable to the first natural period of the structure.

Formulae (A.8-66) to (A.8-71) do not take account of the structural compliance. Special consideration should be made in such cases.

A.8.2.4.8 Floating systems

Floating systems in iceberg and sea ice environments are unique in that they generally have disconnection capability and operate with IM support. These are coordinated using an IM plan that includes an ice alert system for staged shutdown as outlined in Clauses 13 and 17, and A.13, and A.17.

When the floating system is connected, it is necessary to consider global ice actions for the stationkeeping system and hull for the parameter distributions associated with managed ice. Of particular concern are those features at the upper end of the managed ice distribution for which the actions approach the capacity of the stationkeeping system. It is also necessary to consider ice actions on the hull for disconnected states and when in transit. Factors influencing ice actions on floating systems are provided in 13.4.

For iceberg environments, design ice actions can be determined from the frequency of impacts, and the joint distribution of iceberg size, relative speed between iceberg and floater at impact, ice pressure, contact area and other subsidiary conditions. While IM and disconnection influence the frequency of impacts and the distributions of impact parameters, the procedure for calculation of ice actions on floating systems is similar to that for fixed structures. A key difference is that the flexibility of the stationkeeping system should be factored into the relationship for dissipation of kinetic energy on impact. Other provisions for stationkeeping are addressed in 13.7.

For sea ice environments, IM and disconnection can reduce the frequency of severe ice events. The ice reaching the structure is typically a slurry of broken ice pieces containing some larger floes and possibly glacial or old ice. Ice events resulting in actions relevant to design are generally governed by thick ice features that cannot be detected within the surrounding ice cover or that prove more difficult to manage than anticipated, and interactions on the side of ship-shaped structures when weathervaning is impeded.

Actions from managed sea ice are best determined from full-scale data. Reference [170] outlines a method that uses full-scale action data from the Kulluk conical drilling platform in the Beaufort Sea, for which ice actions have been associated with the size and thickness of the managed ice. This method is also described in Reference [171]. While other methods based on full-scale icebreaking vessel performance trials have been developed, they have not yet been described in the open literature. Additional full-scale measurements are encouraged.

A.8.2.4.9 Multi-leg structures

The calculation method shown below is based mainly on laboratory tests. The global limit stress action on a multi-leg structure can be determined by first using the guidelines provided in A.8.2.4.3 or A.8.2.4.4 to obtain a quasi-static action on one leg. The global action is then as given by Formula (A.8-72):

$$F_S = k_s k_n k_j F_1 \quad (\text{A.8-72})$$

where

- F_1 is the ice action on one leg;
- k_s accounts for the interference and sheltering effects;
- k_n accounts for the effect of non-simultaneous failure;
- k_j accounts for the ice jamming.

The ice action depends on the clear distance, L , between the legs in the front row of legs interacting with ice. If this distance is large, each leg interacts with the ice sheet independently of the other legs. In this case, the sheltering factor, k_s , approaches the number, n , of the legs. Where all legs are on a line

perpendicular to the drift direction, data from limited model tests suggest that the legs act independently of each other if the ratio of the clear distance, L , between the legs and the width, w , of an individual leg is greater than 5. Field evidence from the Confederation Bridge suggests some interaction between piers for L/w ratios of about 10. For a typical multi-leg structure where the legs are not in a single line, the legs become independent at a higher value of L/w . For a typical multi-leg structure with four legs, the maximal sheltering factor varies from 3,0 to 3,5. The angle of incidence of the ice drift influences the ice action.

The peak values of the actions on different legs are not likely to occur simultaneously unless the structure is very compliant. This can be considered by the reduction factor k_n . In the absence of test data, this parameter can be assumed as $k_n = 0,9$.

Ice jamming between the legs can usually be expected if L/w is less than 4. This can, but not necessarily always, lead to an increase in the ice action. Experimental data can clarify the influence of ice jamming in a particular design case. Where there is any chance that ice can jam between the legs, both the jammed and unjammed cases should be considered and the maximum value of ice action selected. In the analysis of the jammed case, the limit stress action should be checked for each leg to ensure the action path is feasible. Ice jamming is more likely with a FY ridge because of the associated ice rubble in the keel. The critical spacing can be wider.

It is emphasized that the characterization of sheltering and jamming processes considered in Formula (A.8-72) can be complex, particularly when the ice sheet is composed of different ice features and ice thicknesses. There can also be uncertainty associated with the non-simultaneous failure factor, k_n . In addition, if risers are present within the legs and could potentially impede the movement and clearing of ice, their effect should be included in the analysis of ice actions.

It should be recognized that the ice actions arising in the limit stress conditions described above can be limited due to other failure mechanisms described in A.8.2.4.2. While evaluating these processes, one should consider the possibility that an isolated ice floe stops after interacting with the leading leg. Stopping can also occur at a later stage, before all legs interact with the ice sheet. Guidelines provided in A.8.2.4.6 can be used to estimate the limit kinetic energy action, F_E . Based on this analysis, an initial estimate of the representative action value is selected as the minimum of F_E and F_S obtained from Formulae (A.8-69) and (A.8-72).

If the ice floe stops after an initial interaction with the multi-leg structure, the penetration can still continue if a ridge building process (see A.8.2.4.2 and A.8.2.4.6) becomes active and the limit force action, F_B , obtained from Formula (A.8-64), is greater than F_E . In such a condition, the representative action on a multi-leg structure is selected as the minimum of F_S and F_B . Further guidance on multi-leg structures can be found in Reference [172].

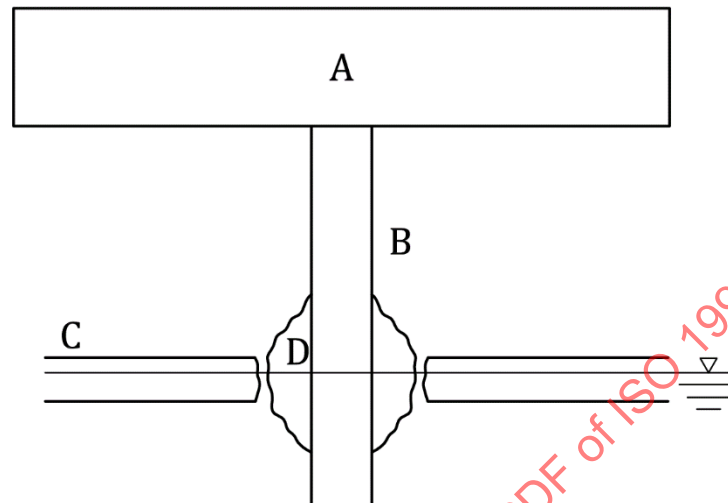
A.8.2.4.10 Adfreeze action effects

A.8.2.4.10.1 Adfreeze to piles and supports

Ice can freeze to a structure as an ice bustle in areas where the tidal amplitude is sufficient to fail the ice around the structure with each cycle (see Figure A.8-22). Usually, the new ice formation spreads from the maximal to minimal levels of flood/ebb tides. The rate of the ice growth can be as high as 2,5 cm per cycle

and the thickness of this formation can reach several metres. If the spacing between the structure's piles or supports is insufficient, then ice can begin to grow between piles.

For further information, see Reference [173].



Key

A quay structure
B pile

C ice surface
D ice bustle

Figure A.8-22 — Schematic of ice bustle formed on quay piles

A.8.2.4.10.2 Horizontal actions due to adfreezing

Ice bustles can cause an increase in the magnitude of horizontal ice actions. This can occur first of all due to an increase in the contact area. Secondly, ice accumulations on the surface of sloping structures can make the contact angle of the oncoming ice steeper, also resulting in increasing vertical and horizontal action due to possible ice crushing instead of flexural failure of the ice.

Another adfreeze phenomenon is the condition where the structure freezes within a level ice sheet. This can occur in the following situations:

- when the structure is located in a sheltered area;
- when the structure is located in an open sea, but the change of the water level during the tide/ebb action or the air pressure variation is very limited, and the ice moves very slowly or is stationary for a long time.

When the ice begins to move, horizontal actions can exceed those of the drifting level ice with the same parameters because the ice thickness of the adfrozen ice in the vicinity of the structure is greater. An increase in the ice action can occur also after a stopping condition when the ice does not freeze to the structure. This can happen due to healing of the cracks that exist in the ice edge.

The rubble formed during interactions between an ice sheet and an upward-sloping structure can freeze together and adfreeze to the structure. This kind of rubble can create a false bow ahead of the structure. False bows with a thickness of 2 m and a width of 3 m have been observed in the field on a pile with a

diameter of 1,8 m. Subsequent ice failure events can create actions that cannot be predicted by models derived for sloping structures. When sufficient adfreeze strength is present, the effective structure diameter should include the adfrozen ice mass in calculations.

A.8.2.4.10.3 Vertical actions due to adfreezing

An ice bustle formed on the piles of a structure can impede vessel access and create additional vertical actions that should be verified in the design. Ice bustle thickness tends to reach a limit after some time, as the formation process is controlled by the water surface at high tide. When the water level changes, the ice cover that is attached to a structure bends and creates a vertical action. The limits of ice adfreeze bond strength or ice flexural strength restrict the magnitude of this action.

During water level fluctuations, pile uplift can be of concern for light structures. Adfrozen ice pulls the pile upwards, soil sloughs into the cavity under the pile bottom and prevents the pile from sinking to its original depth after the water level recedes. Adhesion or bending failure breaks the ice free from the pile. During repeating adfreeze and water level fluctuations, the pile can be gradually jacked up. Pile motions of over 2 m have been observed for water level fluctuations of less than 20 cm.

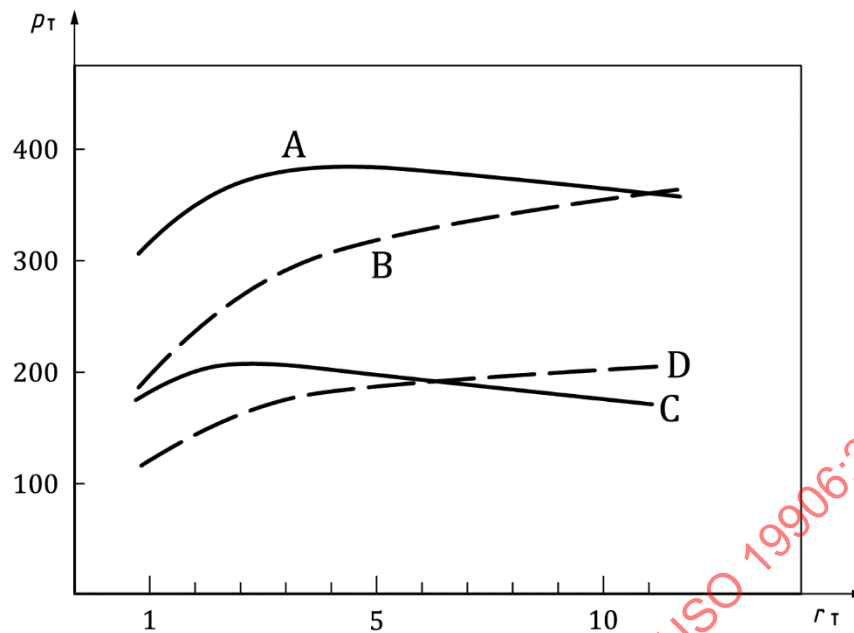
Natural processes that reduce the break-out action are:

- the slow initial action build-up, which limits the ice action;
- the progressive non-simultaneous adfreeze failure.

A.8.2.4.11 Thermal action effects

In sheltered areas and areas near the shore, ice actions can occur due to rising temperatures when ice expansion is restricted by fixed structures or other obstructions. Based on full-scale measurements made in Russian and Canadian sea areas, sea ice does not expand appreciably for ice temperatures above $-10\text{ }^{\circ}\text{C}$ for salinities greater than 3 g/kg or above $-7\text{ }^{\circ}\text{C}$ for salinities greater than 1 g/kg.

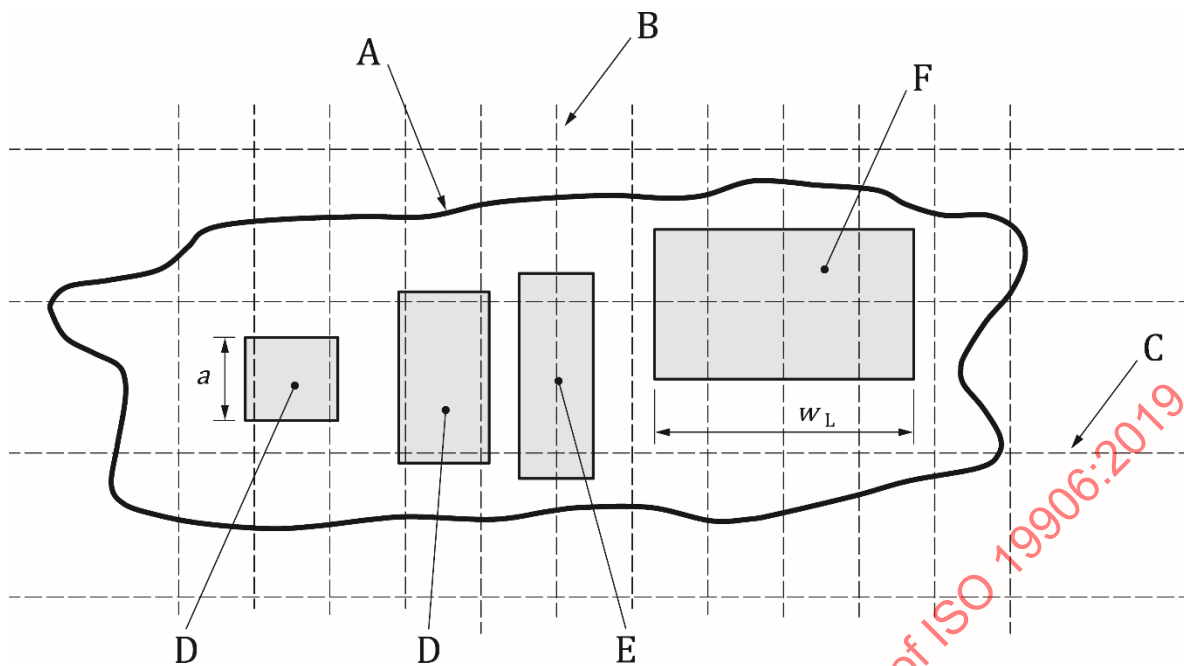
The thermal ice action depends mainly on the initial ice surface temperature and the rate of temperature increase. This is shown in Figure A.8-23 for freshwater ice sheets with complete lateral restraint.

**Key**A $T_i = -30\text{ °C}$ and $h = 1,0\text{ m}$ B $T_i = -30\text{ °C}$ and $h = 0,5\text{ m}$ C $T_i = -20\text{ °C}$ and $h = 1,0\text{ m}$ D $T_i = -20\text{ °C}$ and $h = 0,5\text{ m}$ p_T thermal ice pressure, expressed in kilonewtons per metre r_T rate of temperature increase, expressed in degrees Celsius per hour h ice thickness**Figure A.8-23 — Thermal ice action versus the rate of temperature increase of the ice surface**^[174]

For a preliminary assessment of thermal actions, indicative values in the range of 150 kN/m to 300 kN/m can be used regardless of the ice thickness^{[174][175][176]}. Thermal actions in freshwater ice are larger in magnitude than those in sea ice.

A.8.2.5 Local ice actions**A.8.2.5.1 Overview of local ice actions**

While global actions are calculated from average pressures over the nominal contact area, there can be many areas within the nominal contact area that are subjected to higher local pressures, see Figure A.8-2. Consequently, global average pressures should not be used for local design and a separate consideration of local pressures is necessary. Local pressures should be used, for example, in the design of shell and stiffening elements as illustrated in Figure A.8-24. The same concept for loaded area applies to concrete structures.



Key

A	global interaction area (grows as interaction proceeds)	a	loaded height
B	frames	w_L	loaded width
C	stringers		
D	local area for plate design		
E	local area for frame design		
F	local area for stringer design		

Figure A.8-24 — Definition of loaded areas for local actions, example for a transversely-framed structure

Ice interactions can produce local pressures that can be considered as constant over a local design area, A , as given by Formula (A.8-73):

$$A = a \cdot w_L \quad (\text{A.8-73})$$

where

- a is the height of the loaded local area;
- w_L is the width of the loaded local area.

An example of local ice loading on a transversely-framed structure is given in Figure A.8-24 and the same concepts can be applied to a longitudinally-framed structure. For plating design, the local area is defined in terms of a loaded width, w_L , and a loaded height, a . For plating, frame (or stiffener) and stringer design, several local design areas and locations (and corresponding pressures) should be checked as illustrated in Figure A.8-24 to determine the largest action effect. Typically, pressure patches with aspect ratios of up to 3:1, either horizontally or vertically, can be considered for icebergs and 1(vertical):3(horizontal) for sea ice.

Local ice pressures differ depending on the thickness of the ice encountering a structure. The approach outlined in A.8.2.5.2 is based on data for sea ice up to about 1 m thick, where the proximity of the upper

and lower free surfaces of the ice limits the local ice pressure. In contrast, the method outlined in A.8.2.5.4 is based on data for thick MY ice and icebergs, which are capable of providing the confinement required to produce higher local pressures over the same loaded area. While not specifically calibrated, the methods described in A.8.2.5.2 and A.8.2.5.4 are intended to provide local ice pressures associated with the ELIE ice thickness used for estimating the EL ice action. The method described in A.8.2.5.3 is based on ship impacts with MY ice, and involves an extremal analysis of annual maxima from which EL and AL characteristic ice pressures can be obtained directly.

The formulae provided in A.8.2.5.2 to A.8.2.5.4 are based on datasets for specific regions and loading conditions. When the local pressure formulations presented in this document are applied to other regions and structure types, differences in loading characteristics, ice conditions and exposure should be addressed.

A.8.2.5.2 Local actions from thin FY ice

A.8.2.5.2.1 Overview

A method is described in A.8.2.5.2 for determining local pressures from FY ice up to approximately 1 m thick. This method applies to level ice, rafted ice and consolidated layers of FY ice ridges. Considerable data exist from full-scale local pressure measurements for level and rafted ice conditions. Pressure panels were used to measure the average pressure on an area approximately 1 m wide over the full ice thickness. Based on these data, the largest actions on vertical structures tend to occur at low ice velocities. In such situations, local ice failure occurs simultaneously over a major proportion of the ice thickness because of the ductile behaviour of the ice. The approach described in A.8.2.5.2 is based on Reference [177].

A.8.2.5.2.2 Representative values of local actions

Local action effects can be assessed by the application uniformly over a local design area of the action, F_L , expressed in meganewtons, as given by Formula (A.8-74) for a greater than 0,14:

$$F_L = 3,72 \cdot \sqrt{a} \cdot w_L \quad (\text{A.8-74})$$

where

a is the height of the local design area, expressed in metres;

w_L is the width of the local design area, expressed in metres;

Formula (A.8-74) is valid for the following conditions:

- a) $w_L/a \leq 10$;
- b) $a \leq 0,4 h_E$, where h_E is the representative ice thickness for ELIE.

If the height of the local design area exceeds $0,4 h_E$, Formulae (A.8-75) and (A.8-76) can be used to determine the local actions. It is not necessary to consider local actions for w_L/a greater than 10.

A.8.2.5.2.3 Full thickness local pressure

Full thickness local ice pressure is associated with the full ice sheet (floe) thickness. Formula (A.8-74) is based on an interpretation of data from the Gulf of Bothnia^[178]. Its derivation is based on an upper bound value for the full thickness pressure, p_F , expressed in megapascals, as given by Formula (A.8-75):

$$\begin{aligned} p_F &= 2,35 h^{-0,50} & \text{for } h > 0,35 \text{ m} \\ p_F &= 4,0 & \text{for } h \leq 0,35 \text{ m} \end{aligned} \quad (\text{A.8-75})$$

where h is the ice thickness, expressed in metres.

In a deterministic design, the local pressure acting on the loaded area, see Formula (A.8-73), is given by Formula (A.8-76):

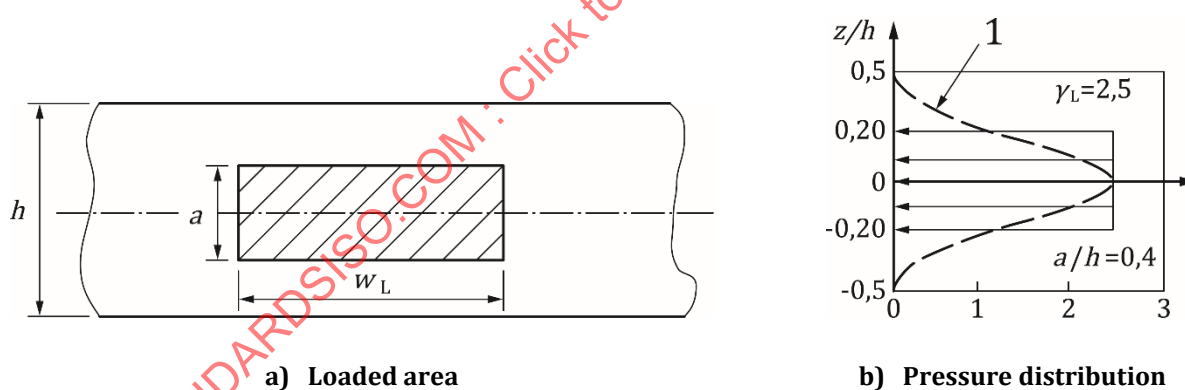
$$p_L = \gamma_L p_F \quad (\text{A.8-76})$$

where

γ_L is equal to 2,5;

p_F is the full thickness pressure defined by Formula (A.8-75), equal to $p_F(h)$.

The coefficient, γ_L , reflects a simplified vertical distribution of the full thickness pressure on the loaded area, A , which is equal to $a \cdot w_L$, as illustrated in Figure A.8-25.



Key

1	data obtained from field measurements	γ_L	pressure distribution coefficient
h	ice thickness	a	loaded height
z	distance from mid-depth of ice	w_L	loaded width

Figure A.8-25 — Distribution of the full thickness pressure on the loaded area

A.8.2.5.2.4 Local design at discontinuities in the structure

Local stress concentrations can occur close to discontinuities such as the corners of a rectangular structure. In these areas, the magnitude of full thickness pressures can reach 2,5 to 3,0 times the usual full thickness pressure. Higher design pressures should be considered over a horizontal distance from the corner equal to the ice thickness^[179].

A.8.2.5.2.5 Probabilistic local design

The method described in A.8.2.5.2.1 to A.8.2.5.2.4 can also be used for probabilistic analyses by determining a joint probability density function for the ice thickness and the full thickness local pressure, and then applying the guidelines of A.8.2.2. Direct use of Formulae (A.8-74) and (A.8-75) in a probabilistic analysis will yield overly conservative results for EL and AL actions, since the constants 3,72 and 2,34 respectively are formulated from the data to represent upper bound conditions associated with the ELIE ice thickness. For probabilistic analysis to better reflect true design conditions, coefficients representative of expected values rather than extreme values are needed.

A.8.2.5.3 Probabilistic model for local ice pressures

A.8.2.5.3.1 Short duration impacts with fixed structures and floating systems

A probabilistic local pressure model has been developed based on data from ship impacts with MY ice floes in Reference [180]. The model can be applied for relatively short duration interaction events (i.e. on the order of seconds) of icebergs, bergy bits or MY fragments or any other ice impacts with fixed structures and floating systems. Longer duration interactions with wide structures are considered in A.8.2.5.3.2.

The model gives a probability distribution for the maximum annual pressure, p , corresponding to an annual exposure, μ , which represents the annual number of equivalent impact events with icebergs, bergy bits and MY ice.

The cumulative probability distribution given by Formula (A.8-77) can be used for the local pressure p , representing the decrease of pressure, expressed in megapascals, acting on an area A , expressed in square metres:

$$F_p(p) = \exp[-\mu \exp(-p/\alpha)] \quad (\text{A.8-77})$$

$$\alpha = B_p \cdot A^{-0.7} \quad (\text{A.8-78})$$

$$\mu = v \cdot r \cdot t / 0,70 \quad (\text{A.8-79})$$

where

B_p is the empirical coefficient representing ice strength;

μ is the annual exposure factor;

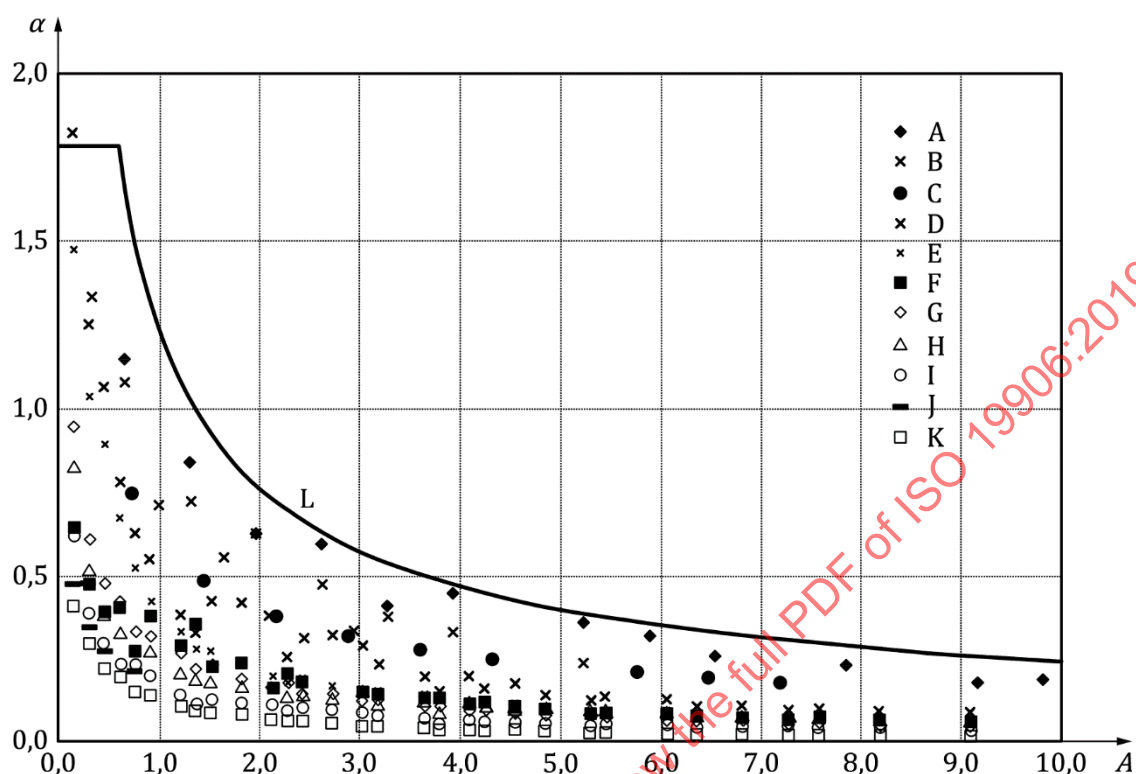
v is the expected number of interactions per year;

r represents the probability of hitting a panel given an event (0,5 in Kigoriak analysis, a value of 1 can be used to provide some measure of conservatism such as for the use of these relationships for iceberg impact, unless an alternative value can be justified);

t is the interaction time, expressed in seconds.

Based on Kigoriak ramming trials with MY ice, the empirical coefficient B_p is 1,25^[180]. As illustrated in Figure A.8-26, B_p varies depending on the ice regime, and collection of regional data is encouraged. The

constant 0,7 in Formula (A.8-79) represents the time in seconds corresponding to the average duration of Kigoriak rams.



Key

A	Oden; $B_P = 1,11$, exponent $-0,81$	H	Polar Sea, South Chukchi Sea 1983; $B_P = 0,24$, exponent $-0,68$
B	Terry Fox; $B_P = 0,77$, exponent $-0,61$		Polar Sea, Antarctica 1984; $B_P = 0,18$, exponent $-0,71$
C	Louis St. Laurent; $B_P = 0,61$, exponent $-0,61$	J	Polar Sea, South Bering Sea 1983; $B_P = 0,17$, exponent $-0,63$
D	Polar Sea, Beaufort Sea 1982; $B_P = 0,53$, exponent $-0,77$	K	Polar Sea, Bering Sea 1986; $B_P = 0,12$, exponent $-0,78$
E	Polar Sea, North Chukchi Sea 1983; $B_P = 0,38$, exponent $-0,79$	L	original design curve based on Kigoriak, $\alpha = 1,25 A^{-0,7}$
F	Polar Sea, North Bering Sea 1983; $B_P = 0,28$, exponent $-0,62$	A	loaded area or local contact area, expressed in square metres (m^2)
G	Polar Sea, Beaufort Sea 1984; $B_P = 0,28$, exponent $-0,74$	α	local pressure parameter, expressed in megapascals (MPa)

Figure A.8-26 — Local pressure parameter α vs local contact area A for Oden, Terry Fox and Polar Sea ship ram trials where design curve corresponds to Kigoriak trials^[181]

The equivalent number of rams, μ , in Formula (A.8-79) should reflect the expected annual number of rams, ν , and the expected duration, t , of each ram in seconds. To illustrate, for an expected interaction duration of 3,5 s, the exposure factor, μ , is adjusted according to 3,5 s divided by 0,7 s, or 5.

Formula (A.8-77) is appropriate when considering a single panel as is usual in design. If the maximum action on n panels is required, an exposure of $n\mu$ should be used instead of μ .

To estimate design pressure, Formula (A8-77) is rewritten as

$$p = x_0 + \alpha \{ -\ln [-\ln F_p(p)] + \ln \mu \} \quad (\text{A.8-80})$$

where x_0 is a constant representing the offset of the design distribution, which is typically negligible.

For design actions corresponding to 10^{-2} and 10^{-4} annual exceedance probability levels, $F_p(p)$ is 0,99 and 0,999 9 respectively. To illustrate the use of Formula A.8-80 for iceberg impacts, local pressure design curves for 10^{-2} and 10^{-4} annual exceedance probability targets for three (3), 3.5 second impacts per year is given in Figure A.8-27.

The model is applicable to local contact areas less than 10 m^2 , and for practical application, local pressures should be capped at a minimum local contact area of $0,6 \text{ m}^2$, consistent with local measurements. For design, x_0 is typically taken as 0 but the designer can choose alternative values based on analysis of appropriate regional local pressure data when available^[181].

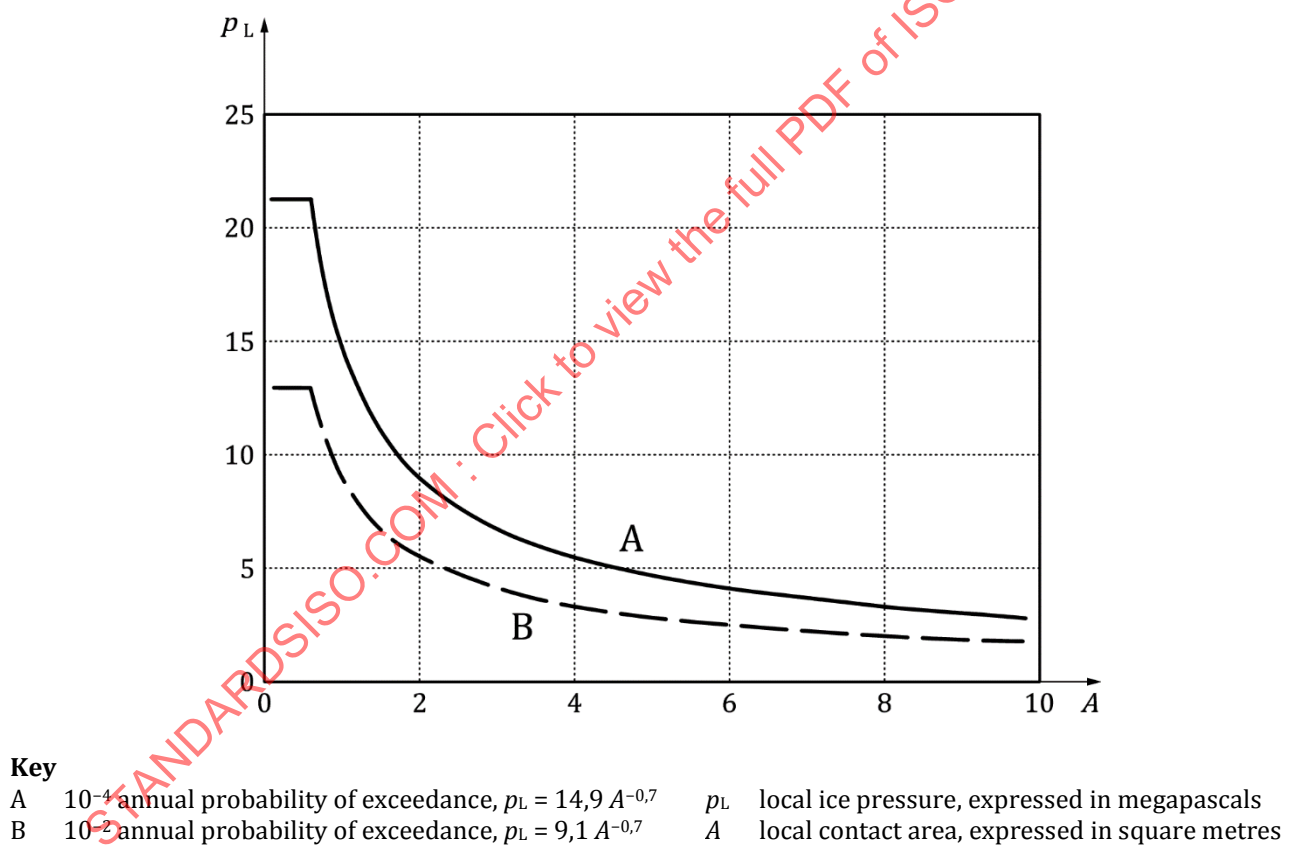


Figure A.8-27 — Illustration of local pressure curves for 10^{-2} and 10^{-4} annual exceedance probabilities for three (3) 3.5 second impacts per year

A.8.2.5.3.2 Long-duration interactions with wide structures

The method outlined in A.8.2.5.3.1 has been extended to model data from continuous MY interaction with the fixed platform Molikpaq^[182]. An approximate analysis of exposure has been deduced. It was found that 10 min (i.e. 600 s) of continuous MY ice exposure with a wide structure such as the Molikpaq was equivalent to one ram of the kind in the Kigoriak trials. This methodology provides an estimate of

exposure for wide fixed structures subjected to longer duration events, recognizing that ice crushing occurs in localized regions of the global contact area for only a small proportion of the total duration.

For such cases, Formula (A.8-77) applies with the following parameters:

$$\begin{aligned}\alpha &= B_P A^{-0,7}; \\ \mu &= \nu \cdot t / 600\end{aligned}\tag{A.8-81}$$

where

- B_P is an empirical coefficient, equal to 1,25;
- ν is the number of MY ice floe interaction events;
- t is the mean duration of each event, expressed in seconds.

For estimation of ν , refer to A.8.2.2.5. It is noted that the model reflects speeds observed during measurements of ice interaction with the Molikpaq platform.

A.8.2.5.4 Local pressures for thick, massive ice features

Local pressures due to massive ice features having a thickness in excess of 1,5 m can be determined using data shown in Figure A.8-28^[183]. These data have been derived from indentation tests in the Beaufort Sea and from measurements made on the ice pressure panels of the Molikpaq structure in the same area. These data are a mixture of different tests with different exposures.

Based on these data, the local pressure, p_L , expressed in megapascals, acting on the loaded area can be determined as given by Formula (A.8-82):

$$\begin{aligned}p_L &= 7,40 A^{-0,70} \quad \text{for } A \leq 10 \text{ m}^2 \\ &= 1,48 \quad \text{for } A > 10 \text{ m}^2\end{aligned}\tag{A.8-82}$$

where A , expressed in square metres, is the local design area (see Figure A.8-24). The basis for this expression, as noted in Figure A.8-28, is the mean plus three times the standard deviation of the data, which were binned according to contact area. It is noted that the probability of exceedance for three times the standard deviation, assuming the data are normally distributed, is 0,13 %.

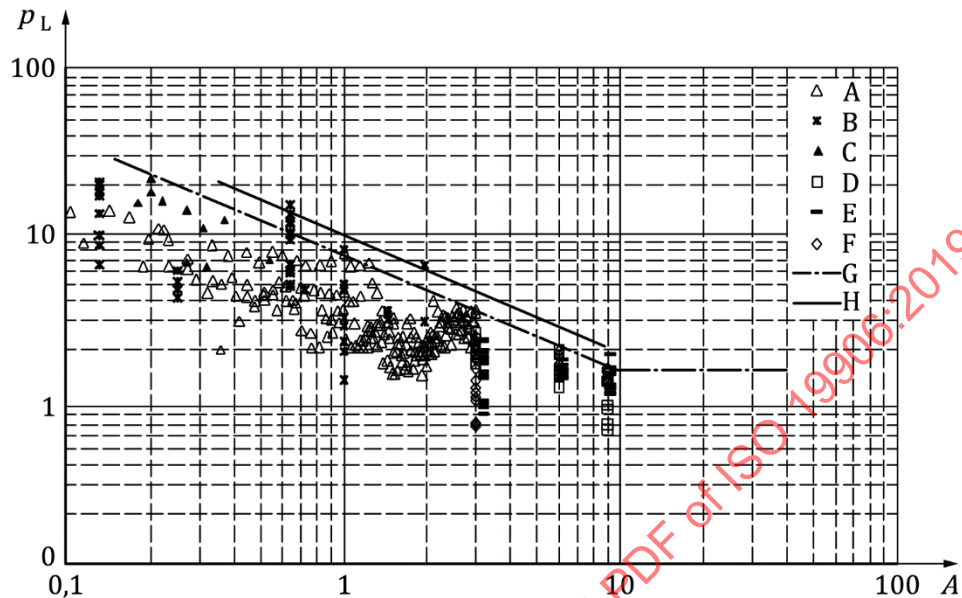
If a 1 % exceedance is applied to the data in Figure A.8-28, a quantile regression analysis^[184] yielded the corresponding formula for local pressure

$$p_L = 9,6 A^{-0,74} \quad \text{for } A < 10 \text{ m}^2\tag{A.8-83}$$

Since this document aims to satisfy EL and AL ice actions at annual exceedance probabilities of 10^{-2} and 10^{-4} , it should be understood that Formulae (A.8-82) and (A.8-83) only represent exceedance probabilities on the pressure data and not values for EL actions. EL and AL values should consider time and the number of interactions in a year, as outlined in A.8.2.5.3.

It is noted that data in Figure A.8-28 do not consider exposure and should be used with caution. Using Formula (A.8-83), and local pressure parameter α according to Formula (A.8-78) with $B_P = 1,25$, the

significance of exposure is illustrated noting that Formula (A.8-82) corresponds to four (4) equivalent impacts per year and a 10^{-2} annual exceedance probability. For further illustration, the expression for 22 impacts per year is provided as line H in Figure A.8-28.



Key

- A 3 m² Pond Inlet test data
- B flat jack test data
- C 1989 Hobsen's Choice test data
- D Molikpaq BW data
- E Molikpaq N face data
- F Molikpaq E face data

- G $p_L = 7,4 A^{-0,7}$, mean plus three times the standard deviation, 4 equivalent rams per year, $A \leq 10 \text{ m}^2$
 $p_L = 1,48$, for $A > 10 \text{ m}^2$
- H $p_L = 9,6 A^{-0,74}$, 22 equivalent rams per year, $A \leq 10 \text{ m}^2$
- p_L local ice pressure, expressed in megapascals
- A local contact area, expressed in square metres

Figure A.8-28 — Compilation of data for ice pressures as a function of the loaded area^[183]

A.8.2.5.5 Local ice pressure combinations

This subclause addresses the simultaneous application of background ice pressures outside of the areas where local ice pressures are applied for local design of the structure, see Figure A.8-24. As shown in Figure A.8-29, a local ice pressure, p_L , is applied over a local area, A , while there can be a lower ice pressure, p_0 , over a much larger portion of the structure with an area, A_0 . For design of plating, the local ice pressure, p_L , might be applied between frames of a transversely-framed (i.e. longitudinally-stiffened) hull structure, while an average ice pressure, p_0 , could be applied simultaneously over the space between bulkheads.

Considering force equilibrium, the ice pressure surrounding the local area is less than p_0 , and can be determined as given by Formula (A.8-84):

$$p_0^p = \frac{p_0 A_0 - p_L A}{A_0 - A} \quad (\text{A.8-84})$$

In Formula (A.8-84), the ice pressure, p_L , is the total pressure over the local area, which is not added to p_0 .

The local ice pressure, p_L , used for design can be obtained from A.8.2.5.2, A.8.2.5.3 or A.8.2.5.4. The global ice pressure, p_0 , applied in conjunction with p_L , can potentially be obtained from Formulas (A.8-21), (A.8-25), (A.8-67) or (A.8-70). The use of an EL value for the local ice pressure, p_L , with an EL value for the surrounding (or global) ice pressure, p_0 , can potentially lead to an overly-conservative design.

In practice, peak global actions and peak local pressures need not occur at the same instant in time, as would be implied by using Formula (A.8-21) for EL ice actions in conjunction with an EL local ice pressure. The designer is encouraged to use available and relevant data to justify more realistic background ice pressures.

Some judgment is also required for determining the combination of local areas and background areas over which ice pressures are applied for use in the design. Some combinations are more critical than others, and the process of determining these is one of trial and error. Because of the considerable variability of structure or hull configurations, no prescriptive set of combinations can be specified.

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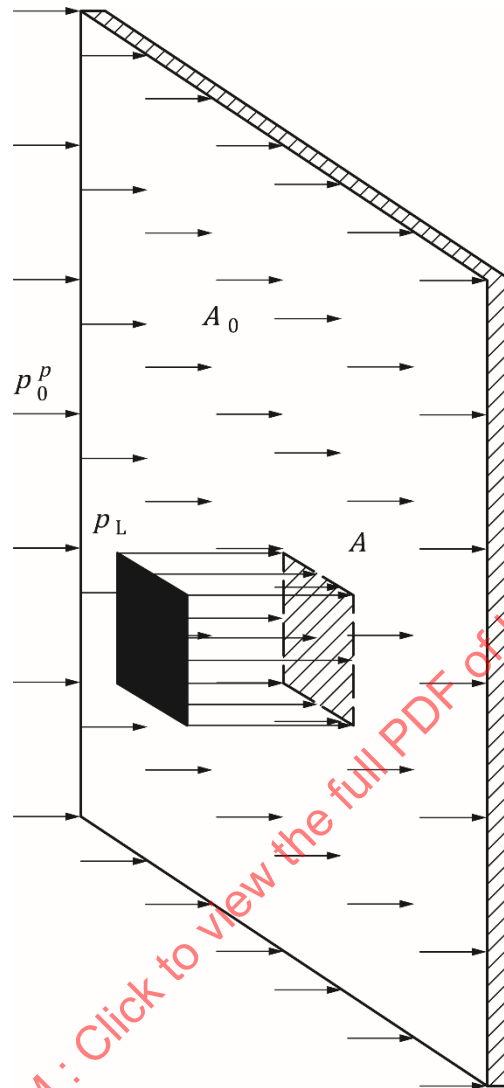
**Key** p_L local ice pressure patch A local contact area, expressed in square metres p_0^p background ice pressure A_0 background area

Figure A.8-29 — Method of combining the local ice pressure with a pressure acting on a larger area

A.8.2.6 Dynamic ice actions

A.8.2.6.1 Dynamic actions on vertical and near-vertical structures

A.8.2.6.1.1 General

Ice-induced vibration is observed for practically all vertical and near-vertical fixed structures exposed to moving ice conditions, such as production platforms in Cook Inlet, the Bohai Sea and the Sea of Okhotsk and lighthouses and light piers in the Baltic Sea. Severity of observed ice-induced vibration varies significantly depending on structural properties and ice conditions.

Ice-induced vibration is observed when the ice fails predominantly by crushing. Figure A.8-30 illustrates the three primary modes of interaction in terms of the ice action, $F(t)$, and the corresponding structural displacement at the ice action point, $u(t)$. These loading traces are typical for vertical and near-vertical piles or multi-legged structures. The dynamic ice-structure interaction process is influenced significantly, but not exclusively, by the ice velocity and the waterline displacement of the structure. As a result, the three modes are not necessarily observed for all structures. In general, all three dynamic ice-structure interaction modes are observed for narrow vertical structures. For wide structures, intermittent crushing has been observed in severe ice conditions^[186]. The processes involved in these three modes of interaction are described in A.8.2.6.1.2.

The structural response in the three primary modes of interaction is important primarily for FLS design. The challenge for FLS design is to determine the combinations of ice drift velocities and ice properties for which each of the three modes can be expected to develop. Guidance for determining velocity ranges associated with frequency lock-in can be found in References [187], [188] and [189]. One aspect of this process is the potential decrease in the load borne by the ice as the ice velocity relative to the structure increases^{[188][189]}.

Frequency lock-in can cause resonant loading and can contribute significantly to fatigue accumulation in structures. This dynamic loading state can cause low-cycle fatigue in steel structures and can also cause liquefaction in the soil foundation. Vibrations can also affect topsides structures, such as flare booms, see 15.1.1.3. The vulnerability of structures to frequency lock-in is addressed in A.8.2.6.1.4.

Once the expected modes of interaction are identified for a structure, the structural response can be determined:

- based on ice action data from a similar structure in similar ice conditions;
- using prescribed force-time histories applied to finite-element or other types of structural dynamics models;
- using numerically-generated loading based on a knowledge of ice mechanics applied to finite-element or other types of structural dynamics models.

In the case of intermittent crushing, the ice action peaks can also be important for ULS design.

When ice action data from other structures are applied, it is emphasized that the dynamic interaction problem is strongly non-linear which puts stringent requirements on the similarity. With numerically-generated loading it is emphasized that different theories regarding the development of ice-induced vibration can result in different predictions. Prescribed force-time histories are given in A.8.2.6.1.3 for intermittent crushing and in A.8.2.6.1.5 for frequency lock-in.

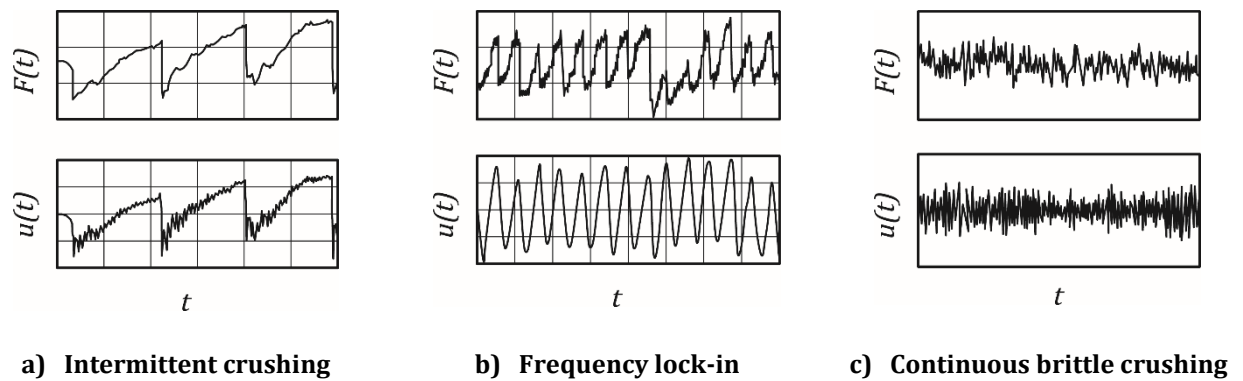
**Key** t time u structure displacement F ice action

Figure A.8-30 — Modes of time-varying action due to ice crushing and the corresponding dynamic structure response. Note that the plots are schematic and the vertical axis of the response in the different modes is not to scale.

A.8.2.6.1.2 Time-varying interaction processes

Intermittent ice crushing, depicted in Figure A.8-30 a), can arise if a compliant structure is exposed to actions from slowly moving ice. The interaction involves load build-up and unloading phases.

During the loading phase, the ice action increases and ice edge contact increases due to local crushing and ductile deformations. The velocity of the structure at the waterline is approximately the ice velocity. Elastic energy accumulates in the structure until local brittle ice failure occurs at the edge of the contact area, which spreads quickly to the entire loaded contact area. During the subsequent ice crushing phase, the structure springs back as the elastic energy of the structure is dissipated in ice crushing and converted into kinetic energy. The responses for the dominant structural modes tend to decay before the next cycle starts.

The structure displacement and ice action time histories at the waterline typically display a sawtooth pattern, growing linearly prior to a rapid unloading phase. A double-stroke waveform has also been observed in full-scale data^[190], with the translational and tilting modes of the superstructure both contributing to the process.

Frequency lock-in, depicted in Figure A.8-30 b), can occur at intermediate ice speeds, with typical speeds for Baltic Sea structures ranging from 0,04 m/s to 0,1 m/s. In this case, the ice failure frequency in crushing adapts to one of the lowest natural frequencies of the structure. Particularly for circumstances with low structural and foundation damping, structural response can be amplified significantly due to resonant behaviour. The period between subsequent sudden ice crushing failures and the amplification depends on the ice properties, the ice velocity and the dynamic properties of the structure. Similar to intermittent crushing, frequency lock-in exhibits alternating phases of ductile loading and brittle unloading.

For frequency lock-in, the motion of the structure is close to sinusoidal while the time history of the ice action depends on the characteristics of both the ice and the structure. Based on field experience, structures with a lowest natural frequency in the range of 0,4 Hz to 10 Hz have experienced frequency lock-in when the total structural damping (as a fraction of critical) has been low.

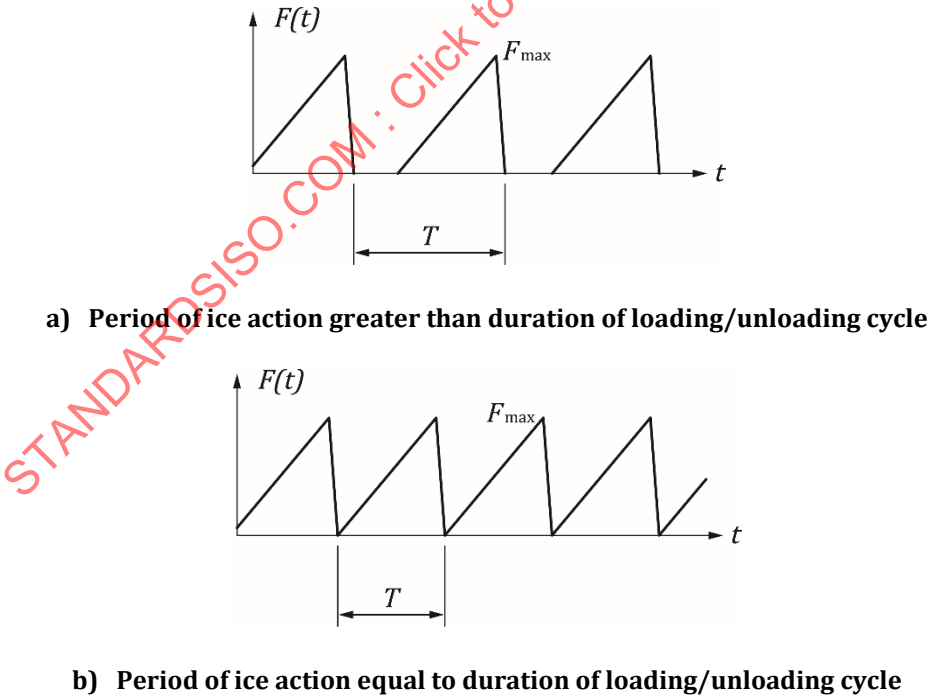
Continuous brittle crushing, Fig. A.8-30 c) shows typical records of the ice action and the structural displacement response at ice velocities well above the maximum velocity for which frequency lock-in occurs. In this case, both the ice action and the response of the structure are random. The response of the structure can be calculated in the frequency domain using the power spectral density for the random ice action.

A.8.2.6.1.3 Dynamic response to intermittent crushing

Figure A.8-31 shows idealized time histories of ice actions that can arise due to intermittent crushing. The ice action build-up and failure cycle period, T , of the ice action is much longer than the longest natural period of the structure. The time history shown in Figure A.8-31 a) can also arise from an ice spalling failure mode where the period, T , of the ice action is longer than the duration of the loading/unloading cycle.

General-purpose FE software can be used to calculate the response of the structure due to these assumed repeating ice actions. The peak action, $F_{\max}$, can be determined by the method described in A.8.2.4.3 as the static global ice action, F_G . For an FLS analysis, the period, T , can be assumed to decrease linearly with increasing ice velocity until a velocity is reached at which frequency lock-in is expected to develop. The number of load cycles can be estimated by dividing the ice movement distance at each ice thickness by the static deflection of the structure for the ice thickness in question.

The dynamic analysis is focused on effects of the decaying oscillations of the structure following unloading. As a result, it is often sufficient to determine the response to a single loading cycle.



Key	
t	time
F	ice action
NOTE Both $F_{\max}$ and T can vary randomly	
$F_{\max}$	maximum value of ice action
T	period of ice action

Figure A.8-31 — Idealized time histories of the ice action due to intermittent crushing

A.8.2.6.1.4 Vulnerability to frequency lock-in

Based on field measurements and observations, the ice failure frequency typically locks in to some of the lowest natural-mode frequencies of the structure. For complex structures, lock-in frequency is not always immediately apparent and an eigenvalue analysis is required to determine the lock-in frequency. The condition of dynamic stability can be used to assess which natural modes are vulnerable to frequency lock-in^{[190][191]}. To ensure dynamic stability of a natural mode, n , the relative modal damping coefficient, ξ_n , of the structure should be larger than the opposite contribution of the ice action to dynamic instability. The damping coefficients, ξ_n , of the lowest natural modes of the structure should be large enough to dissipate the energy inflow due to ice action by satisfying Formula (A.8-85):

$$\xi_n \geq \frac{\phi_{nc}^2}{4\pi f_n M_n} h\theta \quad (\text{A.8-85})$$

where

ξ_n is the structural damping of the natural mode, n , as a fraction of critical;

ϕ_{nc} is the natural mode, n , amplitude at the ice action point;

M_n is the true modal mass, expressed in kilograms, calculated in the same natural mode coordinate system as ϕ_{nc} ;

f_n is the natural frequency of the natural mode, n , expressed in hertz;

h is the level ice thickness, expressed in metres;

θ is a coefficient, the suggested value of which is 40×10^6 kilograms per metre-second.

M_n has to be calculated in the same natural mode coordinate system as ϕ_{nc} .

The suggested value for θ was obtained from ice strength vs stress rate dependence studies from Cook Inlet, see References [192] and [193]. It is noted that this parameter implicitly includes the influence of structure width and ice strength on the contribution of ice action to the dynamic instability. For conditions deviating significantly from those mentioned in the references, the parameter should be adjusted accordingly.

Formula (A.8-85) is used for identifying the natural modes that are vulnerable to vibration associated with frequency lock-in. The dynamic response of the structure can then be calculated based on A.8.2.6.1.5 or by using one of the alternative methods for response calculation suggested in A.8.2.6.1.1.

A.8.2.6.1.5 Dynamic response to frequency lock-in

The dynamic response of the structure for modes below 10 Hz that are susceptible to frequency lock-in, as identified in A.8.2.6.1.4, can be calculated by numerical integration, including all the natural modes up to 20 Hz. A simplified forcing function at the resonant frequency, without any random variations, as shown in Figure A.8-32, can be used to estimate the structural response in the case of frequency lock-in. In this method, the frequency, $f = 1/T$, of the forcing function is assumed to be equal to the frequency of one of the unstable natural modes identified in A.8.2.6.1.4. The analysis presented in this subclause is for a simple structure; a multi-leg structure or piled jetty would require a more complex analysis.

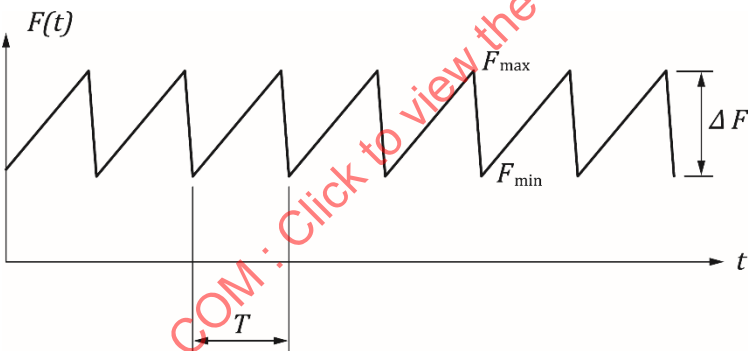
The peak values, $F_{\max}$, as well as the double amplitude, $\Delta F = F_{\max} - F_{\min}$, can be assumed as constant in the ice action time series. The peak value, $F_{\max}$, can be estimated as the global ice action, F_G , on the structure (see A.8.2.4.3). The amplitude range, ΔF , which depends on the natural modes of the structure and the ice velocity, can be expressed as a fraction, q , of the peak action, $F_{\max}$, as given by Formula (A.8-86):

$$\Delta F = q F_{\max}$$

(A.8-86)

An initial estimate for the coefficient, q , can be selected in the range between 0,1 and 0,5. Based on results of the response analysis, the coefficient, q , should then be scaled so that the velocity of the structure at the waterline is 1,4 times the ice velocity for which frequency lock-in has been determined to develop. The factor of 1,4 is used to provide some conservatism in the analysis because it leads to an increased amplitude range.

In the analysis, the duration of the ice action time series should be sufficient to ensure a steady-state response. It is possible that no steady-state response can be obtained for which the velocity response of the structure at the waterline is 1,4 times the ice velocity for the range of parameter, q , defined above. In that case, frequency lock-in cannot occur for the specified combination of ice velocity and peak ice action. When the structure response velocity in the direction of ice movement exceeds the ice velocity, the ice action F becomes zero, preventing further energy inflow from the ice to the structure and the consequent response amplitude growth.



Key

t	time	ΔF	difference between maximum and minimum values of ice action
F	ice action	T	period of ice action
$F_{\max}$	maximum value of ice action		
$F_{\min}$	minimum value of ice action		

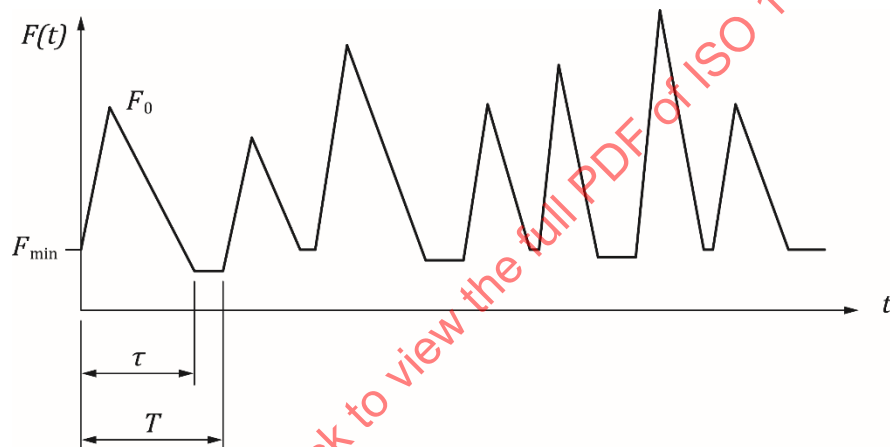
Figure A.8-32 — Assumed ice action history for frequency lock-in conditions

A.8.2.6.2 Dynamic actions on conical and inclined structures

Ice-induced vibration is known to occur with conical structures under certain circumstances and are known not to occur under different circumstances (based on full-scale experience in the Bohai Sea). The physical explanation is due to repeating loading peaks as ice edge climbs up the inclined structure surface and breaks the ice in bending mode. The action level depends on cone angle, ice thickness and contact area. The bending failure distance from the inclined face is typically several times the ice thickness. This, together with the ice velocity and slope angle, determine the distance at which ice failures repeat and the resulting ice bending failure frequency. Hence, at certain conditions a resonant-type forced vibration can occur. However, it is known that the presence of ice rubble accumulations on the conical surface during

interactions mitigates vibration. The scale can also be a determining factor: at a large contact area, random ice failures are more likely due to the existing random cracks produced during previous ice failures. Other factors include the friction coefficient of the conical surface material, and the surface condition of the ice (snow on top of ice increases rubble formation and damping).

Full-scale experience from the Bohai Sea has shown that a conical waterline geometry of the structure reduces the magnitude of horizontal ice actions and ice-induced vibration, as compared to a corresponding vertical structure, regardless of the increased waterline diameter. On the other hand, the same data indicate that structures with a narrow cone at the waterline can still experience ice bending-failure-rate dependent ice-induced vibration. The vibration is enhanced when stable ice rubble does not form on the front face of the cone. The time history for this kind of ice action is illustrated in Figure A.8-33. The dynamic response of the structure due to this kind of random forcing function is less than that due to frequency lock-in on a similar waterline diameter vertical structure.



Key

t	time	$F_{\min}$	minimum value of ice action
F	ice action	τ	duration of loading/unloading cycle
F_0	peak value of ice action	T	period of ice action

Figure A.8-33 — Idealized time history of the horizontal action on a conical structure

The time-varying action, $F(t)$, is a function of several parameters, including the width of the structure, slope angle and the frictional actions involved. The stationary action component $F_{\min}$ arises mainly from the ice rubble that is present on the face of a conical or sloping structure. Vibrations have been recorded in the Bohai Sea ice regime on multi-leg structures that have cones with a waterline diameter of 4 m. Due to an effective clearing of the ice rubble, the stationary action component has been in the range of $F_{\min} = 0,1F_{0,\max}$ on these structures. For other measurements in the Baltic Sea, severe vibration did not occur for a conical structure with a waterline diameter of 10 m. The prevailing stationary action component was found to be around $F_{\min} = 0,45F_{0,\max}$ in this case.

The peak action, F_0 , can be considered as a random parameter that follows a normal distribution. The maximum value, $F_{0,\max}$, of this parameter can be estimated using instructions given in A.8.2.4.4. According to field data on narrow cones where the action component, $F_{\min}$, is very small, the coefficient of variation of the peak values can vary from 0,20 to 0,60 in different events. Consequently, it is suggested that the coefficient of variation for the double amplitude, $\Delta F = F_0 - F_{\min}$, of the time-varying action be 0,40.

Assuming that the maximum value corresponds to a non-exceedance probability of 0,95, the mean value of the random peak action can be estimated as given by Formula (A.8-87):

$$F_{0,\text{mean}} = F_{\text{min}} + 0,56(F_{0,\text{max}} - F_{\text{min}}) \quad (\text{A.8-87})$$

The period between action peaks can be calculated as given by Formula (A.8-88):

$$T = \frac{l_b}{v} \quad (\text{A.8-88})$$

where

l_b is the breaking length of the ice sheet;

v is the ice velocity.

The ice breaking length, l_b , is a function of ice thickness, ice strength, structure diameter and ice drift velocity. It varies in the range of 3 to 10 times the ice thickness, and this ratio typically decreases with increasing ice thickness and ice velocity. The period between two individual peaks is a random parameter with a coefficient of variation of 0,40 to 0,70. As an average, the standard deviation can be assumed to be 0,50 times the mean value of the action period.

The ratio of the duration of the actual action pulse, τ , to the average period, T , can vary between 0,3 and 1,0.

A.8.2.6.3 Fatigue accumulation due to ice actions

The fatigue of an offshore structure and its foundation (see 9.4.7, 11.8 and 12.3.5.3) results from the cumulative effect of wave, wind and ice actions. Fatigue resulting from ice actions should be analysed to the same level of detail as that from metocean actions. Fatigue should be assessed over the design service life based on the difference between the maximum and minimum stresses over continuous time records.

For the assessment of fatigue life, a basic service period of one year can be considered. The different kinds of ice actions that occur within this period are classified by defining a set of action processes $F_k(t)$ for $k = 1, 2, \dots$. Typical action processes include:

- time-varying quasi-static actions due to ice thickness, rafting and water level variations;
- ridge actions;
- time-varying actions due to intermittent ice crushing;
- dynamic actions due to continuous ice crushing;
- vibration due to ice crushing or flexural failure of level ice or rafted ice.

Each of the action processes is analysed on a statistical basis. The analyses yield a set of ice action spectra $\Delta F(\eta^k)$, where η^k is the number of ice actions that vary at an amplitude ΔF during the service period of one year. The amplitude, ΔF , of the ice action is defined as the difference between a peak value and the

subsequent minimum value. Different ΔF ranges and the number of cycles at each range can be determined by e.g. the Rainflow method. The effects of dynamic amplification should be considered in the determination of the spectrum when vibration arises due to dynamic action processes.

The accumulation of fatigue damage is determined separately for each of the action spectra. The total damage due to ice actions is then obtained as a linear accumulation of the damage due to the individual action spectra as given in Formula (A.8-89):

$$D_{\text{ice}} = \sum_k D^k \quad (\text{A.8-89})$$

where

D^k are the damage accumulations due to the individual ice action spectra;

D_{ice} is the total damage due to ice actions.

Specific guidelines for determining the cumulative damage depend on the structure characteristics under consideration.

A.8.2.7 Operational measures to reduce ice actions

A variety of operational measures can be used to modify the frequency and the magnitude of ice actions. Active IM techniques are considered in Clause 17, while passive techniques (such as spray-ice or other barriers) are considered in Clause 16. These can have a major influence on the representative actions used for design, and can allow floating production structures and lightly reinforced structures to operate in ice environments.

When operational measures are used to reduce ice actions, a key aspect is the quantification of success of such measures. It can be difficult to assess success a priori, and the best benchmark of anticipated success is likely to be past success under operational conditions. Kulluk ice action data^[170] show that actions in managed ice with good clearing were significantly less than actions in unbroken ice less than 1,5 m thick. In spite of this, it is the reduction in actions for the conditions contributing to the representative ice actions that is most relevant.

Although ice actions can be reduced through icebreaking and iceberg deflection, there are circumstances when the ice is unmanageable or not easily managed. Examples can involve thick sea ice that cannot be managed using the available icebreaker fleet or icebergs that are too large to deflect. Consequently, it is important that management success be ascertained based on site-specific ice conditions and the capabilities of the IM system. Reference should be made to Clause 17 to ensure proper characterization of IM performance.

Ice actions due to managed sea ice can require special treatment because of the presence of large quantities of broken ice. The best approach is to use full-scale data, and the analysis of ice actions should reflect the particular ice environment and expected management resources.

Changes to ice actions as a result of IM measures can be reflected in the hazard curve through the use of fault trees. Particular attention should be given to ensuring that estimates of success associated with

these measures reflect the uncertainties in the specification of physical environmental parameters and the effects of the physical environment on these measures.

A.8.2.8 Physical and mechanical properties of ice

A.8.2.8.1 Overview of physical and mechanical properties of ice

Physical and mechanical properties of ice are needed for the calculation of ice actions on structures. Furthermore, knowledge about the properties is required in order to compare different full-scale measurements on ice actions and to simulate full-scale conditions in model tests. Special care should be given to model tests in broken ice, as the broken ice properties in model scale and full scale should be measured in a similar way.

Mechanical properties of ice have been studied for many decades, and reliable dependencies have been established between physical properties (temperature, salinity, density) of ice and its strength parameters. Engineers can choose to use these dependencies instead of new strength tests. If a designer decides to perform new strength tests anyway, these new tests should be conducted following the International Association of Hydraulic Engineering and Research (IAHR) procedures for strength tests^[194].

Measures of ice strength can not only reflect ice properties but can also depend on the testing equipment. Depending on the type of ice event, knowledge of the following list of parameters can be required for the calculation of ice actions on marine structures:

- compressive strength;
- tensile/flexural strength;
- fracture toughness;
- friction, adhesion;
- shear strength and cohesion of ice rubble;
- elastic modulus;
- density.

Some ice events can create a shear failure across an ice sheet. Compressive strength and the tensile strength can be used in such cases to establish the failure criterion. Therefore, shear strength is not considered herein as an independent material parameter.

Locally grown sea ice covers consist mostly of vertical columns with a random horizontal *c*-axis. At consistent current direction, the *c*-axis can be oriented, which has an effect on strength properties. The grain size of the columnar ice increases with the ice cover depth.

Icebergs and some sea ice features can consist of granular ice, composed of generally equi-dimensional crystals with a random crystallographic orientation.

In contrast to freshwater ice, sea ice crystals have a substructure that consists of parallel platelets, between which brine pockets are distributed. These brine pockets reduce the strength of sea ice relative to that of freshwater ice.

For most of the mechanical properties of sea ice, the strength has been related by experiments to the brine volume or the total porosity, which is the sum of the relative brine volume and the relative air volume. Brine volume and porosity determination methods are provided in A.6.5.1.4.

A.8.2.8.2 Compressive strength

A.8.2.8.2.1 General

The compressive strength of sea ice depends on the brine volume, the amount of air entrapment, the action direction relative to the sample and/or crystal orientation, grain size, strain rate, multi-axiality of the stress state, temperature and ice type (columnar or granular).

Most common in ice mechanics is the uniaxial compressive strength, which is used for theoretical calculations of ice actions on marine structures. To generate information on uniaxial strength, ice specimens are loaded along one axis but not along the two others. However, real ice-structure interaction can cause complex three-dimensional states of stress (as discussed in A.8.2.4.3.1), and a more relevant concept for these theoretical calculations is a three-dimensional failure envelope, in which the ice strength data as a function of multi-axial state of stress are also considered. These strength data are typically obtained from ice specimens loaded along the three (*XYZ*) axes, referred to as triaxial tests. These can be generated from ice specimens inside a pressure cell that are loaded along one axis at a given confinement pressure (see Reference [195]). They can also be generated via true multiaxial loading tests using cubic specimens, allowing independent control in each of the three loading directions (see Reference [196]).

A.8.2.8.2.2 Uniaxial compressive strength of FY ice

The uniaxial compressive strength has its maximum at a strain rate of approximately $\dot{\varepsilon} = 10^{-3} \text{ s}^{-1}$, where the ice fails at the transition between ductile and brittle deformation. If a designer has no information about the actual strain-rate range in the design scenario, a strain rate of 10^{-3} s^{-1} should be applied. The influence of the ice texture and action direction on uniaxial compressive strength of FY sea ice has been tested extensively. In References [197] and [198], experimental fits were made on data from more than 500 experiments on FY sea ice. Reference [197] provides mean values, whereas Reference [198] provides an upper envelope.

The data of Reference [197] include a porosity range from 0,03 to 0,19 (only up to 0,12 for vertical columnar ice) and a strain-rate range from 10^{-7} s^{-1} to 10^{-3} s^{-1} , and Formulae (A.8-90) to (A.8-92) represent the mean value, expressed in megapascals, of respectively horizontally loaded columnar sea ice, vertically loaded columnar sea ice and granular sea ice as a function of both total porosity (ν_t , given as a fraction between 0 and 1) and strain-rate ($\dot{\varepsilon}$).

$$\sigma_c = 37 \dot{\varepsilon}^{0,22} \left(1 - \sqrt{\frac{\nu_t}{0,27}} \right) \quad (\text{A.8-90})$$

For vertically loaded columnar ice, the uniaxial strength, σ_c , is given by Formula (A.8-91):

$$\sigma_c = 160 \dot{\varepsilon}^{0,22} \left(1 - \sqrt{\frac{v_t}{0,20}} \right) \quad (\text{A.8-91})$$

For granular sea ice (composed of granular crystals usually with a random c -axis orientation), the uniaxial strength, σ_c , is given by Formula (A.8-92):

$$\sigma_c = 49 \dot{\varepsilon}^{0,22} \left(1 - \sqrt{\frac{v_t}{0,28}} \right) \quad (\text{A.8-92})$$

The data of Reference [198] include a porosity range from 0,02 to 0,38 and a constant nominal strain-rate of 10^{-3} s^{-1} . Formulae (A.8-93) and (A.8-94) provide an upper limit, expressed in megapascals, of the data for respectively horizontally and vertically loaded sea ice:

$$\sigma_c = 8 \left(1 - \sqrt{\frac{v_t}{0,7}} \right)^2 \quad (\text{A.8-93})$$

$$\sigma_c = 24 \left(1 - \sqrt{\frac{v_t}{0,7}} \right)^2 \quad (\text{A.8-94})$$

where the porosity is given as a fraction between 0 and 1.

Formulae (A.8-90) to (A.8-94) are based on experiments on FY sea ice and their application should be limited to that ice type.

A.8.2.8.2.3 Uniaxial compressive strength of MY ice

Measurements on the compressive strength of MY ice have shown that:

- strength values of MY ice range from 4 MPa to 12 MPa, depending upon the strain rate;
- the strength of MY ice is similar to the strength of FY ice when the ice is very cold (i.e. -20°C); but
- MY ice is considerably stronger than FY ice when the ice temperature is warmer.

A.8.2.8.2.4 Ice strength under multi-axial stress state

Multi-axiality of the stress state has a large effect on the strength of ice and on its mode of failure. Under triaxial loading, the confining stresses tend to suppress cracking and increase ductility, which can lead to an increase in strength. It is useful to express ice strength under multi-axial loading as a three-dimensional failure envelope that can change with the brine volume, air bubble content, grain size, strain rate, temperature and ice type (columnar or granular).

Ideally, failure envelopes for FY and MY sea ice can be developed from site-specific strength tests performed under multi-axial stress conditions. More practically, a simplified envelope can be developed

from existing multi-axial field data from other sites and laboratory test data, with due consideration for differences in ice composition and temperature.

A.8.2.8.2.5 Ice borehole strength

The borehole jack has been used extensively to characterize the in situ strength of ice and to determine a relative strength index. The jack consists of a high strength, stainless steel hydraulic cylinder with a piston, or actuator, onto which is attached a curved indenter plate that pushes on the opposite sidewalls of an ice borehole. The borehole compression test measures the ice strength in a three-dimensional stress state. The tests are conducted in situ, which minimizes changes in the physical properties of the ice (brine drainage, for instance) prior to testing.

The mechanical analysis of borehole experiments is more challenging than for small-scale laboratory experiments^[199]. Several failure modes are typically observed, and the definition of the borehole strength, p_u , depends on the failure mode^{[199][200][201]}. When expressed over the full thickness of the ice, the depth-averaged borehole strength ranges from 3 MPa to 30 MPa for FY sea ice^[202] and up to 34 MPa for MY sea ice^[200] over the range of ice temperatures tested. Strengths of 49 MPa have been measured in cold MY ice^[200], which is considerably higher than the 32 MPa maximum borehole strength of cold FY ice^[202].

Attempts have been made to relate the borehole strength, p_u , to uniaxial compressive strength, σ_c , i.e. Formula (A.8-95):

$$s_{\min} \sigma_c \leq p_u \leq s_{\max} \sigma_c \quad (\text{A.8-95})$$

where $s_{\min}$ and $s_{\max}$ are empirically determined constants. Reference [203] gives $s_{\min} = 2$, $s_{\max} = 4$, whereas Reference [204] gives 3, 5 and 5. Considering the wide range of coefficients to relate borehole strength to uniaxial compressive strength, borehole jack test results provide a relative strength index that correlates with uniaxial compressive strength.

Results of borehole jack tests can be used to estimate the thickness of the fully consolidated layer in ice ridges and to qualitatively compare severity of ice conditions in different areas when, for example, comparing and analysing ice actions measured on a specific structure.

A.8.2.8.3 Flexural strength

The flexural strength of ice sheets, rafted ice and the consolidated layer of ridges is used for estimating ice actions on sloping structures. A nominal flexural strength is usually defined under the assumption of linear elastic brittle first-order beam theory for a homogeneous material.

The nominal flexural strength is often measured either by:

- the simple beam test with four-point action application, more reliable than the three-point application; or
- the cantilever beam test, preferable for in situ conditions. A cantilever, fixed at one end, is formed by cutting and then removing ice from three sides of a rectangle. The cantilever is then loaded at the free end.

Cantilever beam tests promote stress concentrations at the beam root, but the effect is less than predicted by purely elastic analysis^{[205][206][207]}. The cantilever beam (or 4-point bending specimen) needs to be relatively long and narrow for standard formulae to give reasonable results. Commonly, the length of cantilever beams should be 6 times the thickness and the width less than 2 times the thickness. In longer beams, the effect of the water foundation will be noticeable. If site-specific tests or small-scale tests are conducted, the recommendations on testing methods^[194] should be taken into account. Based on a large number of experiments, the mean of flexural strength, σ_f , expressed in megapascals, of sea ice as a function of brine volume^[208], is given by Formula (A.8-96):

$$\sigma_f = 1,76 \exp\left(-5,88 v_b^{1/2}\right) \quad (\text{A.8-96})$$

where v_b is the brine volume fraction.

For sea ice, the downward breaking in situ flexural strength, σ_f , has typical values of 0,3 MPa to 0,5 MPa for winter, while values of 0,2 MPa are typical for warmer conditions^[209].

A.8.2.8.4 Tensile strength

The tensile strength is measured directly with an ice specimen that has been machined in the shape of a dumbbell, where the larger end-surfaces are frozen to end cups, which are connected to the testing machine. The tensile strength is nearly independent of the strain rate in the range of $10^{-5}/\text{s}$ to $10^{-3}/\text{s}$.

The tensile strength in the growth (vertical) direction of columnar-grained ice is about twice as high as in the horizontal direction (see Table A.8-6). The tensile strength depends on the brine volume of the sea ice.

Table A.8-6 — Tensile strength values

Temperature °C	Ice type	Salinity g/kg	Action direction	
			Vertical MPa	Horizontal MPa
-10	sea ice	4 to 6	1,7	0,9
-10	Baltic ice	0,2	2,2	1,0

Based on the data shown in Table A.8-6, the tensile strength can be expressed as given by Formula (A.8-97) for the vertical direction and Formula (A.8-98) for the horizontal direction^{[210][211]}:

$$\sigma_t = 2,2[1 - (v_b/0,31)^{1/2}] \quad (\text{A.8-97})$$

$$\sigma_t = 1,0[1 - (v_b/0,14)^{1/2}] \quad (\text{A.8-98})$$

where

v_b is the brine volume fraction;

σ_t is the tensile strength, expressed in megapascals.

MY ice can consist of mixtures of granular and columnar grains. While there are limited data on the tensile strength of MY ice, available measurements suggest that the tensile strength of MY ice can vary in the range from 0,5 MPa to 1,5 MPa^[212].

A.8.2.8.5 Shear strength

Shear failure can be a relevant action-limiting mechanism for which an example is shown in Figure A.8-10. Ice is seldom in a state of pure shear while acting on a structure, and the effect of tensile and compressive normal stresses should be assessed when calculating ice failure actions.

Reported values of shear strength vary in a range from 0,2 MPa to 2,5 MPa. This range is wide due to the difficulty in excluding the effects of the normal stress from the shear strength values. Limited but consistent data indicate that the shear strength varies in the range from 0,4 MPa to 1,3 MPa.

Full-scale experimental data are scarce. "Bone-shaped" torsion test beams produce pure shear without side effects due to normal stresses or stress concentrations. In situ beams with a cross-section of approximately 0,4 m × 0,4 m for Baltic Sea ice (1 g/kg salinity) had a shear strength of 0,6 MPa^[213].

The shear strength also depends on brine volume or total porosity. Small-scale tests described in Reference [214] indicate that the shear strength can be expressed as given by Formula (A.8-99):

$$\tau = 1,5 \left(1 - \sqrt{\frac{\nu_t}{3,9}} \right) \quad (\text{A.8-99})$$

where

- ν_t is the total void volume fraction (brine and air);
- τ is the shear strength, expressed in megapascals.

A.8.2.8.6 Fracture properties

As sea ice is a brittle or quasi-brittle material, fracture mechanics can be used to describe its mechanical behaviour. The simplest approach is to use a one-parameter criterion and quantify the fracture toughness, K_{Ic} (which equals the critical stress intensity factor). Experiments on Mode I fracture have been done, both in laboratories and in the field^[215]. Fracture toughnesses derived from laboratory-scale experiments are about 100 kPa·m^{1/2}, whereas the full-scale experiments argue for a size effect and values of about 250 kPa·m^{1/2} were derived. However, the usefulness of one-parameter fracture mechanics is questionable. A more advanced model is the visco-elastic cohesive crack model^[216]. This is an energy-based model that predicts crack growth initiation when a certain amount of energy is dissipated in a Fracture Process Zone in front of the crack tip. Material softening occurs and has been measured in this zone. The energy criterion is expressed through a stress-separation curve.

A.8.2.8.7 Friction coefficient

Frictional effects influence the ice actions acting on sloping and conical structures. Friction tests have been carried out in laboratories as well as in the field to establish the friction coefficient between ice and

material surfaces, such as concrete and steel of various conditions (corroded, smooth, painted, low-friction coatings).

The influence of the following parameters has been investigated in laboratory conditions: static versus kinetic friction, normal action, relative velocity, surface roughness, ice temperature and surface lubrication by the seawater. Test results show that:

- the static friction coefficient has been measured to be up to five times greater than the kinetic friction coefficient at 0,1 m/s, and higher ratios are possible;
- the kinetic friction coefficient decreases with increasing contact pressure;
- the coefficient of kinetic friction increases with a decrease of the sliding velocity and also with a decrease of temperature;
- the seawater that can be present at the ice-structure interface does not materially influence the kinetic friction.

Kinetic friction coefficients for ice against steel and concrete, based on laboratory measurements, are shown in Table A.8-7, based on References [217] and [218]. If the sliding speed, v_s , is not known, the coefficients for $v_s \leq 0,01$ m/s should be used. Other values can be used if supported by experimental data.

Ice-ice friction decreases with increasing sliding speed, from a maximum of $\mu = 1$ at $v_s = 10^{-6}$ m/s to $\mu = 0,02$ at $v_s = 1$ m/s, with $\mu = 0,1$ at $v_s = 10^{-2}$ m/s^[219]. If v_s is not known, a value of $\mu = 0,1$ is recommended.

Depending on the design scenario, temperature and memory effects of ice-ice friction potentially need to be considered^[220].

Table A.8-7 — Measured values of kinetic friction coefficient

Construction material	Influence of sliding velocity					
	v_s					
	$v_s \leq 0,01$ m/s		$v_s = 0,1$ m/s		$v_s = 0,5$ m/s	
	mean	st. dev.	mean	st. dev.	mean	st. dev.
Smooth steel	0,10	0,02	0,05	0,01	0,05	0,01
Smooth concrete	0,12	0,02	0,05	0,015	0,05	0,01
Corroded steel	0,15	0,03	0,10	0,03	0,10	0,03
Rough concrete	0,22	0,05	0,10	0,03	0,10	0,03

A.8.2.8.8 Material parameters for unconsolidated part of FY ice ridge keels (rubble properties)

Any ice rubble property is partly a function of the formation process and partly of the consolidation during its lifetime. The strength of ice rubble can be described in a continuum sense through parameters describing the shear and volumetric behaviours, or through the discrete element approach. The current ice rubble action formulation (see A.8.2.4.5) applies the Mohr-Coulomb criterion, which includes the two parameters of friction angle and cohesion. A relatively wide range of these properties has been reported, partly due to different experimental set-ups and different ways of relating measured forces to the shear and normal stresses used in the Mohr-Coulomb criterion, and partly due to natural variations. Another reason is that the Mohr-Coulomb criterion does not account for the dependence of the friction angle on

volumetric changes^[221], so when those changes occur the friction angle does not have a unique value. In the following, friction angle and cohesion from Mohr-Coulomb material and rubble porosity will be treated. They all vary in time and space, so any choice of single values should be made with care.

Friction angles from 10° to 80° can be found in the literature, but in the review in Reference [222] a range from 25° to 45° is recommended.

Reported rubble cohesion values vary from 0 kPa to 100 kPa and all of these values are potentially realistic. Firstly, there is a difference between ice rubble peak-action and ice rubble action during continuous deformation. In continuous deformation the cohesion is much lower, perhaps close to zero^[223]. Secondly, the cohesion should vary through the depth and be a function of the keel depth. The highest cohesion is probably that between the consolidated layer and the rubble. As with other phenomenological parameters, rubble cohesion can neither be directly linked to, nor quantified through, physical phenomena. Nevertheless, it is reasonable to assume that the compressive state and the strength of the ice matrix and the initial freeze-bonding play important roles. Freeze-bonds are known to become stronger when formed from cold ice during high confinement^[224], so that the cohesion can be stronger in a larger keel formed from colder ice. In Reference [225] full-scale experiments were conducted in the Baltic Sea and analysed, from which a constant (in space) and peak (in time) rubble cohesion of about 10 kPa was estimated. Laboratory and full-scale experiments indicate that the cohesion is a function of block thickness, and the cohesion/block thickness ratio derived directly from full-scale experiments is about 20 kPa/m^[222]. The rationale for such a dependency is not clear.

The rubble macroporosity, here called rubble porosity, is determined by drilling holes in a ridge and dividing the cumulative lengths of voids and weak ice by the total length of the borehole (as measured in the drill holes). Values between 30 % and 40 % are often determined (see References [226], [227] and [228]), although Reference [229] gives limits of 12 % to 28 %. The porosity varies in both time and space. The spatial variation in the Baltic Sea is different than that observed in other places. In the Baltic Sea, References [226] and [227] reported the highest porosities in the lower parts (50 %), but also reported a mid-keel porosity minimum. Reports from other oceans suggest an increasing porosity downwards throughout the rubble, starting from about 20 % below the consolidated layer and increasing to 50 % close to the keel bottom^[230]. This difference between these locations can have to do with the time at which the ridges were examined, and in differences in the consolidation/deterioration processes in the low-salinity Baltic and high-salinity ocean waters. Temporally, the rubble porosity changes throughout the season, and it seems that the porosity decrease accelerates during the ridge deterioration, or decay, phase in late spring and summer. Rubble porosities in FY ridges in early melt season as low as 10 % have been determined^[230].

A.8.2.8.9 Elastic modulus and Poisson ratio

A distinction should be made between the 'true' (Young's, E) and 'effective' (quasi-static, E_f) elastic moduli. Young's modulus is representative of deformation mechanisms of a purely elastic, time-independent nature, and is obtained from dynamic measurements (e.g. acoustic), involving extremely high deformation rates. The effective modulus is for processes involving time-dependent recoverable strain, and non-elastic non-recoverable deformation (creep). The effective modulus is significantly lower at lower strain rates, in most scenarios of engineering relevance^{[231][232]}.

The effective modulus, E_f , varies as a function of temperature, time and brine content. For saline ice, temperature is factored in the brine content determination (see A.6.5.1). The relationship between E_f and the brine volume, v_b , follows Reference [233].

$$E_f = 5,31 - 0,436 v_b^{0,5} \quad (\text{A.8-100})$$

where

v_b is the brine volume fraction;
 E_f is the effective elastic modulus.

In determining representative values of ice actions in cases when no information is available on loading rate or brine volume, values of 3 GPa and 5 GPa for the effective elastic modulus can be considered representative for saline and freshwater ice, respectively.

The Poisson ratio for ice is 0,33 assuming a purely elastic behaviour. However, as is the case for the elastic modulus, it is the 'effective' Poisson ratio that is relevant for most engineering applications^{[234][212]}. This ratio incorporates some deformation of non-elastic, or creep, nature. A value of 0,42 is recommended^[235].

A.8.2.8.10 Density

There are several different methods to measure the density of ice, ρ_i . The most common technique is the mass/volume technique whereby an ice block is cut from an ice sheet and trimmed to a standard size, which provides the volume. Weighing the sample provides the mass. The ice density is then calculated as given by Formula (A.8-101):

$$\rho_i = \frac{m}{V} \quad (\text{A.8-101})$$

where

V is the volume of the ice sample;
 m is the mass of the ice sample.

Other methods can be more accurate, but are also more difficult to perform in the field^{[236][212][237]}. Measurements conducted by a large number of researchers^{[236][212]} show that:

- sea ice density ranges between 720 kg/m³ and 920 kg/m³;
- in situ densities are different above and below the waterline;
- above the waterline, the density ranges from 840 kg/m³ to 910 kg/m³ for FY ice and from 720 kg/m³ to 910 kg/m³ for MY ice;
- below the waterline, the density is more consistent, ranging from 900 kg/m³ to 920 kg/m³ for both types of ice.

Ice density, water density and rubble porosity can be used to determine the effective buoyancy of an ice ridge keel, as per Formula (A.8-52). If applying estimates for the ice density in ice action calculations, the uncertainty regarding density can have a significant impact on the results. As the rubble volume can change during a ridge-structure interaction event, the ice rubble density can also change. Particular care is needed for modelling of density in ice model basins, due to deviations between water density and ice rubble density from full-scale magnitudes. Numerical methods can be used to assess these sensitivities.

A.8.3 Metocean related actions

A.8.3.1 Metocean actions on structures

A.8.3.1.1 General

Guidance and requirements concerning the actions of winds, waves and currents on steel-framed structures, large volume and gravity structures, and floating systems and moorings are given in ISO 19901-1 (metocean), ISO 19902 (fixed steel structures), ISO 19903 (fixed concrete structures), and ISO 19904-1 (floating systems).

A.8.3.1.2 Snow accumulation on the structure

No additional guidance is offered.

A.8.3.1.3 Ice accumulation on the structure

A.8.3.1.3.1 General

Guidance with respect to atmospheric and saltwater spray-ice accumulations is provided in A.6.3.5.

Pieces of floating ice can accumulate and lodge between the members of a structure within the splash zone. Hydrodynamic actions on the ice are transmitted into the structure and add to the horizontal action.

The growth of ice on piles (ice bustle) can also increase the waterline area and, thus, cause an increase of the horizontal actions from waves and currents. When the water level decreases, water left on the pile freezes and ice accumulates. Similarly, ice accumulations on the surface of sloping structures make these structures steeper, and possibly increase the non-linear amplification of water surface elevations. Ice actions associated with ice bustles are covered in A.8.2.4.10.

A.8.3.1.3.2 Wave and current actions

No additional guidance is offered.

A.8.3.1.3.3 Wind actions

No additional guidance is offered.

A.8.3.1.3.4 Dynamic and static responses

Information on static, dynamic and stability analyses is contained in the document relevant to the structure type, i.e. ISO 19902, ISO 19903 and ISO 19904-1. Additional information on the stability of floating systems in intact and damaged conditions is contained in 13.6.

The presence of ice can lead to unexpected action effects, for example, torsion in members due to an eccentric accumulation of ice.

The mass of the icing adds additional static vertical actions that can be considerably offset from the centre of gravity of the ice-free structure. The vertical actions can influence static position, stability, resistance to other actions and dynamic response. For a floating system, the consequences of additional offset mass can include list, increase in draught, and reduction of freeboard, any of which can increase the possibility of green water (or floating ice) impacting the deck. Changes in the metacentric height can have consequences for stability, roll and pitch stiffness, and responses.

A.8.3.1.4 Particular considerations for large-volume structures

Information on model testing in general and large-volume structures in particular can be found in ISO 19903. Some of the non-linear features associated with the interactions of waves with large-volume structures are described in Reference [238].

Hydrodynamic effects on ice impact conditions are addressed in A.8.2.4.7.

A.8.3.1.5 Freeboard and deck elevation

No additional guidance is offered.

A.8.3.2 Wave-induced velocity of ice features

The addition of wave and current velocities is a vector process. The largest sum is obtained by combining the current with the particle velocity, either at the wave crest or at the wave trough. The relative magnitude of the two cases depends on the difference in direction between the wave and the current.

Pieces of ice with maximum dimension less than $1/15$ of the incident wavelength can be conservatively assumed to follow the water particle velocity. For pieces of floating ice with horizontal dimensions of $1/15$ of the incident wavelength and greater, this approach becomes less accurate and generally overestimates the velocity of the ice induced by the incident wave field. Their velocities can be obtained by solving their equations of motion. Diffraction analysis (including linear and slow-drift effects) can be used to calculate wave actions on the ice. Wind, current and wave drag actions can be obtained from drag models. Computational fluid dynamics or model testing can also be used to estimate induced velocities and actions.

The effect of slopes and changes in water depth has been described in Reference [239].

A procedure has been described for calculating the probability distribution of the velocity of an ice mass in the presence of waves^[240]. This approach assumes that the ice mass follows the water particle velocity, that the wave-induced velocity follows a standardized normal distribution, and that the surge velocity at

impact is proportional to the sum of the drift and wave-induced velocities. Based on these assumptions, it can be determined that the ice collision velocity follows a “Special Rayleigh” distribution.

In the evaluation of the structural consequences of ice impact, reference can be made to the sections on collision and impact damage in the ISO document for the type of structure of interest.

A.8.4 Seismic actions

No additional guidance is offered.

A.9 Foundation design

A.9.1 General

No additional guidance is offered.

A.9.2 Geotechnical data acquisition and identification of hazards

A.9.2.1 General

Reference should be made to ISO 19901-4 and ISO 19901-8 for further guidance on site investigations in temperate waters. In the following sections, no further guidance is given unless arctic-specific and cold region-specific.

A.9.2.2 Bathymetry survey

No additional guidance is offered.

A.9.2.3 Geophysical survey

No additional guidance is offered.

A.9.2.4 Geotechnical investigation

Guidelines for the description of frozen soils are provided in Table 2.1 of Reference [241]. This table provides an approach to describe visible and non-visible ice in soil samples, for use in addition to the standard soil description and classification methods.

Permafrost can be detected using the cone penetration test, CPT^[242]. Frozen soil generally shows a very high tip resistance. Temperature measurements during cone penetration can be helpful to identify frozen soils^[243] but it is necessary that the temperature be adjusted to compensate for warming of the penetrometer and surrounding soil as a result of the penetration process^[244]. Reference [245] gives an example of the use of a CPT through a sand/silt tailings deposit with buried ice layers. When the layer is pure ice, the tip resistance and pore pressures are high while the sleeve friction is negligible.

Special sampling and handling techniques can be required for certain sediment conditions, such as gaseous sediments, permafrost and soft-surface sediments. Gas in sediment, either in solution or as

bubbles, can expand and cause sample disturbance. Warm permafrost is also difficult to sample undisturbed because the sediment is close to its freeze-thaw boundary temperature of between 0 °C and -2 °C.

Reference [246] contains a section on site investigation practice for permafrost conditions. Further background to the techniques and methods can be obtained from proceedings of several speciality conferences related to cold regions. Examples of such conferences include:

- the ASCE International Conferences on Cold Regions Engineering;
- the Canadian Conferences on Permafrost;
- the International Permafrost Conferences;
- the International Conferences on Port and Ocean Engineering under Arctic Conditions (POAC);
- the Annual International Offshore and Polar Engineering Conferences (ISOPE);
- the ASCE “Arctic 85” Conference, San Francisco, California, 25-27 March, 1985.

Of particular note is that thermal disturbance to permafrost samples at temperatures close to freezing is almost impossible to prevent. In situ testing using the CPT and the pressuremeter is, therefore, commonly used to evaluate the behaviour of piles in permafrost. Because of the rate sensitivity of frozen soils, the standard 20 mm/s CPT is not appropriate. Special test methods are required to determine creep parameters, such as incremental load controlled tests in which the action on the cone is increased in steps and held constant at each step for a given time^[247]. Rate-controlled CPTs have been carried out in permafrost, at rates from 1 mm/s to as low as 10⁻³ mm/s, to determine both stratigraphic detail and creep properties^[248]. Examples of the application of the CPT and pressuremeter to pile predictions are provided in References [247], [249] and [250]. Seismic wave velocities (compression and shear) can also be successfully measured in permafrost^[251] to determine the elastic properties.

Ground temperatures should be measured if permafrost is expected. The most reliable approach is to install a thermistor string in the borehole and to read the instruments once the temperature has stabilised. A less accurate method is to measure the temperature of each soil sample in the field as soon as it is retrieved. Temperature measurements using the CPT have also been reported^[251].

Special laboratory testing procedures are required for permafrost^[246].

A.9.3 Representative material properties

Selection of representative material properties for design of arctic offshore structures requires careful consideration of all of the available experience and a carefully designed site characterization programme including in situ and laboratory tests. This is combined with an appreciation of the uncertainties in measurements and analytical models to select representative values that are compatible with the required structural reliability for each limit state in this document.

The greatest uncertainty in the measurement of engineering parameters is generally that due to sample disturbance, especially for samples taken offshore in permafrost regions. These samples are susceptible not only to mechanical disturbance, but also to thermal disturbance (thawing or freezing) while gas

dissolution (either from pore water or frozen hydrates) also occurs. Similar uncertainty exists in the interpretation of in situ tests.

A.9.4 Design considerations

A.9.4.1 General

Permafrost and gas hydrates are of particular concern in some arctic offshore regions.

Permafrost sediments experience local melting and possible thaw subsidence with the prolonged extraction of warm hydrocarbons during production. This can result in settlement of topsides production systems, displacement-controlled loading on production casings, and reduced foundation resistance. Design considerations for permafrost and gas hydrates include the following.

- a) Specific considerations include:
 - total and differential settlements associated with thawing;
 - reduction in foundation soil shear strength associated with thawing;
 - creep-related settlements for heavy structures founded above ice-rich permafrost.
- b) The design process normally involves:
 - thermal analyses to evaluate the extent of thawing or freezing;
 - deformation analyses to evaluate the extent and time dependence of foundation settlements;
 - stability analyses to consider possible ramifications of a reduction in the foundation shear strength;
 - The limitations of analytical methods should be considered in all such analyses.
- c) Factors to consider in thermal analyses are:
 - thickness and temperature profile of the permafrost;
 - pressure-temperature condition of hydrates^[252];
 - thermal properties of the soils, accounting for freezing point depression and pore water salinity^{[253][254]};
 - thermal boundary conditions associated with the overlying water, structures, wells and the geothermal gradient;
 - range of well operating conditions.
- d) Factors to consider in deformation analyses are:
 - extent and rate of thawing;
 - immediate and time-dependent volumes that change on thawing;

- changing boundary conditions that affect redistribution of pore fluids and consolidation, particularly the moving, thawed soil-permafrost boundary;
- changes in the mechanical properties of foundation soils during and after thawing^[255];
- creep characteristics of the permafrost.

e) Factors to consider in stability analyses related to permafrost or hydrate degradation are:

- changes in soil strength as a result of thawing;
- time-dependent changes in the strength of the thawed soil associated with the dissipation or generation of excess pore pressures;
- the effects on soil or soil properties of high volumes and pressures of gas that could be released by the decomposition of hydrates.

A.9.4.2 Action factors

No additional guidance is offered.

A.9.4.3 Material and resistance factors

Geotechnical practice worldwide includes two approaches for the calculation of the resistance in limit states design. The first is to apply a material factor to the representative undrained strength, s_u , or the tangent of the representative friction angle, $\tan(\phi')$, and to calculate the foundation resistance using this design strength. The second is to calculate the foundation resistance using the representative strength; the foundation resistance is then multiplied by a resistance factor to obtain the design resistance. Hybrid approaches combining material and resistance factors have also been proposed.

Both approaches are acceptable within this document. ISO 19901-4 uses a material factor approach for shallow foundations, i.e. the representative soil strength is reduced by a material factor before the design foundation capacity is calculated. For deep-piled foundations, ISO 19901-4 uses a resistance factor approach, i.e. the pile capacity is calculated using representative strength values and capacity is then reduced by a resistance factor.

For undrained or total stress analyses, the material factor and resistance factor approaches in most cases give the same result and it is a matter of choice as to which approach is used. For effective stress analyses, there can be significant differences because foundation resistance is a non-linear function of effective friction angle. Material factors in effective stress analysis are, therefore, usually specified in combination with the method of analysis in order to avoid large variations in reliability when using this method.

Because ice actions on arctic offshore structures tend to result in greater horizontal action components than in more temperate climates, and because the bearing component is a highly non-linear function of action inclination, the resistance factor approach to design is more likely to result in consistent reliability of foundations. This is particularly the case for structures where the action is transmitted to the foundation through more than one path (e.g. piles in friction, end bearing and lateral resistance, and caisson structures through sliding/bearing on the base and passive pressures against infill soils). In many cases, a single method of analysis is also difficult to specify for arctic offshore structure foundations.

A.9.4.4 Dynamic action effect analysis

Examples of foundation design principles for cyclic loading from waves for bearing capacity as well as for foundation stiffness and displacements can be found in References [256], [257] and [258].

A.9.4.5 Ultimate limit states

No additional guidance is offered.

A.9.4.6 Serviceability limit states

No additional guidance is offered.

A.9.4.7 Fatigue limit states

No additional guidance is offered.

A.9.4.8 Abnormal limit states

No additional guidance is offered.

A.9.4.9 Construction and installation

Soil stabilization techniques can be considered in order to increase the strength and stiffness of foundation soils. It is cautioned that some of these methods have been employed to date only for onshore or land reclamation projects, and that their application offshore requires additional consideration. Possible techniques include the following:

- deep mixing, consisting of pressure injection plus mechanical mixing of a cementing agent into the soil to increase strength;
- artificial freezing, which has been used primarily as a temporary construction support for advancing tunnels and shafts, or as a method to maintain permafrost below foundation components;
- densification, either by mechanical means (e.g. vibroflotation) or blast-induced vibration.

A.9.5 Gravity-based structures

Refer to ISO 19901-4 and ISO 19903 for general information and guidance.

Structures that are subject to horizontal and vertical ice actions need to be checked for global and local actions which have a strong dependence on the loading width. Wide structures can be subject to eccentric loading due to ice actions at the edge of the structure, and these ice actions are transferred to the base of the structure and the subsoil. For gravity-based structures, verifications of stability against torsional loading are required; these verifications are similar to those undertaken for sliding, overturning and bearing capacity.

When an ice action does not act in the centre of gravity of the base of a structure, it produces a torque and base shear, causing a combination of rotational and translational sliding. Various methods to solve this can be found in References [259] to [263]. Generally speaking, only structures that can be hit by large pieces of ice suffer the effects of eccentric loading, as other loading conditions are more uniformly distributed. Circular or near-square structures are less affected than rectangular structures with length to width ratio greater than two.

Torsional actions can be considered in a simplified way in design by utilizing part of the resistance contributions from base shear and potentially skirt walls to resist the torsional actions. Resistance contributions along the periphery of the base area are best suited to resist torsional actions, due to the longer moment arm. The remaining base shear and skirt wall can be used to resist the horizontal actions. A possible reduction in capacity to resist vertical actions and overturning moments should also be considered for the areas fully mobilized horizontally by the torsional action.

Reference [263] provides a review of the analytical solutions, including limit equilibrium analysis^[259], FE analyses^[260], upper bound plastic limit analysis^[261], and compares the accuracy of the simpler solutions for 3-D FE analyses. The simpler methods provide a reasonably accurate estimate of capacity unless the eccentricity of the action (torsion versus horizontal action) is extreme.

The verification of the bearing capacity normally accounts for combined vertical and horizontal actions. To account also for torque, the method of Det Norske Veritas (DNV) (see Reference [32]) can be used as an initial check. In this method the ice action is purely horizontal, resulting in torsional sliding. The horizontal action is increased to account for the eccentricity or torque. The DNV formula is:

$$F_{eq} = \frac{2 \cdot M}{L_{eff}} + \sqrt{F^2 + \frac{2 \cdot M}{L_{eff}}} \quad (A.9-1)$$

where

F_{eq} is the equivalent horizontal action, corrected (increased) for eccentric actions, expressed in kilonewtons;

L_{eff} is the effective foundation width, expressed in metres, calculated from the eccentricity of the vertical action from the centre of the foundation as described in ISO 19901-4, where it is termed L' ;

M is the moment applied to foundation.

The DNV method has the advantage of one simple verification and unity check with the bearing and sliding actions, although the value of F_{eq} has no physical meaning. Application of the DNV method for action cases where torque is dominant should be carefully considered. These conditions will however not occur under normal ice actions, as the eccentricity (generally) is not larger than half the base width.

For more complex geometries and complex soil conditions, a FE verification is recommended. The FE analysis provides insight and analyses to confirm that the analytical method can be used as a lower bound method for calculation of the combined sliding and torsional resistance^[32]. FE analysis can be used to provide a more accurate standardized yield function for combined sliding and torsion, similar to that used for vertical actions and overturning moment in ISO 19901-4.

A.9.6 Piled structures

Refer to ISO 19901-4 for general information and guidance.

Guidance on pile design in permafrost can be found in References [246] and [264].

A.9.7 Design of anchors for floating systems

Recommended design criteria and ultimate limit states (ULS) design safety factors for anchoring systems are given in ISO 19901-7. ISO 19901-4 provides recommendations for the geotechnical design of anchoring systems for floating offshore structures and mobile offshore units. It is applicable to stationkeeping systems with catenary, semi-taut-line or taut-line moorings.

A.9.8 Scour

No additional guidance is offered.

A.9.9 Inspection and performance monitoring

Instrumentation systems and monitoring procedures that have been deployed on fixed offshore Canadian exploration structures are described in Reference [265].

A.9.10 Seismic analysis

A.9.10.1 General

The main thrust of the seismic analysis of shallow-founded structures such as a GBS is the proper treatment of dynamic soil-structure interaction (SSI). SSI analyses can be classified based on the following:

- sequence of analysis: direct or impedance method;
- domain of analysis: frequency or time domain;
- soil behaviour: equivalent linear or non-linear analysis.

Table A.9-1 presents a summary of the common types of SSI analyses, along with the corresponding common domain of analysis and soil modelling. Also included are various issues that require careful consideration for each method.

**Table A.9-1 — Summary of the common types of SSI analyses,
along with the corresponding common domain of analysis and soil modelling**

Type of analysis	Domain of analysis	Soil modelling	Issues
Direct method	Time domain	Equivalent linear or non-linear	Soil component size Modelling hysteretic damping Extent of soil mesh Input boundary motion Permafrost/melting permafrost
Impedance method	Frequency domain	Equivalent linear	Soil component size Secondary soil non-linearity Permafrost/melting permafrost
Impedance method	Steps 1, 2: Frequency domain Step 3: Time domain	Steps 1, 2: Equivalent linear Step 3: Equivalent linear or non-linear	Soil component size Added soil mass Cross-coupling Foundation capacity Modelling hysteretic damping Foundation flexibility Secondary-soil non-linearity Permafrost/melting permafrost

A.9.10.2 Direct method

SSI analysis by the direct method consists of developing a coupled soil-structure model with a sizable portion of soil, and establishing the input earthquake motion at the lateral and bottom boundaries of the model. The boundary motions should be consistent with the design earthquake time histories, the far-field soil properties, and the presumed type of incident wave train. The extent of the soil mesh should ensure that spurious wave reflection at the boundaries does not affect the response motions of interest.

A.9.10.3 Impedance method

The impedance method, also known as the three-step method, involves:

- determining the foundation input motion, which is the response of a massless foundation to the incident seismic wave train;
- establishing the dynamic stiffness or impedance of the foundation for a range of frequencies;
- subjecting a coupled structure-foundation model to the computed foundation input motion.

A.9.10.4 Analysis domain and soil behaviour

The direct method is commonly executed using FE models in the time domain. They are, hence, suitable for explicit consideration of soil non-linearity, but require thoughtful choice of soil component sizes and properties, and careful determination of the location of lateral and bottom boundaries.

The first and second steps of the impedance method are typically executed in the frequency domain, with equivalent linear soil properties. This is due to the existence of consistent transmitting boundaries for various seismic wave patterns that prevent spurious wave reflections at the boundaries, which avoids

the need for a large soil model. The third step can be executed in the frequency or time domain. The impedance method involves the following considerations.

- In the frequency domain, the dependence of impedance on frequency is explicitly retained, as well as the cross-coupling between various degrees of freedom, especially the coupling of rocking and horizontal impedance functions.
- In the time domain, the dependence of impedance on frequency can only be approximated using linear springs, perhaps with added soil mass. Cross-coupling requires special considerations.
- Non-linear foundation stiffness can be introduced in the third step of the impedance method using non-linear springs representing global foundation behaviour. The latter should be adequately established, using non-linear analysis of the foundation-soil system accounting for embedment and skirts.

Alternative methods, other than the direct and impedance methods, have also been suggested, such as the online response test method which incorporates physical testing and analysis in real time. This method is a lumped-mass analytical method combined with direct shear test on soil specimens taken from the construction site of the offshore structure. Further details of the online response method can be found in References [266] and [267].

A.10 Man-made islands

A.10.1 General

No additional guidance is offered.

A.10.2 Island types

A.10.2.1 Sacrificial beach islands

Sacrificial beach islands use a buffer zone of sacrificial fill material to protect the topsides facilities against ice encroachment, wave run-up and erosion. The sacrificial fill material typically requires replenishment on multiple occasions during the design service life. Sacrificial beach islands typically are employed in shallow water or protected locations, where the anticipated replenishment rate is sufficiently low to be economical over the design service life.

A.10.2.2 Slope-protected islands

A slope-protected island employs armour units to protect the island fill and topsides facilities against wave and ice attack. In contrast to a sacrificial beach island, the intent is to prevent rather than accommodate wave-induced erosion. Representative armour types include, but are not limited to, quarry stone, pre-cast concrete units, linked concrete mats, gabions and geotextile containers (such as sandbags and tubes). Slope protection systems that use armour units also typically incorporate one or more filtration media to retain the island fill material.

A.10.2.3 Sheetpile-retained islands

Sheetpiles can be used for an island perimeter, reducing the seafloor footprint and eliminating the need for armoured slopes. Sheetpiles are also often used for quay walls, and as a secondary line of defence behind an armoured slope. In arctic and cold regions, the fill behind sheetpile walls can be frozen and can provide resistance to local ice actions.

Another type of sheetpile structure is a cofferdam. A cofferdam can be used as a connection between two sites, for protection of vulnerable areas, or as a quay wall/mooring dock. Cofferdams are limited in width and more likely than other sheetpile structures to undergo large deformations, rotational instability or overturning failure and internal shear failure.

Cellular sheetpiles use tensile action to maintain the interlock between pile components, thereby retaining fill and resisting external actions. Plan designs include closed configurations that rely on the tension ring created by the structure and open configurations that rely on soil restraint to anchor the sheets and maintain the tension.

A.10.2.4 Caisson-retained islands

Caisson-retained islands are similar to sheetpile-retained islands, except that the retaining system is composed of pre-built caissons that are ballasted down onto the sea floor to create a retaining ring behind which interior fill can be placed. Caissons can be constructed of steel or concrete, have sloping or vertical faces, and can incorporate ice and wave deflectors. Caisson-retained islands offer the potential advantages of occupying a smaller footprint, requiring less fill and having the retaining caissons serve as slope protection against waves and ice. Potential disadvantages include susceptibility to wave run-up and overtopping, and to scour at the base of the caisson.

A.10.2.5 Hybrid islands

A hybrid island is distinguished by a prefabricated core, such as a barge containing topsides facilities, which is surrounded by fill material. The core can be ballasted onto the natural seabed or placed on an underwater berm. The fill material is protected against wave and ice attack using sacrificial beaches, slope armour, sheetpiles or caisson units.

A.10.2.6 Underwater berms

Underwater berms can be combined with sheetpile and caisson-retained islands to reduce the height of the retaining structures. Underwater berms can also be used to reduce the size of steel and concrete platforms.

A.10.2.7 Barriers and breakwaters

Detached barriers and breakwaters can be used to protect an island from wave and ice effects. These structures can be constructed of fill material protected by slope armour, or as stand-alone caissons.

A.10.2.8 Causeways

A causeway connects an offshore structure (such as an island) to other offshore structures or to the natural shoreline. Causeways can be constructed of fill material and/or caissons, and can contain breaches to permit the passage of marine life and the mixing of water masses on opposite sides of the structure. If the causeway is constructed of fill material, protection against wave and ice attack can consist of sacrificial beaches, slope armour, sheetpiles or caisson units.

A.10.2.9 Coastal pads

A coastal pad consists of fill material placed on or near a natural shoreline and protected against wave and ice attack by sacrificial beaches, slope armour, sheetpiles or caisson units. Coastal pads can be constructed on natural islands as well as on mainland shorelines.

A.10.3 Design considerations**A.10.3.1 General design considerations**

Adaptive design has also been called the observation method and interactive design in geotechnical engineering. It is a continuous, managed and integrated process of design, construction control and monitoring to enable modifications to be incorporated during and after construction of foundations and earth structures.

Traditional methods for analysis of sheetpiles do not consider this mode of loading, so that EN 1993-5^[37] is insufficient in this respect. Numerical methods used for analysis of sheetpiles loaded by ice should include appropriate structural elements and soil with a constitutive model that includes plastic deformation and allows for realistic unloading and reloading of the soil element. The provisions in this document (Clause 11) and ISO 19902 would apply to such analyses.

Identification of sources of fill is generally required at least a year before construction begins.

A.10.3.2 Considerations for man-made islands**A.10.3.2.1 General**

No additional guidance is offered.

A.10.3.2.2 Shape and orientation

No additional guidance is offered.

A.10.3.2.3 Facilities

No additional guidance is offered.

A.10.3.2.4 Spill containment

Islands are often built of natural porous “fill” material. In the event of a spill, the polluting fluid infiltrates the fill and can eventually impact the environment. A potential mitigation option is a fluid-impermeable surface with a certain storage capacity as a first line of defence, in combination with a geomembrane within the fill material with an appropriate drainage system as a second line of defence. The elevation of the geomembrane should be selected based on the range of expected water levels, the location of the freeze-front and ease of removal during decommissioning.

A.10.3.2.5 Marine access

No additional guidance is offered.

A.10.3.3 Design for ice

A.10.3.3.1 Ice-structure interaction scenarios

Ice rubble that has formed in front of an island can be considered as additional resistance to ice actions. The occurrence of ice rubble adjacent to an island is more likely for wide structures than for narrow structures. The oncoming ice is pushed through this ice rubble to a certain height. The maximum rubble height is somewhat dependent on the geometry of the structure as well as ice thickness. Maximum rubble heights vary with the respective ice regime.

A.10.3.3.2 Ice actions

No additional guidance is offered.

A.10.3.3.3 Ice encroachment

Ice ride-up occurs as ice is pushed against a structure by an advancing ice sheet and slides up onto the structure. On a continuous slope, unimpeded ice ride-up can extend a large distance, which can be a concern for topsides structures or evacuation routes. Ice ride-down can occur when ice is deflected downward, especially when ice rubble has formed next to the structure.

Ice pile-up generally occurs as broken ice pieces encounter an instability in the ride-up process. Rather than moving up a sloping structure, the ice piles into a mound, often rapidly (in a few minutes). It can be desirable to induce ice pile-up near the waterline in order to limit ice ride-up over a structure. Ice pile-up can also occur against the perimeter structure of an island, such as sheetpile.

The presence of any ice rubble (encroached ice) at certain places on an island can be undesirable even if the action it generates is low. For example, living quarters close to the edge of an island can become threatened if ice is piling up against the building, even if no significant damage results. Ice encroachment or exclusion zones are typically used on islands for this reason.

Mitigation of the effects of ice encroachment can be active or passive. Active mitigation systems rely on ice monitoring and ice forecasting so that appropriate actions can be taken to reduce the effects. IM

upstream of the facility (from an ice perspective) using support vessels is an effective way to reduce the impact of an ice encroachment event.

Effective passive mitigation systems can include:

- an ice perimeter or ice encroachment exclusion zone without any facilities;
- deflectors at the island perimeter;
- ice protection barriers some distance away from the island;
- an above-water bench to encourage ice pile-up and to accommodate ice storage;
- concrete or steel walls on the island surface to shield key (critical) facilities.

A.10.3.4 Geotechnical considerations

A.10.3.4.1 Geotechnical data acquisition

No additional guidance is offered.

A.10.3.4.2 Fill characterization

No additional guidance is offered.

A.10.3.4.3 Cyclic actions

No additional guidance is offered.

A.10.3.4.4 Thermal changes

No additional guidance is offered.

A.10.3.4.5 Failure modes

Potential failure modes for man-made islands can involve the following issues.

Global sliding — For global sliding, all relevant ice interaction scenarios during a winter season should be considered.

Decapitation, which should be accounted for in the design of low-crested breakwaters and man-made islands — Consisting of widespread failure in a horizontal plane, decapitation can be associated with the layer immediately beneath a frozen crest on the structure, in which case the resistance should be calculated using the weight of the sliding crest and the friction and interlocking along the slide plane. The exact location of the slide plane should be determined using frost penetration analyses combined with geotechnical analyses. The appropriate ice conditions (thickness, pressure and rate of action application) over the design service life should be considered in determining the potential for decapitation.

Passive edge failure — The actions for edge failure analysis should be determined, accounting for fill material size, gradient and smoothness of the side slope, ice thickness and ice pressure. In general, the crest of the structure should be at least twice the representative ice thickness above the mean high water level, and the armour layer thickness should exceed the representative ice thickness. Edge failure is typically a local failure of a few individual armour units, caused by large local actions.

Passive wedge failure — For sheetpile-retained islands, the island level should be high enough to prevent passive wedge failure behind the sheetpile under ice action.

Sheetpile resistance — The failure modes in EN 1993-5^[37] (failure in the soil, structural failure, and combination of failure in the structure and soil) should be checked as a result of ice actions. Methods to avoid local yielding near the waterline, where local ice actions can be highest, include reinforcement with concrete behind the wall or treatment of the backfill with grout. Frozen fill or soil behind the sheetpile can be accounted for in resistance calculations where justified by analysis or monitoring. Contrary to modern practice (slender sheetpiles with low mass to section modulus ratio and low flange thickness to flange width ratio), sheetpiles in arctic and cold regions can require heavier sections and interlock strength design.

Tie-backs and anchors — Sheetpile retaining systems can require tie-backs to anchors for stability where the retained height is significant, such as at quay walls. The design should consider that ice actions will reduce the anchor loads temporarily, possibly as a cyclic action. This relaxation of anchor loads can cause inelastic displacements of the sheetpile, soil, tie-back and anchor system that should be considered over the design life of the island.

A.10.3.4.6 Deformation

No additional guidance is offered.

A.10.3.4.7 Soil improvement

No additional guidance is offered.

A.10.3.5 Coastal engineering

A.10.3.5.1 Design for wind, water level, waves and currents

The water level at a given island site fluctuates under the influences of astronomical tides, wind-induced storm surge and setdown, changes in the atmospheric pressure and long-term fluctuations in the water body caused by seasonal, climatic or hydrologic effects. The last effect can be particularly important in enclosed seas and lakes. Additionally, islands constructed in or near riverine environments can experience short-term fluctuations in response to hydrologic flow events. Further guidance on data collection is found in ISO 35106.

Strudel scours occur when river outflows inundate the coastal ice and drain through cracks or holes in the sea ice; see 6.6.4. The turbulent vortices that form can erode the seabed and create craters in the sea floor. Because tidal cracks typically form in the ice cover along the slopes of offshore islands, strudel scours have been found to occur adjacent to islands. While slope-protection armour units are resistant to

damage or displacement by the strudel scour vortices, the unprotected toe of the armoured island slope can be readily eroded by the strudel scour process. Down-slope armour displacement can result from such an event.

A.10.3.5.2 Side slope profile

The major difference in slope protection and beach design in cold ocean regions as compared to other regions is the presence of ice. Ice has both beneficial and detrimental effects. On one hand, the presence of ice limits the wave climate and erosion. On the other hand, ice can damage slope protection, and can ride up and damage surface facilities. Designs should provide a balance between surface smoothness to encourage ice bending (to minimize the ice actions and movement of individual stones) and surface roughness for dissipating wave energy.

The limiting of wave run-up and overtopping to acceptable levels requires understanding of the interaction of wave impacts on the selected island slope. The accommodation of possible ice ride-up and pile-up scenarios requires analyses to quantify the interaction of sea ice with the island slope. The selection of the island slope profile is a significant factor in controlling both wave overtopping and ice encroachment. Island slopes can be planar, incorporating side-slope values that are compatible with the armour systems utilized. Compound slopes involving a near-water bench have been employed successfully to reduce wave overtopping and for accommodating ice accumulations due to ride-up and pile-up processes. Near-water level benches should be configured in accordance with the recommendations for crest design in A.10.3.4.5.

To date, man-made islands have been protected by armour stone, pre-cast concrete units, articulated mats of concrete or steel blocks, and sandbags. Armour stone can be subjected to normal and shear stresses along the surface. These stresses introduce a rotation, dislodging the individual stones. For this reason, it is desirable that the surface of the armour stone be relatively smooth and the stone layer be well keyed in this respect. Angular stones tend to nest together and interlock. It follows that smoother stone surfaces reduce shear stresses. The projection of individual rocks above the surrounding armour surface can potentially lead to freeze-in and displacement as a result of ice movement.

A.10.3.5.3 Wave run-up and overtopping

The risk of wave overtopping can be reduced by:

- increasing the island elevation;
- inclusion of an above-water bench to dissipate wave run-up;
- introducing a small slope in the ice perimeter (ice encroachment exclusion zone, see A.10.3.3.3);
- building a small wall some distance away from the island edge (e.g. at the landward edge of the ice perimeter);
- having a sloped face rather than vertical face for the island edge.

A.10.3.5.4 Coastal stability

The stability of the coastline is important in the site selection and design of coastal pads and facilities. Shorelines and coastal bluffs can experience long-term change, which can vary considerably over short-term periods. Knowledge of the coastal processes of a project area should be obtained during the early phases of the design process. Given an understanding of the design service life, it is prudent to position the coastal pad or structure a safe distance landward of the shore or bluff to allow coastal changes to occur without affecting the structure or facilities.

A.10.3.6 Slope protection

A.10.3.6.1 General

Design methods for wave interaction with revetments have been developed to a high level. The design methods are based on years of large- and small-scale model testing and monitoring of actual projects. This has resulted in fit-for-purpose design methods, including criteria for damage (damage levels or damage numbers) which can be applied to achieve the required safety levels. A similar design method to predict the required armour layer for ice interaction is not available. Current experience is site-specific, with solutions depending on both locally available materials and severity of ice actions.

A general procedure is to:

- review available materials, given the remote locations of most sites and availability of rock or sand, and select the type of slope protection;
- determine the ice interaction scenarios, considering both local and global failure;
- optimize the slope geometry in order to minimize the ice actions and to ensure global stability of the structure (This would typically mean increasing the crest height/freeboard, decreasing the slope inclination, smoothing the surface and improve the interlocking. Smooth surfaces can lead to higher crest levels.);
- design the armour layers for waves using existing design methods for waves; and
- monitor slopes regularly so that repairs and maintenance can be undertaken to maintain satisfactory safety levels over the operational life of the facility.

Local failure modes of slope protection systems include local damage or displacement caused by wave and ice impacts. Such damage should be identified, and periodic maintenance and repair should be undertaken. Such damage, if addressed in a timely fashion, does not threaten the structural integrity of the island.

More extreme damage can occur as a result of a particular event or series of discrete events, and can threaten the efficient functioning of an island. Significant accumulation of localized damage, left unrepaired, can also lead to impacts on island function. Serious armour loss or displacement, while not extending over large areas, can create significant weakness in a given sector of the island, leading to significant losses in fill material, or locally high rates of wave overtopping or potential ice encroachment.

Widespread and potentially global damage can occur if wave overtopping inundates the island work surface or widespread ice encroachment occurs, thereby creating a threat to life, the environment and the production facilities.

Further information can be found in References [268] to [281].

A.10.3.6.2 Quarry stone

There is limited use of quarry stone in arctic and cold regions, due largely to lack of local availability. Rock armour has been used in the North Caspian Sea as ice protection in that ice environment. The man-made islands in the North Caspian Sea are partly protected by detached rubble mound barriers that act both as a breakwater in the summer and an ice barrier in the winter. The slopes of the structures have been designed for a gradient not steeper than 2,5H(horizontal):1V(vertical). Stone size and number of layers have been determined using design methods for rock stability, e.g. Reference [282]. Rocks of two different qualities have been used: low-density rock ($1\,750\text{ kg/m}^3$), which has high degradation risks, and high-density rock ($2\,600\text{ kg/m}^3$). The low-density rock was applied to temporary structures, e.g. protection for temporary construction phases or during drilling phases. High-density rock has been applied to permanent structures.

Reference [268] provides three rules of thumb to design a rock-armoured breakwater for ice conditions similar to the North Caspian Sea.

- a) The minimum crest freeboard should be twice the maximum ice thickness. A higher crest is not effective as a method to prevent local failure. In addition, to prevent progressive failure, the fill should not be exposed to the open water (waves) and ice, and an armour layer is required.
- b) The thickness of the armour layer should be at least equal to the maximum ice thickness.
- c) The rock size should be at least half the maximum ice thickness.

These three rules of thumb have been used as a basis for preliminary design. However, they likely cannot be extrapolated to thicker FY and MY ice conditions that occur in the Arctic. Further, if model testing is considered to verify stability of the armour layer, the scale factors should be limited and the ice is best modelled with natural ice rather than model ice. Investigations into damage to a subsea rock berm offshore Sakhalin Island over several winters indicated that localised damage and removal of the top layer of rocks by ice likely could not be prevented with any certainty, as there is a lack of confining stress or interlock to hold the rocks in place. An ongoing monitoring and maintenance programme is therefore recommended whenever rock armouring is used in ice environments.

At Nome, Alaska, where FY ice grows to a thickness of about 1 m, the city frontage and harbour structures have been protected by large (5 t to 14 t) quarrystone. Damage by ice impacts has been limited to the occasional displacement of smaller stones on the higher slopes. This bulldozing by ice is limited to the more exposed areas of offshore breakwaters and has not been noted along the coastal revetment that protects the city shoreline.

A.10.3.6.3 Sand- or gravel-filled geotextile bags

Geotextile bags filled with sand or gravel can be used as slope protection in areas where they are capable of withstanding the anticipated wave and ice conditions with an acceptable level of damage. This seemingly primitive slope protection system is attractive in remote areas because the bags can be filled on-site using local sediments.

Early Arctic oil industry experience established the utility of high-strength fabric bags for protected coastal sites and nearshore environments. These applications utilized bags of 1,5 m³ capacity (weighing about 2 800 kg) in shallow waters (generally 4 m water depth or less) having limited exposure to storm waves and ice impacts. In deeper waters, larger bags of 3 m³ capacity have been used with success. The larger bags, weighing about 5 600 kg, can withstand greater wave actions before displacement occurs. Given the larger footprint area of these bags (4,6 m²), fewer bags are required to cover a given slope relative to the 1,5 m³ bags. By virtue of their greater stability against wave forces and the larger slope coverage per bag, the bags of 3 m³ capacity have been favoured for most slope protection applications.

Geotextile bags or mattresses can be constructed for various applications, limited only by the ability of the fabricator to sew the fabric form and by the filling and installation methods. Bag fabric strengths are sufficient to support the use of bags even larger than 3 m³ capacity, but such large bags are not widely used.

Geotextile armour can be damaged or displaced readily at exposed offshore sites where ice movements and large waves occur. A combination of ice damage that tears the bag fabric followed by wave-induced loss of bag fill can result in bag failure, yielding high maintenance costs. At shallower near-shore sites where ice movements are more limited and wave conditions are modest, geotextile armour has been installed for periods exceeding 25 years. At such sites, bag damage can be noted during periodic inspections and maintenance activities can be conducted in a timely fashion.

Fabrics used for arctic slope armour have evolved since the 1970s to exhibit increased tensile strength (~1 900 N/cm), mass (~800 g/m²), seam strength (~800 N/cm), and resistance to ultraviolet radiation (sunlight). The fabric should be permeable to allow water to enter and exit the bag.

Geotextile bags are usually filled using a gravity-feed hopper system, although high speed conveyor systems have also been used. The bag closure utilizes a double drawstring, tied by hand by workers who also control the feeding of the fill material into the bag. The filled bags are carried within pipe sections 2,7 m long ("bag barrels") affixed to front-end loaders. The filled bags are released from the bag barrel via a hinged door at the bottom of the barrel. Bags are usually placed by a large crane using tongs composed of rounded pipe. In the absence of tongs, the bags can be lifted and placed by crane hooks using high-strength polyester straps that encircle the bag. This latter method of bag placement is not favoured for below-water placement, given the need for divers to release each bag.

Geotextile armour should be underlain by a strong and permeable filter fabric to ensure that the island core material is not washed out from beneath the armour by wave action. These underlying filter fabrics should be sewn together into wide panels to allow efficient placement underwater using a spreader bar lifted by a crane. Filter-fabric panels having a width of 15 m have been commonly used. Trapezoidal panels should be used to cover island corners. Sufficient overlap (2 m to 3 m) of adjacent fabric panels is necessary to prevent the loss of gravel fill. For efficient installation, filter fabric should sink readily in seawater, which suggests the use of polyester material having a specific gravity of 1,25. Typical filter-

fabric characteristics for use under geotextile armour include high tensile strength (1 440 N/cm), fabric mass (750 g/m²), and seam strength (620 N/cm).

Large-scale physical models have been performed to determine the stability and wave run-up characteristics for various bag placement schemes on a variety of side slopes. A stair-stepped configuration requiring bags to overlap by 50 % of their length is conventional, as a balance between improved bag performance and ease of placement. The wave height that can induce instability of 3 m³ capacity gravel bags placed in a 50 % overlapped configuration on a 3H(horizontal):1V(vertical) slope is about 2,5 m.

Given the stair-stepped nature of overlapped geotextile bags and the use of compound side slopes, wave run-up cannot be accurately predicted without the use of large-scale physical models. To lower the elevation of an island or coastal pad that uses a smooth armour (e.g. linked concrete mat) associated with high wave run-up, geotextile bags can be used on the upper slope where damaging ice impacts are less frequent and where the overlapped bags effectively dissipate wave energy, thereby reducing wave run-up.

Once the critical wave conditions (height, period, steepness) necessary to initiate bag movement are exceeded, a progressive deterioration of the slope armour commences. If the bags are initially overlapped by 50 % of their length, a 100 % redundancy exists in the slope armour system (i.e. twice the number of bags needed to completely cover the slope are installed). Wave-induced bag displacement will pull bags downslope from the wave impact zone. Bags from the upper slopes will slide down into the areas where bags have been removed. At the conclusion of the storm, the areas that are devoid of bag coverage will likely be near or above the water level, and can be easily observed by inspectors and bag repair crews.

The damaging effects of sea ice on bag fabric have been well noted in the field. Damage to geotextile armour by ice impact can occur during all seasons whenever ice is present. Ice movements in the winter and spring can tear bag fabric, and physically displace bags even if the bag fabric is not torn. During the summer and fall, ice floes of all sizes driven by ocean waves and currents can puncture and tear the bag fabric. Under continued wave action, the contents of the bags can eventually be lost through bag tears that can be as short as 15 cm. With time, bags that have been damaged lose significant quantities of fill material and are subsequently dislodged from the slope by wave action. While bag damage caused by ice keel impacts can be noted below water, significant above-water damage can also occur as a result of ice ride-up events.

In addition to natural damage caused by waves and ice forces, errant construction and island maintenance activity can be quite destructive. Bag damage caused by heavy equipment during snow removal operations is noteworthy. As snow removal occurs around the work surface perimeter, a steeply sloping gravel berm constructed inshore of the bags can freeze in winter and can serve to protect the perimeter bags when snow is bladed over the edge of the work surface. In all cases, care should be taken by maintenance crews to avoid equipment-induced bag damage.

Additional information regarding geotextile bags is provided in Reference [269].

A.10.3.6.4 Linked concrete mats

Concrete mats composed of individual concrete blocks that are linked together have been used successfully in coastal engineering applications. Individual blocks can be physically connected by cables

that pass through the blocks or by chain/shackle linkages. The linkage is critical in that the system is composed of individual concrete units that, if not linked, can otherwise be readily displaced by wave and ice actions. Linked mats perform as an integrated unit in the wave and ice impact zone. Concrete mats are more resistant to ice impacts, relative to the softer geotextile armour systems. The smooth, featureless slopes exhibited by concrete mats limit the ability of ice to displace the blocks. Linked-mat systems are underlain by durable filter fabric to contain the island fill material. Wave run-up on these smooth surfaces can be excessive, leading to the incorporation of a composite slope profile with rougher armour units placed on the upper slope. The modular nature of the linked concrete mat system allows for relatively quick installation and localized repair when damage occurs. Failure of linked concrete mats can result from ice impact or wave-induced uplift, and these mechanisms should be considered in the design.

Linked concrete mats can be used to protect man-made island slopes. This armour type is used in ice and wave environments that are too severe for the use of geotextile armour or where the design lifespan of the island suggests the need to avoid long-term geotextile maintenance. In the Alaskan Beaufort Sea, effective use of linked concrete armour dates to the mid-1980s and includes long-life oil production islands.

Advantages of linked concrete armour include low mass per unit area by virtue of inter-block linkage, resistance to moderate ice impacts, the ability to accommodate changes to the subgrade without permitting catastrophic losses of fill material, the ability to construct and repair the armour system using prefabricated modular panels, and reasonably complete recovery of the armour during decommissioning at the conclusion of the project life. In some areas, use of concrete as a slope armour material has been found to create hard-bottom habitat that attracts and promotes environmentally valuable assemblages of marine biota.

Disadvantages of the linked concrete mat slope armour include the need for mild sea states to support installation, the need for diving operations to link adjacent mat sections underwater, long-term corrosion of the steel linkages, potential damage caused by the impact of large ice floes or shifting of the winter ice sheet, and the absence of well-documented design procedures. In addition, the smooth concrete mat surface promotes high wave run-up, usually requiring a backing slope of overlapped geotextile bags or a vertical wall to allow the island designer to lower the island surface elevation to cost-effective levels.

Physical models have shown that the linked mats are dynamic and should accommodate wave-induced uplift. Given the use of this armour type in Alaska since 1985 at a nearshore location (3,5 m water depth)^[270] and since 2000 at an offshore site (13 m water depth)^[273], the damage mechanisms and repair scenarios have been documented.

A number of proprietary and non-proprietary designs for linked concrete mats exist, although few have been installed in arctic and cold regions environments. A well-documented design incorporates pre-cast blocks having plan dimensions of 1,2 m × 1,2 m, with a height of 23 cm. Each block is reinforced with two layers of welded wire mesh, and contains forged steel rods (diameter 2,5 cm) with eyes on both ends. The tensile strength of each linkage rod is 32 t. Chain links and shackles connect the eyes of adjacent blocks in both the up-slope and across-slope directions, providing a nominal spacing of 50 mm between the edges of the blocks. A similarly shaped block with more robust steel reinforcement and enhanced concrete characteristics has been utilized at an exposed offshore site, and resulted in improved performance against ice damage while exhibiting considerably greater block construction complexity and much higher cost.

Two action scenarios should be considered in determining the strength of the linkage system: the lifting actions imposed during installation and the environmental actions (waves and sea ice) that will be experienced during the life of the structure or platform. During installation, the linked mats are placed in large, pre-assembled panels using high-capacity cranes. To maximize construction efficiency and to minimize to the extent possible the need for below-water linkage of adjacent mat panels, the mat dimensions need to be as large as can be safely accommodated by the crane. For one platform, mat panels were assembled for placement that were 3 blocks wide (3,8 m) and 18 blocks long (22,9 m), yielding a panel weight of 42 t.

To span island corners, a sequential series of trapezoidal blocks should be fabricated and assembled into panels. One platform required 36 different trapezoidal block shapes to be fabricated. Accurate grooming of the island slopes is required to allow the proper alignment and side-to-side connection of trapezoidal panels.

The linked mat should be anchored at the top of the slope to prevent downslope displacement under the influence of ice shear forces and wave-induced mat uplift acting in concert with wave back-wash. If the mat is used as toe protection at the base of a sheetpile wall, the mat can be connected directly to the wall by chain/shackle linkages at regular intervals. Alternatively, the mat can be connected at its up-slope edge to deadman anchors buried in the island fill.

The selection of the filtration medium to be placed beneath the linked concrete mat is a critical design feature. The underlayer retains the underlying core fill material and promotes the release of hydraulic pressure within the fill through the provision of adequate permeability. While rock or concrete rubble underlayer can provide these requirements, lack of available resources can dictate the need for a robust filter fabric. The fabric should be very strong ($2\,200\text{ N/cm}$), heavy ($1\,530\text{ g/m}^2$) and exhibit high permeability (permeability = $2,0\text{ s}^{-1}$); i.e. strength and flow characteristics that are not usually mutually compatible. The filter fabric should be provided in 15 m-wide panels for placement by a crane-lifted spreader bar. Sufficient fabric panel overlap should be provided ($\geq 3\text{ m}$) and, given the likelihood of periodic wave-induced uplift of both the mat and underlying fabric, consideration should be given to physically attaching the sides of adjoining panels. This can be accomplished below water by divers tying the panels together using prefabricated loops along the panel sides. The abrasion resistance of the filter fabric is a primary concern, given the potential for repeated uplift of the mat during large storm events. To protect the fabric underlayer, a heavy geogrid can be placed atop the filter fabric as an abrasion guard.

Additional information regarding linked concrete mats is provided in Reference [270].

In exposed arctic and cold regions offshore environments, pre-cast concrete mats can sustain structural damage from ice forces. Thick MY ice floes can directly impact the armoured slopes, and large ice fragments can be propelled into the armour by large plunging waves during summer storms. In order to sustain these large ice forces, concrete mats can be structurally reinforced to a significant degree. Likewise, concrete strength should be increased e.g. by added cement content, the inclusion of silica fume, high-quality angular aggregate, and steam curing. The cost of these enhancements can be quite high at remote locations, as expensive transportation of the armour units from distant fabrication sites would be required.

A.10.3.6.5 Linked steel mats

The high cost of improved linked concrete mat armour has been found to be comparable to the cost of solid steel blocks of similar shape and linkage scheme. Since the initial installation of steel blocks in 2007^[274], the blocks have been impervious to damage by sea ice. Because the density of steel is about three times that of reinforced concrete, the steel block thickness is designed to be about one-third that of the concrete block to preserve the same lifting and installation plan. Thus, the usual concrete block thickness of 23 cm is reduced to 7,7 cm for the steel blocks. These linked steel blocks are placed as multi-block panels in the same way as the linked concrete mats. The higher density of the steel (~45 % increase in submerged weight relative to concrete) and the lower aspect ratio (67 % reduction in block height) improve block stability under wave actions. These weight and dimensional improvements in concert with the smooth surface finish allow the steel blocks to resist displacement by the bulldozing effects of sea ice moving against the armoured slope.

Reference should be made to A.10.3.6.4 for further guidance.

A.10.3.6.6 Pre-cast concrete units

Large pre-cast concrete armour units provide island slope protection, although the experience of this type of armour in ice environments is limited. A variety of pre-cast concrete units exist, with distinct shapes, sizes, masses and degree of interlock. They can be subdivided into single-layer units (e.g. Accropode, Xbloc, cubes) and double-layer units (e.g. Tetrapods, cubes, Dolosse, Antifers).

Unreinforced concrete units can be an economical solution in case wave actions are high (significant wave height, $H_s > 3$ m) or rock or other material is scarce. The design method to determine the structure geometry and armour size is similar to that of armour rock with a few changes. First of all, slopes armoured with concrete units are generally steeper and rougher than a rock slope, due to the increased interlocking and increased energy dissipation. This conflicts with the optimized geometry from an ice interaction perspective. Secondly, special high-stability elements such as Xbloc, Accropode II, Tetrapod and Dolosse can be damaged due to high local ice actions. This requires additional checks of the concrete strength of the special elements^[283].

Recent developments have shown that single-layer concrete cubes can be an efficient protection against wave actions. An armour layer with single-layer cubes has a smooth surface, which could be attractive for ice actions in combination with high wave actions. However, wave overtopping concerns can require a compromise with the preferred smooth slopes for ice. Verification using proven design methods for wave overtopping should be used.

A.10.4 Seismic design

Seismic design of man-made islands involves prevention of global and local failure of the island fill materials during an earthquake. Failure of the retaining system should also be evaluated. Issues that should be addressed are summarized in the following.

- Global design: this involves lateral failure of the island at the sea floor, below the sea floor or through the island due to seismic lateral actions. Available methods include 2-D or 3-D linear or non-linear methods.

- Local design: this involves local regions of settlement during the earthquake (especially uneven settlement), due to consolidation or liquefaction. Lateral spread of the island materials during an earthquake requires consideration.
- Retaining system: this involves stability of the island's slopes in earthquakes. Typical methods of slope stabilization should be used for natural or engineered slopes. Sheetpile retaining systems should use methods applicable for pier and wharf design. Caisson retaining systems should consider methods suitable for retaining walls. In some cases, the caissons can act as small GBSs with a shallow foundation, and the methods described in Clause 9 should be used.

A.10.5 Construction

A.10.5.1 Operational requirements

No additional guidance is offered.

A.10.5.2 Fill quality control

Resistance to liquefaction under static or cyclic actions has been a key requirement for hybrid man-made islands in the Canadian Arctic. The Nerlerk berm failures^[284] are a well-documented example of liquefaction flow slides of hydraulically placed sand fill induced by static actions. Cyclic loading caused partial liquefaction of the Molikpaq core^[285] during an ice event on April 16, 1986. The Molikpaq was a hybrid island consisting of a steel caisson-retained sand fill (the core) founded on a sand berm; both the core and berm were hydraulically placed sand fill. In situ density of sand fills is the primary determinant of liquefaction resistance, and density is best quantified in terms of the state parameter^[285] or relative density.

The preferred method to determine in situ density of island fills is the cone penetration test (CPT), and developments in arctic and cold regions in the 1980s spurred much research and development on interpretation of the CPT measurements. (The measurements themselves are relatively straightforward and should be to acceptable standards such as those cited in ISO 19901-8 or ISO 22476-1, application level 2). Where pore pressure measurement can be included in the CPT, that should be done, i.e. a CPTu. Interpretation should be carried out by competent geotechnical engineers; screening methods used in seismic engineering based on the reference stress level (where the tip resistance is adjusted to q_{c1N}) and corrections for the percentage of fines or silt sizes in the sand are to be avoided. The reference stress level and fines corrections are empirically derived and calibrated to conditions that are not applicable to arctic and cold regions structures and man-made islands. Reference [285] contains a detailed discussion of CPT interpretation as well as many of the learnings from the liquefaction case records noted above. A general CPT interpretation reference that includes liquefaction assessment is found in Reference [286].

Structures for offshore exploration and production in arctic and cold regions are sufficiently large and complex that development of a site-specific relationship between CPT parameters (i.e. tip resistance) and in situ density is warranted. A traditional and comprehensive approach is to obtain a large sample of representative material and to conduct large calibration chamber tests, e.g. References [287] to [289]. A more modern and cost-effective approach is to conduct centrifuge CPTu tests with miniature cones, which require smaller samples, and then confirm the correlations with as few as two full size calibration chamber tests. In the absence of centrifuge or calibration chamber tests, a minimum requirement is to conduct triaxial tests to determine the relevant properties of the sand, i.e. the critical state line and stress

dilatancy parameters, so that a numerical or semi-analytical model can be used to establish a rational relationship, e.g. References [285], [290] and [291].

In the event that CPT testing is not locally available, or the fill is too coarse for the CPT, an alternative test method should be used. The alternative method should be able to show that the fill density is adequate to support the structures and the applicable actions (e.g. seismic loading).

There is considerable empirical evidence that the grain size distribution of hydraulic fills has a significant effect on the density that is achieved in situ by any given placement method. (Placement method is equally important, see for example Reference [292].) For this reason, quality control of fill materials is essential during construction and consists largely of determining grain size distribution. Grain size distribution can be checked in the fill source, while dredging or during transportation to the island site, and again once the fill has been placed within the island. The latter defines the final acceptability of the material, but testing in the fill source and in transit allows for rejection of material before it is placed in the island or for selective placement of better materials in critical zones of the fill.

Construction in arctic and cold regions using hopper dredges allowed for sampling from the dredge lines and within the hoppers, but the analytical results are needed in real time. The ASTM standard test method, which takes several hours, cannot be followed in practice but alternatives and/or approximations exist. Optical particle size analysers can be used to measure particle sizes in water, while microwave ovens can be used to speed up drying of material for sieve analysis. Whenever sampling occurs, the engineer should recognize the effect that the sampling procedure will have on the measured grain size distribution (compared to the actual grain size) and also how the grain size distribution will change with further handling and placement of the material as island fill. In general, some of the fines are washed from samples throughout the dredging, transportation and placement process.

Fill materials are naturally variable, and this raises the question of how many samples of fill for grain size analysis should be obtained, or how many CPTs should be carried out to adequately characterize the material. Some guidance on these issues can be found in References [293] and [285].

Given the volumes of fill involved, and the importance, hundreds of grain size analyses will typically be carried out as part of a quality program for a man-made island. Larger projects would include thousands of grain size analyses.

A sufficient number of CPTs for a constructed fill should recognize both natural variability of fill quality and density, and that for liquefaction purposes the engineer typically needs a characteristic value of tip resistance in the 10 percentile to 30 percentile range. Liquefaction behaviour is dominated by the looser material within the fill, not the average density material. Reference [294] suggests that around 15 CPTs are just about sufficient for a relatively uniform hydraulic fill in an approximately 70 m × 70 m area. Further, a minimum of 10 tests is required to adequately define a reasonable percentile value. These numbers form the basis for the minimum requirement in 10.5.2 for 10 CPT tests, as well as the minimum requirement for a test every 500 m² plan area.

A.10.5.3 Armour rock quality control

No additional guidance is offered.

A.10.6 Monitoring and maintenance

Collection of data for ice encroachment and interaction events provides valuable guidance for design and operation of islands and facilities located on them. Data for ice encroachment events that should be gathered include:

- structural parameters (freeboard, orientation of the face, type of face (sloping or vertical), slope angle, length of face, material for slope armour, etc.);
- encroachment parameters (type of encroachment, mean and maximum pile-up height, ice encroachment distance, etc.);
- ice parameters (ice type, ice thickness, ice drift speed and direction);
- metocean parameters (water level, wind speed and direction).

A.10.7 Decommissioning and reclamation

A case history describing the abandonment of Mukluk Island in the Alaskan Beaufort Sea is provided in Reference [271].

A.11 Fixed steel structures

A.11.1 General

In addition to the provisions of ISO 19902, the design of structural elements that behave as beams, columns or beam-columns can be performed in accordance with national or regional standards; see, for example, References [15], [29], [28], [37] and [44].

A.11.2 General design requirements

No additional guidance is offered.

A.11.3 Structural modelling and analysis

No additional guidance is offered.

A.11.4 Strength of tubular members and joints

No additional guidance is offered.

A.11.5 Strength of stiffened-plate panels

Design standards for stiffened-plate panel configurations include References [33] and [17].

Reference to membrane action applies only to the plate panel and not to the stiffeners or primary structure supporting the panel.

The use of membrane action should be avoided without careful consideration of the p-delta effects related to primary load paths and maximum deflection under load with and without permanent deflection.

Classification societies have rules for bulkhead deflection under hydrostatic actions that can be in conflict with the local ice action design provisions of this document.

A.11.6 Strength of steel-concrete composite walls

No additional guidance is offered.

A.11.7 Seismic design

A.11.7.1 Framed structures

No additional guidance is offered.

A.11.7.2 Stiffened-plate structures

While there is limited guidance in ISO 19902 for seismic design of GBS-type steel stiffened-plate structures, the general principles of steel structure seismic design, as applied to steel tubular-framed structures, still apply. The following provides some general guidelines.

- Ductile performance in cold temperatures: cold temperature steel should be used for the design of the portions of the structure that are exposed to ambient temperatures and expected to undergo plastic deformations in earthquakes. Such material should have a demonstrated ability to undergo plastic deformations at the design minimum EL temperature.
- Global plastic mechanism: the formation of plastic mechanisms together with the location and nature of plastic hinges in the structure should be clearly identified and reviewed to ensure that they do not lead to global collapse.
- Global deformations: due to lack of large-scale experimental data, designers rely on FE models of the steel structure to obtain global deformations in areas of plasticity.
- Local strain demand: the global deformations should be translated into local strains using detailed FE models. The limits on total strain should be established based on project material data.
- Seismic detailing: in order to ensure that the local components are capable of sustaining plastic deformations, compact section detailing should be maintained, as defined by the provisions of ISO 19902.
- Controlled buckling: in some cases, it is possible to obtain satisfactory ductile performance even with the buckling of some components. In such cases, satisfactory performance should be demonstrated using established engineering principles.
- Capacity design: the components of a ductile GBS should be clearly identified as force-controlled and displacement-controlled, for the purposes of further design and assessment.
- Skirts: if it is desirable to design the steel mud skirts in such a way as to cause a sliding failure prior to development of the GBS plastic mechanism, the upper bound properties of the mud skirts should be considered prior to the design of the adjacent base structure. The allowable stresses in the steel skirts should be decided on the basis of the function of the GBS. When the GBS is, for example, of the re-floatable barge type, the skirt stresses should remain in the elastic range under all load conditions since deformed skirts hamper the re-installation of the structure.

A.11.8 Fatigue

For fatigue analysis associated with ice actions, reference should be made to A.8.2.6.3. High cycle, low amplitude cyclic stresses can be caused by frequent, low intensity ice action events, while low cycle, high amplitude cyclic stresses can be caused by abnormal, high intensity ice action events.

Attention should be given to the validity of $S-N$ curves with respect to low temperature application.

A.11.9 Materials, testing and NDT

Special attention should be given to foundation skirts and piles driven into frozen ground under low temperature conditions.

Materials testing temperatures given in ISO 19902 are consistent with the definition of LAST in this document, but 11.9 has further provisions for arctic and cold regions. If an alternative temperature specification applies (i.e. due to local regulatory requirements or the specific material standard or specification), consideration should be given to conforming to the more onerous of 11.9.2 and the alternative specification. In doing so, the choice of test temperatures should be consistent with the minimum local temperature specification.

Further discussion of LAST and test temperatures for arctic and cold regions is provided in ISO/TS 35105.

A.11.10 Coatings

No additional guidance is offered.

A.11.11 Corrosion and abrasion protection

A.11.11.1 Cathodic protection

No additional guidance is offered.

A.11.11.2 Ice abrasion

No additional guidance is offered.

A.11.11.3 Knife-line corrosion

Experience to date has shown that it is possible to minimize the metallurgical and electrical differences between the weld areas and the parent plates to such a degree that knife-line corrosion is avoided. Various electrical methods have been used to demonstrate that certain levels of potential voltage differences between the different metals correlate well with deterioration rates. Additionally, accelerated corrosion tests can be carried out on welded test specimens to demonstrate that the degree of metallurgical difference in the weld zone (resulting from the welding process) does not subsequently result in high rates of deterioration.

A.11.12 Welding

No additional guidance is offered.

A.12 Fixed concrete structures

A.12.1 General requirements

No additional guidance is offered.

A.12.2 Actions and action effects

No additional guidance is offered.

A.12.3 Structural analysis

A.12.3.1 Dynamic analysis

No additional guidance is offered.

A.12.3.2 Loss of intended internal pressure

No additional guidance is offered.

A.12.3.3 Physical representation

A.12.3.3.1 Soil-structure interaction (SSI)

No additional guidance is offered.

A.12.3.3.2 Other support conditions

Additional transverse shear reinforcement can be provided to transfer the action to the opposite face in order to prevent pull-out and punching-type failures where only part of the thickness of the structural component is activated.

A.12.3.3.3 Thermal effects

Deformation-induced actions such as the effects of temperature differences and thermal gradients can, in general, be determined on the basis of linear analyses. The non-linear elastic behaviour of reinforced concrete due to cracking under the imposed strains can also be taken into account by applying reduction coefficients on the linear elastically determined action effects. For SLS action effects (for ULS and FLS limit states, thermal effects other than for shear are normally neglected), a coefficient of reduction less than 1,0 is generally accepted, provided that the selected value is supported by relevant documentation. For verification of the required tightness and calculation of crack-widths for SLS, the temperature-

induced strains can be considered by taking into account the differences in axial stiffness for the tension and compression sides of the cross-section.

A.12.3.4 Types of analysis

A.12.3.4.1 Linear elastic static analysis

The assessment of the stiffness of a structural member used for structural analysis is computed either from the concrete cross-section alone or by also taking account of the effect of the reinforcing steel. Young's modulus for the concrete should be appropriate for the nature of the action (static or dynamic), and for the age of the concrete.

The effects of deformation actions, such as thermal effects or differential foundation settlements, should be included in the form of strains rather than stresses, and on the basis of elastic behaviour. For instance, in computing crack width, thermal strains should be added to strains from other action effects. For long-term sustained temperature differences, the beneficial effect of strain due to creep can also be considered.

A.12.3.4.2 Non-linear analysis

No additional guidance is offered.

A.12.3.5 Analysis requirements

A.12.3.5.1 Analysis of construction stages

Depending on the size and dimensions, a concrete structure can be erected partially in a dry-dock and partially afloat. The structure should be erected afloat (wet dock) in a predefined sequence to optimize the construction schedule by limiting the stoppages in the different form and concrete lifts. The different concreting steps afloat result in an accumulation of forces and stresses in the lower parts of the structure (the so-called “locked-in” or “built-in” forces and stresses) that can, at the end, depart significantly from the force and stress distributions that can result from an idealized single-step construction sequence. A review of the different construction steps should be carried out using appropriate FE models representative of the construction sequence. Alternatively, the global refined FE model used for the detailed design of the concrete structure can be applied to the different stages by using, for instance, the super-elements technique.

A.12.3.5.2 In-service serviceability analysis

Ice pressure within cracks is not normally included in crack width calculations.

A.12.3.5.3 Fatigue analysis

No additional guidance is offered.

A.12.3.5.4 Accidental and abnormal analyses

No additional guidance is offered.

A.12.3.6 Seismic design

No additional guidance is offered.

A.12.4 Concrete works

A.12.4.1 Design

A.12.4.1.1 Design principles for shell members

No additional guidance is offered.

A.12.4.1.2 Design principles for fatigue

No additional guidance is offered.

A.12.4.1.3 Design principles for durability

No additional guidance is offered.

A.12.4.1.4 Durability considerations

A.12.4.1.4.1 Freeze-thaw cycles

The most important factors influencing the freezing resistance of concrete are the space between air pores, the volume of air pores, the water-cement ratio, the type of binder and the location of the concrete in the structure. The most essential factor is the critical degree of saturation. When this is exceeded, the concrete can be damaged during freezing.

Freeze-thaw resistance should be assessed for the relevant concrete mixes, through new experiments or the application of appropriate published data.

A.12.4.1.4.2 Abrasion

a) Overview of abrasion process

Ice actions can be applied to concrete aggregate stones protruding from the surface once the finer concrete substances have worn off. Ice frozen onto the concrete can, in addition, result in external mechanical actions to the aggregate. The magnitudes of the actions depend both on the ice properties and on the size of aggregate stones. Repeated actions can occur because of the ice failure process.

Reference should be made to relevant field data for the type of concrete used and the ice conditions expected.

b) Abrasion mechanisms

Ice actions can cause different types of stress at the concrete surface. When the surface is smooth after a normal casting and concrete aggregate stones are covered by cement, moving ice causes compression normal to the surface as well as a tangential friction action. The magnitude of the friction action depends on the quality of the surface in question, i.e. the friction coefficient between the ice and the concrete. The value of the dynamic friction coefficient between sea ice and smooth concrete surfaces has been established through tests as 0,24.

Ice frozen onto the concrete can cause tensile actions normal to the surface. The stresses induced have been shown to be rather small. The average bond strength of concrete when frozen onto ice is approximately 0,3 MPa. Abrasion of the concrete surface due to this process is generally slight, and occurs only for new concrete.

The real abrasion of the concrete surface starts when ice acts on the concrete aggregate stones protruding from the concrete surface, partly due to abrasion caused by ice friction and partly due to disintegration of cement stone caused by salt-frost effects. Ice impacting the structure can produce local pressures on the protruding aggregate stones that are significantly greater than the average global contact pressure. Reference should be made to 8.2 and A.8.2 in this regard.

c) Ice processes

Friction effects between concrete and ice have been measured. The factors found to have the most dominant effect on abrasion are the temperature of the ice, the local pressures applied by the ice to the concrete surface, and the strength of the concrete, especially changes in the strength as a result of freeze-thaw cycles. The abrasion rate is greater for lower ice temperatures and for higher stress intensities.

With respect to ice actions, the main parameters that influence the abrasion rate of a surface material (see References [295] to [301]) are:

- normal and shear actions;
- ice temperature;
- relative velocity;
- sliding distance.

The magnitudes of the normal pressures can be evaluated by considering first a smooth contact surface. In these conditions, the highest pressures arise due to brittle ice crushing. The magnitudes of the local pressures are obtained by assuming that the width of the contact area is very small. The method described in A.8.2.5.2 for local ice actions can be applied by assuming that the contact area is very narrow, $w_L \approx 0$, and it follows that the pressure distribution coefficient $\mu = 8,0$ (see A.8.2.5.2).

Ice pressures on very small local areas can increase to a level around 25 MPa to 40 MPa. Higher pressures up to 80 MPa have been measured in the Canadian Arctic on a local area of 100 mm²[302]. These high local pressures can not only abrade the concrete but also lead to accelerated corrosion in steel structures.

While the abrasion rate is not sensitive to the ice temperature if the temperature is higher than –10 °C, the acceleration rate increases significantly in temperatures lower than –10 °C. The effects of ice velocity have been studied because the friction coefficient increases at low ice velocities. Tests have shown that the sliding velocity has only a minor influence on the rate of ice abrasion[297][298][299]. On the other hand, field measurements on a lighthouse in the Baltic Sea indicate that shearing actions can cause more damage to concrete than compressive pressures[303][304][305].

The extent of ice movements of an ice field around a structure can be used to determine the sliding distance between the structure's surface and an ice sheet. The abrasion rate of concrete generally decreases with the sliding distance.

d) Abrasion tests

The abrasion problem of offshore concrete structures for arctic and cold regions is a complex combination of the effects produced by cyclic freezing and thawing in seawater, temperature changes and ice actions, as follows.

- The abrasion depth and resistance of concrete can be determined by means of either abrasion diagrams or laboratory tests. The best results are achieved when using both. With abrasion diagrams, the abrasion depth can be estimated as a function of the compressive strength of concrete and ice sheet movement. The abrasion resistance can also be measured with a 10 min laboratory abrasion test, prior to which the concrete plate should undergo a cyclic thaw test in seawater for 50 cycles at temperatures ranging from –50 °C to +20 °C.
- The most important mechanical factor pertaining to measurement of the resistance to abrasion of concrete is the strength of the concrete. The bond strength of aggregate stones and cement stone and its resistance to repeated freeze-thaw cycles is especially crucial. In order to ensure good resistance to abrasion, the compressive strength of concrete should be at least 70 MPa. Naturally, the concrete should also be frost-resistant; see 12.4.1.4.1. The strength of concrete during repeated freeze-thaw tests is generally highest when the water-cement ratio is not more than 0,30 to 0,35.
- During repeated freeze-thaw tests of ordinary cement concretes, the bond strength of aggregate stones at the concrete surface diminishes more rapidly than either the compressive or tensile strengths. Apparently, changes in temperature exceeding 40 °C deteriorate the bond of stones at the surface and increase surface cracking.
- The best results in both the strength and abrasion tests are achieved with concretes containing silica and blast furnace slag, and the poorest results with lightweight aggregate concretes.
- The resistance to abrasion of concrete can be improved by preventing frost damage, by keeping the entire wall either sufficiently warm or frozen, so that it is not exposed to freeze-thaw cycles.
- If the bond strength of concrete aggregate stones is at least 8 MPa, the resistance to ice abrasion of concrete is considered to be very good.
- If the abrasion depth in the laboratory conditions after a freeze-thaw test of 50 cycles is no more than 10 mm, the resistance to ice abrasion of the concrete can be considered good.

- Increasing the maximum size of the aggregate reduces the abrasion of concrete. Large stones protruding from the concrete surface break the ice before the finer concrete particles are damaged.
- The use of hard, homogeneous concrete in the ice abrasion zone reduces abrasion, because the surface is subjected to even abrasion and there are no stones subjected to ice action.

e) Mitigation measures

In certain circumstances, steel armour can be fitted to the outside of the concrete elements subject to ice abrasion. However, it is necessary to take particular care in designing and installing such devices, because the migration of water between the protected concrete surface and the inside of the armour, with the associated risk of freezing, can result in local damage. Furthermore, steel plating requires adequate cathodic protection that either is not exposed to, or is designed for, ice actions.

A.12.4.1.4.3 Concrete cover

Caution should be taken when increasing the concrete cover for resisting abrasion and wear because, beyond certain limits, an excessively thick concrete cover (in the range of 60 mm to 70 mm) can be a source of spalling even under moderate actions. In that case, skin reinforcement should be provided. Alternatively, steel armour can be provided for abrasion and wear protection without increasing concrete cover, with the subsequent drawback of corrosion and the requirement for corrosion protection.

Where it is proposed to improve abrasion resistance by the use of external steel plates on the external face, care should be taken to avoid delamination resulting from the migration and freezing of water vapour beneath the plate.

A.12.4.1.5 Design principles for buckling

No additional guidance is offered.

A.12.4.1.6 Design principles for imposed deformations

No additional guidance is offered.

A.12.4.1.7 Design for fire resistance

No additional guidance is offered.

A.12.4.1.8 Partial factors for materials

No additional guidance is offered.

A.12.4.1.9 System ductility

No additional guidance is offered.

A.12.4.1.10 Minimum reinforcement

No additional guidance is offered.

A.12.4.2 Materials

An appropriate testing standard for adequate freeze-thaw resistance in concrete is ASTM C666^[24], or equivalent.

For further information on lightweight aggregate for concrete, reference should be made to, for example, Reference [22].

Reinforcement in permanently submerged concrete does not require special corrosion protection, particularly if the structure is fitted with cathodic protection. In parts of the structure with the potential for corrosion of the reinforcement, requirements for concrete quality (resistance to chloride penetration and oxygen diffusion, use of silica fume and fly ash, additives, etc.), coatings and cover are feasible measures, as well as use of galvanized rebar. If improved reinforcement is necessary, stainless steel is preferred over epoxy-covered reinforcement because the latter requires careful handling to avoid damage. Fibre-reinforced polymer reinforcement can be considered since it has already been accepted by some national codes, such as ACI and CSA, but it is necessary to demonstrate its suitability at low temperatures.

Appropriate testing methods for concrete air-voids are found in References [25], [21] and [23].

A.12.4.3 Execution

A.12.4.3.1 Formwork

No additional guidance is offered.

A.12.4.3.2 Pre- and post-tensioning

No additional guidance is offered.

A.12.4.3.3 Protective measures

No additional guidance is offered.

A.12.4.3.4 Concreting

No additional guidance is offered.

A.12.4.3.5 Embedded components

See Reference [30] for embedded items.

A.12.4.3.6 Hydrotesting

Autogenous healing can be effective in sealing small through-thickness cracks that have arisen through early-age thermal effects or restraint introduced during construction. Sufficient time should be allowed to complete the autogenous healing process.

A.12.4.3.7 Hot and cold weather works

A.12.4.3.7.1 Concreting in cold weather

Guidelines for concreting in cold weather can be found, for example, in CSA A23.1-04^[27] and ACI 306R^[14]. Cold-weather concreting, curing and protection of concrete should meet the following requirements.

- a) Special attention should be given to the curing of concrete to ensure maximum durability and minimal cracking.
- b) Seawater should not be used for the initial curing of reinforced or pre-stressed concrete. After three days, concrete can be submerged in seawater to effect the final curing.
- c) Seawater should not be used for cleaning formwork.
- d) For thick, massive concrete sections, heat generation caused by hydration of the cementitious material should be evaluated, and measures should be taken to control cracking and restraint stresses under various conditions of volume change and restraint.

NOTE Measures to protect concrete from severe temperature differentials are described in CAN/CSA A23.1-04^[27] or an equivalent standard.

- e) The concrete should be maintained in a moist condition at a temperature above 10 °C for at least the first three days after placing, or for the time necessary to reach 35 % of the specified 28-day compressive strength. When it is necessary to expose concrete to severe exposure and/or abrasion immediately following the basic curing period (although it is recommended that such situations be avoided), the concrete should be cured either for an additional four consecutive days at a minimum temperature of 10 °C, or for the time necessary to reach 70 % of the specified 28-day compressive strength.

Special requirements for the type and duration of the curing process, together with the details of any special conditions that are necessary to maintain, should be specified.

During freezing weather, water-curing of concrete should be terminated 12 h before the end of the protection period.

Curing compounds should not contain chlorides. Curing compounds should not be used on surfaces where succeeding layers of concrete will be placed and bonded, unless one of the following conditions is met:

- the curing compounds are entirely removed at the end of the curing period by sandblasting or use of an approved solvent;

- conclusive tests show that the residue of the membrane does not reduce the bond to below design limits;
- suitable mechanical means for full bond development are provided.

Curing compounds should not be used on a surface where coatings or paint will be applied, unless prior compatibility with the coating has been confirmed by tests.

When the air temperature either is at or below 5 °C, or is forecast to fall below 5 °C within 24 h of placing, all materials and equipment required for adequate protection and curing should be on hand and ready for use before concrete placement is started.

When referring to concrete construction, cold weather is defined as a period of three consecutive days during which the mean daily temperature drops below +5 °C.

When temperatures above +10 °C occur during more than half of any 24 h period, the concrete should no longer be considered cold-weather concrete.

During cold weather, means should be provided for maintaining the temperature of newly placed concrete above the minimum values contained in codes^[27] referring to concrete placement and workmanship, for a minimum period of three days or until sufficient hydration has occurred to protect the concrete from frost damage.

Aggregate should be free from snow and ice at the time of use.

All snow and ice should be removed before concrete is deposited on any surface. Calcium chloride or other de-icing salts should not be used as de-icing agent in the forms. Concrete should not be placed on, or against, any surface that lowers the temperature of the concrete in place below the minimum values shown in Table A.12-1.

Table A.12-1 — Minimum concrete temperature after placing

Air temperature °C	Minimum concrete temperature after placing °C		
	Minimum dimension of the concrete section		
	<1 m	1 m to 2 m	>2 m
>-1	13	10	7
-18 to -1	16	13	10
<-18	18	16	13

The required minimum temperature of the concrete immediately after placing can be achieved by heating the water or the aggregate, or both (e.g. see recommendations for cold-weather concreting as given in Reference [14].

Once mixed, the concrete should be maintained at a temperature of not more than 6 °C above the minimum temperatures specified in Table A.12-1.

These concrete temperatures should be maintained for a duration that depends on the ingredients used, their position in the mixture and the required strength. The in situ strength development during cold-

weather construction should be monitored to ensure adequate safety associated with the removal of shoring and formwork.

A.12.4.3.7.2 Grouting of pre-stressing duct during cold weather

No additional guidance is offered.

A.12.4.3.7.3 Placing and bending reinforcement during cold weather

No additional guidance is offered.

A.12.5 Mechanical systems

A.12.5.1 Introduction

No additional guidance is offered.

A.12.5.2 Permanent mechanical systems

A.12.5.2.1 Crude oil storage system

GRP (glass-fibre reinforced plastic) pipes can be used as long as brittleness criteria are met. Steel qualities for such use are found, for instance, in Reference [43] or other relevant standards.

A.12.5.2.2 Other storage systems

GRP pipe should be used with caution in ballast and seawater systems, because of the potential damage from differential displacements of the supporting structure.

A.12.5.2.3 Risers and J-tubes

No additional guidance is offered.

A.12.5.3 Mechanical systems — Temporary ballasting/deballasting water systems

No additional guidance is offered.

A.12.5.4 Attachments and penetrations

No additional guidance is offered.

A.12.5.5 Mechanical systems — Design of piping supports

No additional guidance is offered.

A.12.6 Marine operations and construction afloat

No additional guidance is offered.

A.12.7 Corrosion control

No additional guidance is offered.

A.12.8 Inspection and condition monitoring

No additional guidance is offered.

A.13 Floating systems

A.13.1 General

Many solutions, both global and local, are available to the designer of a floating system for use in ice-covered waters. There can, therefore, be cases where discussions on design and assessment of such a structure cannot be logically placed within this document, or where specific requirements are found not to be relevant. In such cases, the design or configuration should be based upon the principles documented in this document, and should achieve a level of safety equivalent or superior to the safety level implicit in this document. The principles documented in this clause are applicable both to steel-hulled floating structures and to structures fabricated from other materials.

This document does not provide detailed instructions for producing reliable estimates of the environmental parameters to consider for all floating systems. In this regard, it is important to incorporate past experience for data gathering and analysis procedures, statistical techniques, and defining the key environmental influences and factors for a particular system, including those associated with IM. Because long-term data are often lacking in arctic and cold regions, operating plans and procedures should recognize specifics of the environment and associated uncertainties. The involvement of ice and metocean experts, as well as experienced mariners in such conditions, is imperative for safe and effective operations. Guidance is provided in ISO 19901-1 and ISO 35106.

When using environmental information, it is also important to be aware of the uncertainties in the parameters provided and the effects of any uncertainties on the overall system being designed or assessed. Assumptions made and operating limits defined for floating systems should also be carried forward as the basis for operating procedures once the system is put into service, and refined as operating experience is gained.

See Reference [19] for provisions relating to tension-leg platforms. While tension-leg platforms and jack-up structures are beyond the scope of this document, the ice environment and action provisions contained in 13.3 and 13.4 can be applied.

A.13.2 General methodology

A.13.2.1 Design and operational philosophy

The range of ice considerations for most floating systems is generally broader than that for fixed structures. This is due to:

- the integration of design and operational aspects of a floating system;
- the variety of systems used to protect it, including IM, disconnection and move-off;
- the effectiveness of operational measures used to protect the floating system;
- the different means by which system reliability can be achieved.

For all except for passive systems, iterative cost-benefit considerations are an important part of the design and assessment process. Due consideration should be given to feasibility of the intended operational measures. Safety should be a part of the cost-benefit considerations.

There are many unique features associated with floaters operating in ice. When a floating structure operates as a ship, there are specific requirements for ice clearing from water intakes, turrets and thrusters. For multi-legged floating structures, ice rubble, small floes or small pieces of glacial ice can accumulate between the legs and influence the effective dimensions of the structure for certain ice conditions.

A.13.2.2 Design and operational approaches

Floating systems that are deployed in ice-covered waters are often supported by IM vessels, with the intended role of modifying the local ice environment, reducing ice action levels on the structures, and enhancing ice clearance around them.

The type of IM system deployed can have a significant influence on the design approach taken for a floating system. This influence depends upon the expected ability to consistently detect potentially adverse ice conditions, forecast drift trajectories, and successfully manage these ice conditions before they interact with the structure (e.g. by towing icebergs or reducing floe size).

A variety of design and operating approaches can be selected for floating systems in ice-prone waters as follows.

- a) **Passive:** at one end of the spectrum, a floating system can be configured to withstand all of the expected ice and other environmental actions, both normal, extreme and abnormal, without any type of physical IM support and without the capability to disconnect and move off location. This is similar to the design approach normally adopted for fixed offshore structures, and for many floating systems in open water environments.
- b) **Semi-passive:** this approach makes use of physical IM support but without the capability to disconnect and move off location. One such example is a structure operating on location where ice presence is infrequent and ice conditions are relatively light and can be handled by a reasonable level of physical IM support.

c) Semi-active: this approach does not make use of any physical IM support. In order to prevent interactions with ice that can exceed the resistance capabilities of the structure, the floating system can be moved off location in the context of well-defined ice alert procedures. One such example is a seasonal platform operating during the so-called shoulder seasons when ice conditions are relatively light. Another example is a structure exposed to infrequent ice threats which would be impractical to manage physically.

d) Active: at the other end of the spectrum, a floating system can be operated to avoid particular ice conditions, for example, by managing the ice in the context of well-defined ice alert procedures. If conditions become too severe, the platform can stop operations and move off location.

A wide range of design and operating approaches can be taken, with varying levels of ice tolerance (in the platform's structural and stationkeeping capabilities), different disconnection and move-off systems (and time frames for this response) and various levels of IM support.

The range of options that can be considered for floating systems in ice-covered waters is illustrated in Figure A.13-1.

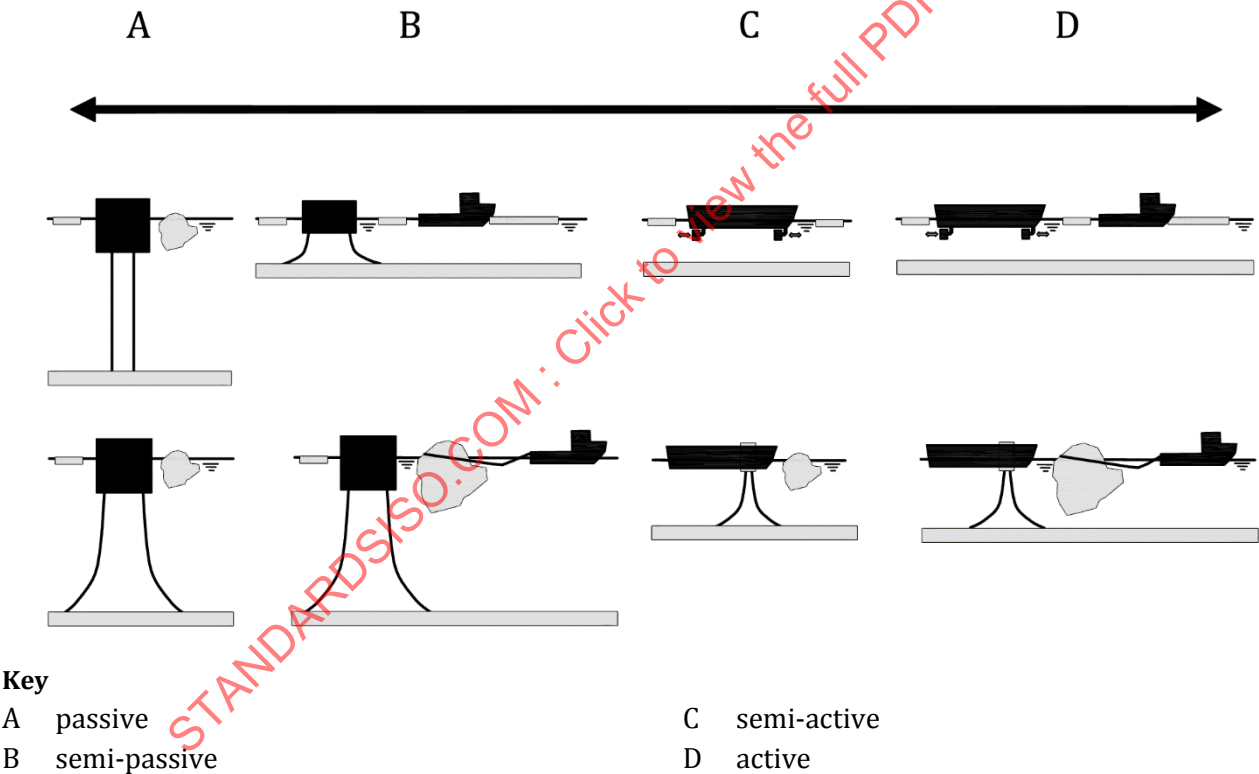


Figure A.13-1 — Range of options for floating systems in arctic and cold regions

For floating systems that operate actively, the importance of reliably detecting adverse ice conditions (e.g. icebergs, MY ice floes, large FY ridges, rubble fields, ice pressure events) prior to their interaction with the structure, and the capacity and reliability of an IM system to contend with adverse ice situations should be clearly recognized. Logic diagrams that show the relationship between the various factors are provided in Figures A.13-2 to A.13-5 for the range of options for floating systems.

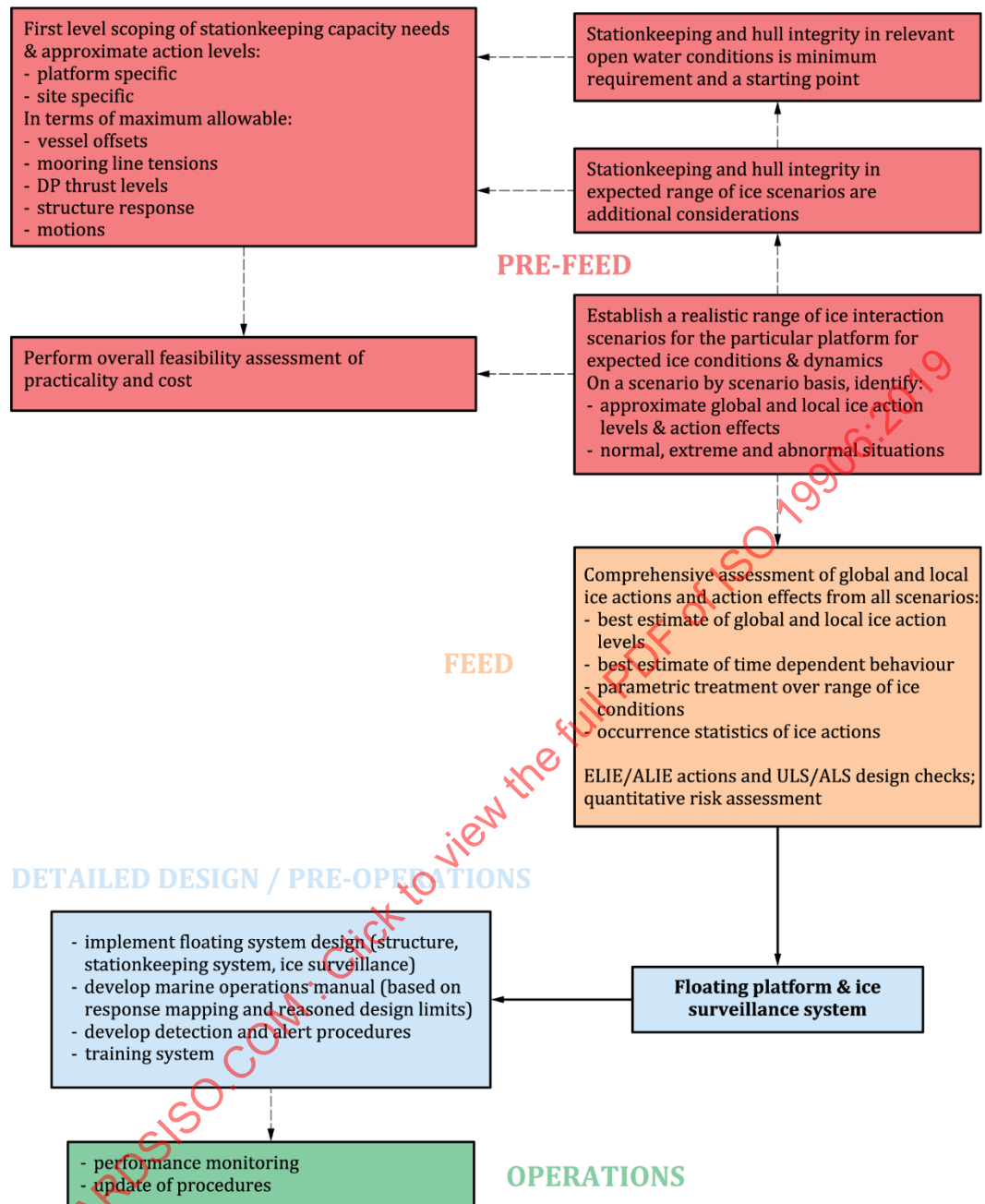


Figure A.13-2 — Relationship between the various factors for passive floater operations in ice environments

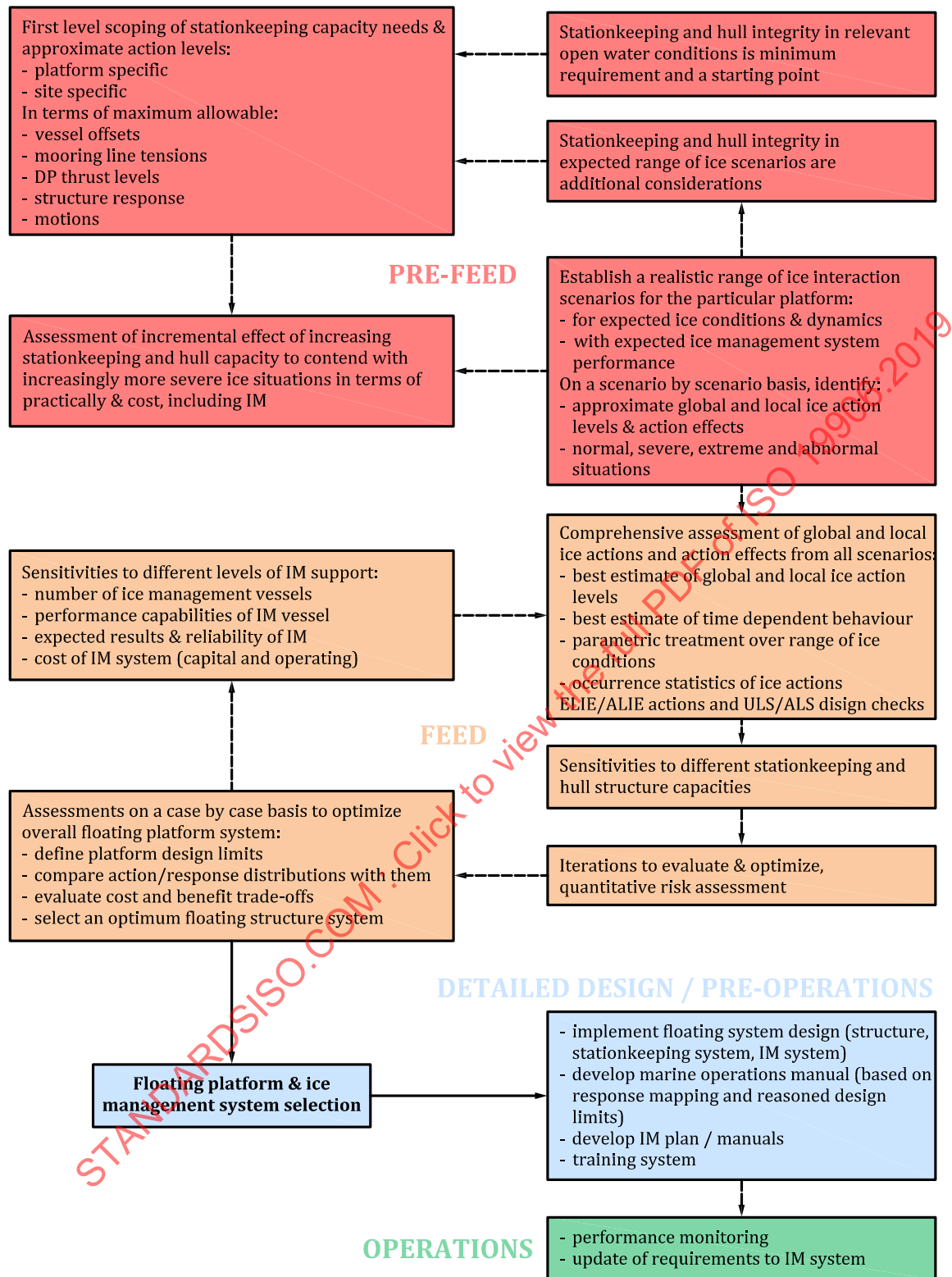


Figure A.13-3 — Relationship between the various factors for semi-passive floater operations in ice environments

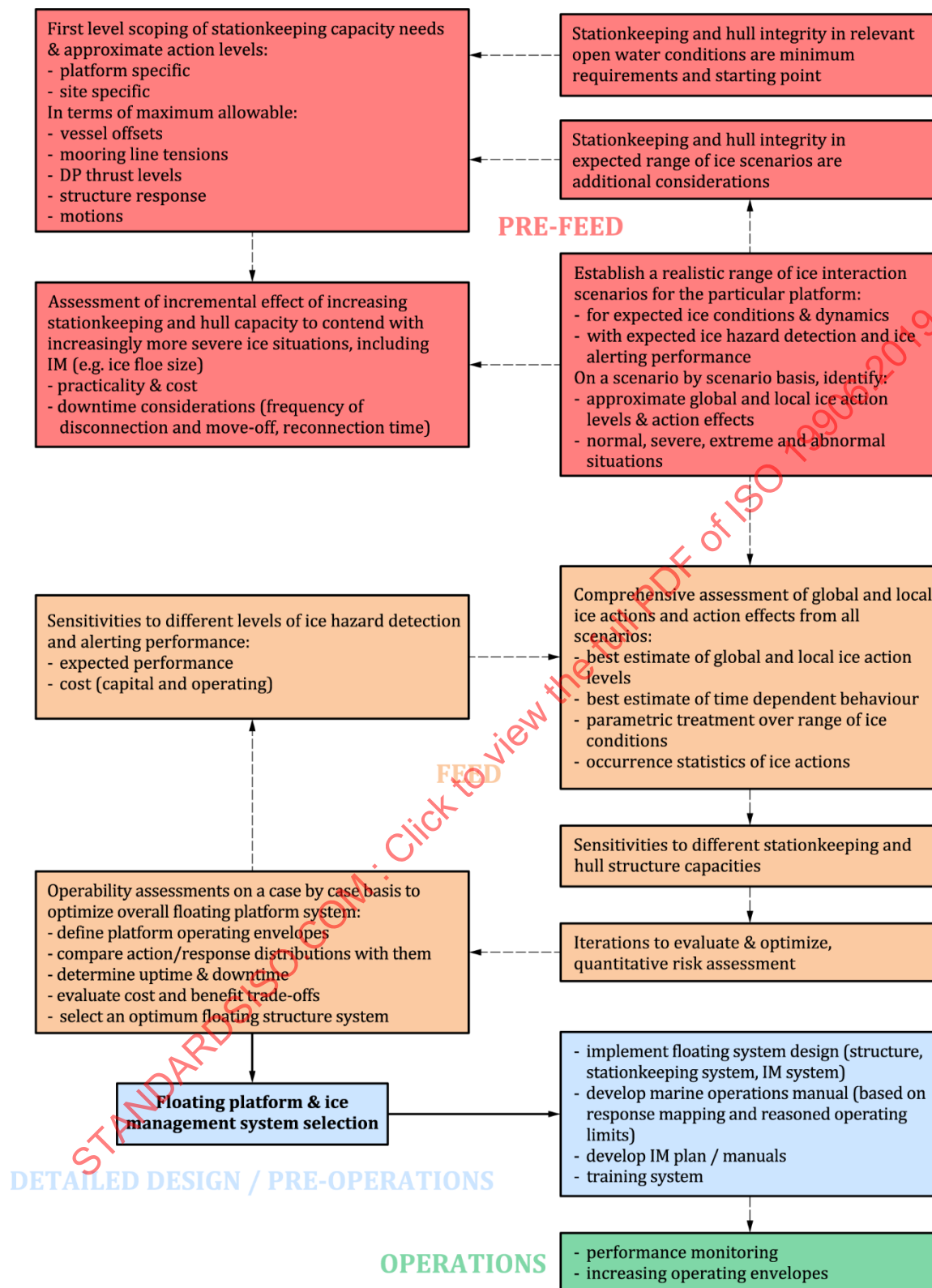


Figure A.13-4 — Relationship between the various factors for semi-active floater operations in ice environments

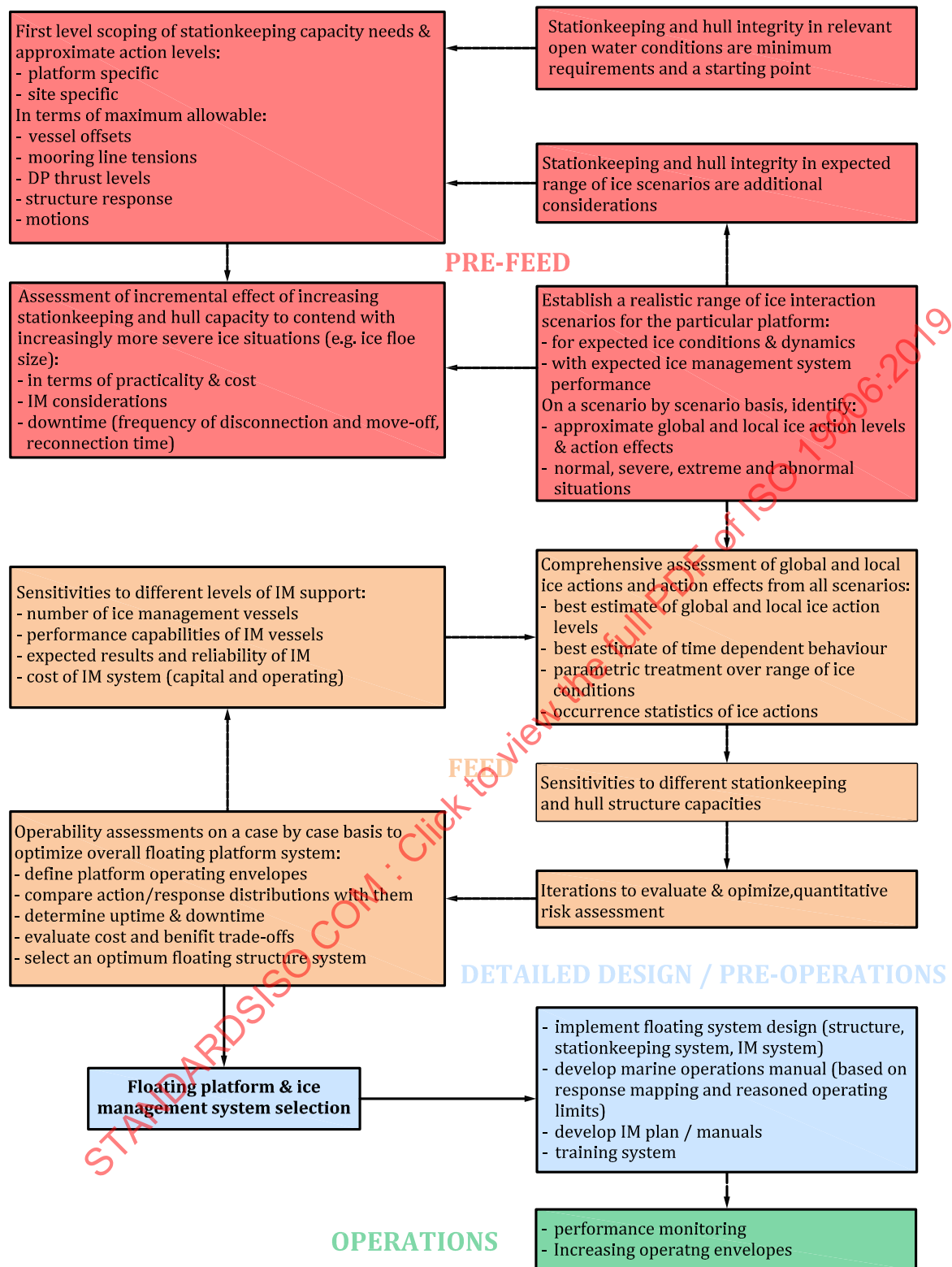


Figure A.13-5 — Relationship between the various factors for active floater operations in ice environments

The consequences of ice actions on the various components of a floating production platform can be influenced by operational measures, such as down-manning, flushing of flowlines and disconnection of subsea equipment. Such measures are used for the designation of exposure levels, as specified in Clause 7. Exposure levels can be applied for the entire floating system or portions thereof. A higher exposure level than required can be specified based on the value of the asset and lost production time. Consideration of hull integrity and stability should be factored into any reduction in exposure level from L1.

A.13.2.3 System considerations

Impressed current, low friction coatings, other coatings suitable for use in ice, or stainless-steel belts can be considered for reducing loss of shell plate thickness through abrasion and corrosion.

A.13.2.4 Ice alert system

No additional guidance is offered.

A.13.3 Environment

No additional guidance is offered.

A.13.4 Actions

A.13.4.1 Applicability

No additional guidance is offered.

A.13.4.2 Ice scenarios

No additional guidance is offered.

A.13.4.3 System-specific ice actions

For all floating systems, and in particular for passive and semi-passive systems, there should be general awareness that partial action factors as provided in Clause 7 are not calibrated for a full range of floating systems, ice situations and operational measures.

Design limits (envelopes) should be specified in the context of the resistance (ULS and ALS) of structural components as well as other system capacities. Operating limits (envelopes) involve additional safety margins to account for relevant operational measures and their maturity. The ice alert system is based on the operating limits.

Both design and operating limits should be translated to practically observable quantities and ice conditions, potentially involving multiple parameters. Specific operational procedures should be well defined and implemented, to ensure that hull and stationkeeping system design and operating limits involving offsets or other floating system response parameters are not violated.

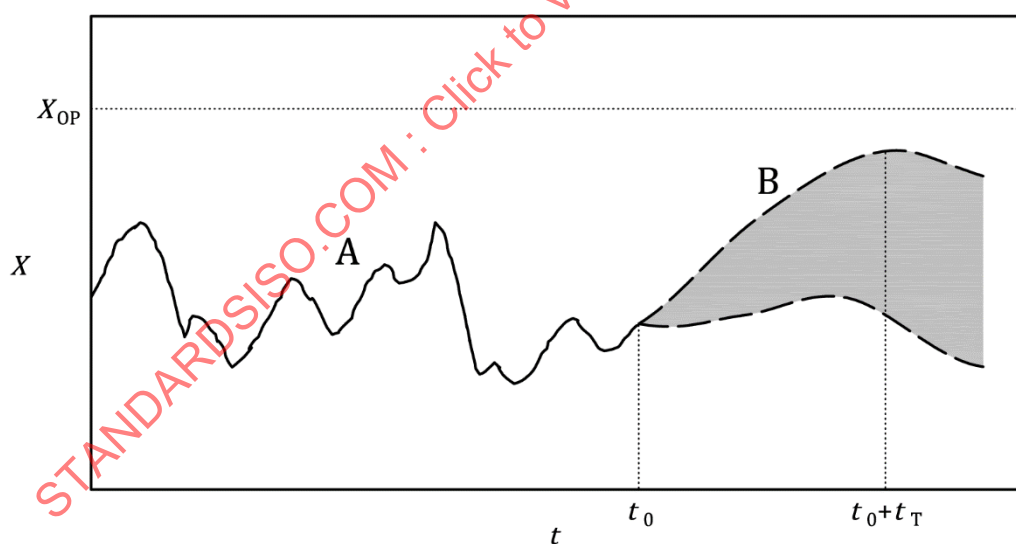
At the start of the operations, the operating limits should be sufficiently less than the design limits to account for uncertainties associated with the operational procedures (see Figure A.13-6). Initially, the ratio of the design limits to the operating limits can be set as 2 (two), until documented otherwise or until more in-ice operating experience is gained. The operating limits should consider the action effect rise times versus the time to invoke all relevant responses associated with the safety barriers in the ice alert system, including the decision-making process.

For semi-passive systems there is a need to demonstrate, both during the design phase and during the operational phases, that the IM system delivers the operating ice envelope, translated into practically observable quantities, upon which decisions can be made with a required degree of confidence.

For active and semi-active systems, minimum safety requirements should involve a demonstration of capability to shut-in, move-off, and/or de-manning for ice conditions or ice events which are in excess of the operating envelope.

ISO 19901-7, is written under the assumption that the design values for ULS are larger than ALS. This is a valid assumption for most environments and has basis in open water design practice. In arctic and cold regions where icebergs and sea ice are present, the requirement to verify ULS in 13.4.3.1 is potentially more severe than specified in ISO 19901-7, where the ULS can be waived without calculation of EL actions. Floating systems in arctic and cold regions should consider situations where

- there are AL ice actions but zero EL ice action (rare occurrence of ice), or
- the AL action is greater than the EL action.



Key

A	measured offsets	t	time
B	forecast envelope of offsets	t_0	present time
X	offset	t_T	T-time or time to shut down operations
X_{OP}	operational offset		

Figure A.13-6 — Example showing graphically how operating limit can be determined on the basis of forecasted action effect rise time during the time to invoke relevant safety barriers

A.13.4.4 Determination of global ice action effects

At present, there is an absence of full-scale data for actions on floaters from icebergs and large, thick sea ice floes. Full-scale data exist from the Kulluk drilling platform documenting actions from thicker managed floes and from unmanaged FY sea ice (see Reference [306]). Considerable amounts of full-scale resistance data exist for icebreakers in a range of sea ice conditions and some data exist for impacts with bergy bits (see Reference [307]). Full-scale data remain as key inputs for global ice actions on stationkeeping vessels. In the absence of such data, numerical approaches can be considered. Data also exist from ice basin experiments on a variety of hull forms for stationkeeping vessels, and opportunities exist for the acquisition of new data on specific floating-structure concepts.

Numerical modelling techniques have seen rapid acceptance and are becoming more capable of solving complex ice-structure interactions. Such models should be used with due consideration of their validity in application to specific structure geometries and stationkeeping characteristics, ice conditions and ice situations.

Careful consideration should be given to corrections for structure geometry, friction coefficients, and stationkeeping characteristics when applying full-scale ice action data to other situations.

Appropriate use of relevant full-scale data, scaled physical tests, and numerical models can involve:

- validation of numerical models based on full-scale data, or where reliable analytical solutions can be achieved;
- pre-simulation of the test matrix to obtain input for blind-testing for the actual modelled conditions and the associated ice behaviour (failure modes) and to optimize the test matrix;
- distorted scale tests to eliminate model scale artefacts and obtain input for validation of numerical models (for sea ice conditions);
- calibrating “as-achieved” results from scaled physical model tests to “target ice conditions” by eliminating deviations and artefacts of numerical models.

Particular attention should be given to misuse of numerical models whose full-scale validation is inappropriate in the context of use for a specific design or assessment.

Particular care should be taken to document actual model test conditions, and attention should be given to reduce boundary and scale effects, and to ensure the representation of realistic failure modes. Where differences between actual and target ice conditions are large, model test results should only be used after appropriate corrections are made.

Physical model tests and numerical models can potentially be used to investigate ice accumulations and under-hull ice transport.

A.13.4.5 Risk to adjacent structures

Avoidance of actions on other structures and facilities can be accomplished through constraints to alerting protocols and by adjustment to the design of the floating system and its components. Potential risks should be identified that could involve IM and other work vessels, anchors, mooring lines, risers, buoys, turrets, and other stationkeeping components.

Changes to the ice cover as a result of IM could include brash ice formation and disruptions or increased ice actions resulting from its consolidation. IM could potentially destabilize an ice cover and alter the actions on adjacent structures. Iceberg calving or floe breaking as a result of IM activities could potentially increase the number of ice features impacting other structures and facilities. Deflection of ice features could increase risks to other structures and facilities.

A.13.4.6 Other ice action considerations

No additional guidance is offered.

A.13.4.7 Action variations

No additional guidance is offered.

A.13.5 Hull integrity

A.13.5.1 Structural philosophy

Some rules for ice-strengthened vessels apply icebreaking mechanisms and action equations that are more appropriate for moving ships than stationary ship-shaped structures. Stationary floating systems cannot selectively avoid extreme features and can have limited manoeuvrability, and should be designed or assessed accordingly.

Vessels intended for seasonal production can experience different or more onerous ice actions during mobilization and demobilization, to which additional consideration should be given.

The design of the hull should be assessed in the context of ISO19901-7, clause 6.4.2.2.3 for disconnectable systems. The design should account for adverse and unforeseen effects, such as failure of the IM system to deliver tolerable ice conditions and failure to disconnect. This design should also apply for all conditions up to and including failure of the stationkeeping system, as well as in a damaged condition following accidental or abnormal-level actions. A specific and appropriate ALS design situation to ensure hull integrity until more operational experience is gathered should be considered.

A.13.5.2 Hull ductility

Any area exposed to low air temperatures should be constructed with ductile materials suitable for operation in this environment. It can be necessary to upgrade structural steel class and grades for weather-exposed plating and for inboard framing members attached to this plating.

A.13.5.3 Structural analysis and design

For discrete impacts from glacial ice, ice ridges and other large ice features, a dynamic model of the impact process incorporating attributes of both the hull structure and the ice feature can be useful for assessing action effects.

A.13.5.4 Structural considerations

No additional guidance is offered.

A.13.5.5 Condition monitoring

No additional guidance is offered.

A.13.6 Hull stability**A.13.6.1 General considerations**

No additional guidance is offered.

A.13.6.2 Subdivision

See Reference [38], the polar code for ships operating in polar waters, for general guidance and for longitudinal subdivision requirements in particular.

Double-hulled vessels include double-side, double-bottom and double-side, and single-bottom designs. In certain situations, such as for floating concrete structures, a double bottom is not necessarily required to provide the necessary damage protection. Adequacy with respect to ice actions should be demonstrated.

A.13.6.3 Intact stability

Reference [38] provides specific guidelines for the intact stability of arctic ships. While focused on ship hull forms, many of the provisions can be applied to other floating systems.

A.13.6.4 Damaged stability

Specific guidelines for damaged stability of ship hull forms are provided in Reference [38].

A.13.7 Stationkeeping**A.13.7.1 General****A.13.7.1.1 Types of systems**

A floating system with suitable means of keeping its position at the specific site of intended operation usually consists of a mooring system connecting the floating system physically to the seabed, or a DP system whereby the floating system is kept in position by means of thrusters, or a combination of mooring and thrusters.

The type of stationkeeping system involved depends on the type of floating system and the chosen system solution. Table A.13-1 gives an overview of the relevant stationkeeping systems.

Table A.13-1 — Overview of stationkeeping systems

Structure type	Primary stationkeeping system	Details
Monohull (fixed direction)	Spread moored	Slack or taut lines fixed or quick disconnect
Monohull (rotatable)	Single-point moored turret	Slack or taut lines fixed or quick disconnect DP or thruster assisted
Semi-submersible	Spread moored	Slack or taut lines fixed or quick disconnect DP or thruster assisted
Spar	Spread moored	Semi-taut, taut or catenary lines
Tension leg platform (TLP)	Vertically tensioned tethers	Fixed system, no possibility for disconnection

A.13.7.1.2 Monohull floating systems

The following positioning systems can be used for monohull floating systems.

- a) Spread mooring: a system consisting of mooring lines terminated at different locations on the structure and pointing outwards, providing an almost constant heading.
- b) Turret mooring: a system consisting of mooring lines attached to a turret with bearings, allowing the floating system to vary its heading. The turret can be of a disconnectable/reconnectable type, allowing the disconnection of both mooring lines and risers from the vessel to avoid direct contact from icebergs or sea ice above a certain action level. Positioning systems include:
 - a passive or active mooring system allowing the structure to weathervane freely;
 - a combination of a passive or active mooring system and thrusters for heading control;
 - a combination of an active or passive mooring system and thrusters for both heading control and reduction in mooring actions;
 - those kept in position by thrusters only.
- c) Single-point mooring: a system consisting of a fixed tower or a single-point mooring system, e.g. single anchor leg mooring (SALM), single point mooring (SPM) or submerged turret production mooring.

A.13.7.1.3 Semi-submersibles and buoy type floating systems

The following positioning systems can be used for semi-submersibles as well as buoy type structures (spars, buoys and SALMs):

- passive or active spread-mooring system;
- combination of a passive or active spread-mooring system and thrusters for reduction in mooring actions;
- those kept in position by thrusters only.

A.13.7.1.4 Tension leg platforms

The tension leg platform (TLP) concept is kept in position by vertical, tensioned mooring components. While the components are normally made of steel, designs using composite materials are also applicable.

Reference [19] contains provisions relating to TLPs.

A.13.7.1.5 Other performance-enhancing systems

Supplementary to the above systems, various performance-enhancing or ice action and action effect reduction means can be utilized. Examples include air bubbler systems and water sprays, special hull paints and added thrusters.

Additionally, each of the above-mentioned mooring systems can be equipped with remote and quick-disconnect mooring systems to facilitate the quick release of all mooring lines.

A.13.7.2 Design of the stationkeeping system

No additional guidance is offered.

A.13.7.3 Disconnection and reconnection

Disconnection of the mooring lines and other connected lines can be done individually, or partly or fully coupled. A ship-shaped floating system can be equipped with the latter option, where all lines are physically connected to a connecting component (disconnectable turret).

A potential design approach for disconnectable turret systems is to allow the turret to drop to a safe depth with respect to the draught of icebergs, sea ice ridge keels, or other large ice features.

A.13.7.4 Stationkeeping system failures

No additional guidance is offered.

A.13.8 Mechanical systems**A.13.8.1 General considerations****A.13.8.1.1 Applicability**

No additional guidance is offered.

A.13.8.1.2 Systems and equipment

Low air temperatures can increase the risk of failure in load-bearing parts as well as in mechanical equipment (for mooring, life-saving, lifting appliances, processing, etc.) due to changes in steel properties.

A.13.8.1.3 Icing and snow

Special ice-phobic coatings can be effective in reducing ice accretion. These coatings have a short useful life. Selective application (e.g. on forward areas of superstructure) of such coatings should be considered, particularly for small vessels operating in areas where icing is known to be a problem. Such coatings should not be used on walking areas due to their inherent slickness.

A.13.8.2 Hull systems

A.13.8.2.1 Sea inlets and cooling water systems

The volume of sea chests should be approximately 1 m³ per 750 kW engine output of the floating system, including the output of the auxiliary engines necessary for the floater's service.

Other arrangements for sea chests and sea bays can be considered, see Reference [40].

A.13.8.2.2 Ballast system

When a tank is situated partly above the ballast waterline, an air-bubbling arrangement, vertical heating coil or other ice growth reduction system, capable of maintaining an open hole in the ice layer, is normally acceptable. Other ice growth systems are ballast- or cooling water recirculation systems. Before the pumping of ballast water is commenced, the proper functioning of level gauging arrangements should be verified and air pipes checked for possible blockage by ice.

A.13.8.2.3 Marine systems instrumentation

Issues for consideration include the following.

- A branch pipe with a small diameter to a sensor can cause many problems with respect to viscosity, freezing, hydrate formation, condensation, etc.
- Icing from the outside of valves can cause problems with regard to the position indication of the valve.
- Handles and wheels of manual manoeuvring units can be exposed to icing.
- Certain types of fire and gas detectors and recording methods can be dependent on their own temperature, the temperature of the environment, riming of lenses, etc.
- Relays can operate slowly at low temperatures.

For pneumatically operated valves, dry air should be used to avoid hydrate formation and blockage of supply lines. For hydraulically operated valves, particular attention should be given to the viscosity characteristics of the fluid at low temperatures to ensure that the valve operates within the required time frame.

A.13.8.2.4 Lighting

No additional guidance is offered.

A.13.8.2.5 HVAC and air systems

No additional guidance is offered.

A.13.8.2.6 Starting arrangements

Self-propelled floaters with engines that are started by compressed air should be provided with not fewer than two air receivers and the total capacity of the air receivers should be sufficient to provide, without replenishment, air for:

- a) 12 starts in the case of a floater with reversible engines;
- b) 6 starts in the case of a floater with non-reversible engines.

The compressed air should be provided by more than one independently driven air compressor, and the air compressors should have sufficient capacity to charge the air receivers from empty to maximum pressure in not more than 30 min.

The capacity of the smallest air compressor should not be less than two-thirds of the capacity of the largest air compressor.

A.13.8.2.7 Propulsion, thrusters and steering for self-propelled floaters

No additional guidance is offered.

A.13.8.3 Offloading systems

The following aspects should be taken into account for the proper design and operation of this equipment:

- protection;
- local heaters;
- hydraulic and/or pneumatic proper for cold environment operation;
- load-bearing units that are checked and validated and the proper selection of materials;
- accessibility and proper operation of all equipment;
- offloading hoses and associated gear;
- rapid disconnect valves and shutdown systems;
- planned and emergency disconnection operations;
- direct and indirect ice actions.

A.13.9 Operations

A.13.9.1 General

Special operational issues for floaters in arctic and cold regions include low ambient light, ice and snow accumulation on the deck and exposed equipment, hypothermia and freezing of exposed skin, and vessel motions in heavy ice conditions.

A.13.9.2 Operations and emergency procedures manuals

Depending on the type of system employed, operational procedures can include, but are not limited to:

- communications;
- prevention and pollution, garbage and refuse;
- mooring procedures;
- cargo transfer operations;
- crew transfer procedures;
- bunker transfers;
- crane operations;
- deck operations;
- engine room operations;
- vessel stability;
- ice alert.

Depending on the type of system employed, emergency procedures can include, but are not limited to:

- a) severe weather and ice conditions;
- b) damaged vessel
- c) power failure;
- d) abandon vessel;
- e) mooring system failure
- f) ballast emergency;
- g) fire or explosion;
- h) blowout;

- i) detection and leakage of gas;
- j) medical emergency;
- k) helicopter emergencies;
- l) man-overboard and search and rescue.

A.13.9.3 Deck surfaces

No additional guidance is offered.

A.13.9.4 Damage control

No additional guidance is offered.

A.13.9.5 Equipment and doors

Prior to conducting any activity, operating personnel are expected to take due precautions for safe operation as specified in the operations manual. Conditions include, but are not limited to:

- checking of actual wind chill conditions;
- checking of proper lighting in all work areas;
- provision of proper heating;
- proper functioning of all equipment;
- proper protective clothing;
- proper and fully operable communication equipment;
- use of a buddy system;
- removal of snow and ice.

A.13.9.6 Inspection and maintenance

Some systems might not be accessible for part of the year. Properly engineered solutions lead to safer operation until access is possible. For more information on the design of floaters with respect to provisions for inspection and maintenance, see Reference [39].

Systems that are immediately accessible, like a fire system, can be readily monitored and inspected. Normal inspection frequencies ensure proper operation. Cold temperatures, ice growth or changed characteristics can prevent their efficient operation. Increased inspection frequencies can be required in such circumstances.

Some equipment like the mooring system and subsea components connected to the floater are not immediately accessible. Consideration of the following alleviating methods can ensure the proper functioning of such systems at all times:

- overdesign of the critical components;
- installation of a full back-up;
- installation and use of remote control inspection methods and systems.

A.13.9.7 Planning and operations

No additional guidance is offered.

A.14 Subsea production systems

A.14.1 General

A.14.1.1 System components

A number of design approaches and technical solutions developed for subsea pipelines in arctic and cold regions can also be applied to the calculation of ice actions and action effects on subsea equipment.

A.14.1.2 Exposure level for system components

No additional guidance is offered.

A.14.1.3 General provisions for ice actions

No additional guidance is offered.

A.14.1.4 Repair

No additional guidance is offered.

A.14.2 Ice and seabed considerations

A.14.2.1 Interactions above the sea floor

No additional guidance is offered.

A.14.2.2 Interaction for gouging ice features

A.14.2.2.1 State of practice

Interaction of gouging ice features with pipe and subsea structures and equipment has been the subject of study since exploration and production of hydrocarbons was first considered. A good summary of the history and state of practice can be found in Reference [308], as well as examples of pipeline projects in ice-gouged regions. References [309] to [325] provide further information on the specific physical mathematical and numerical techniques that are described below and the uncertainties associated with them.

A.14.2.2.2 Sub-gouge soil deformations

A gouging ice feature can produce large sub-gouge horizontal and vertical deformations in the surrounding soil. Three zones of ice-soil-pipe interaction have been identified; see Figure A.14-1:

- Zone 1 — soil layer displaced by the ice feature;
- Zone 2 — soil layer subjected to permanent deformations;
- Zone 3 — soil layer subjected to elastic deformations.

The burial of pipe and other equipment should be within Zone 3, or designed to tolerate the soil deformations and actions in Zone 2.

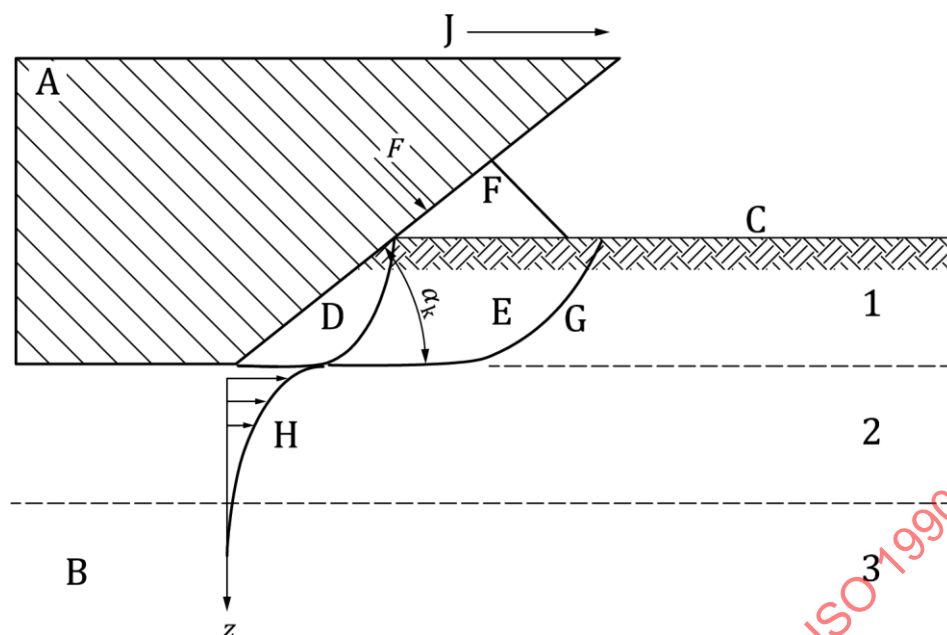
A.14.2.2.3 Ice gouging parameters and measurements

No additional guidance is offered.

A.14.2.2.4 Mathematical models of the ice gouging processes

Models of the ice gouging process can be broken down according to function:

- characterization of parameter distributions (often used);
- estimation of ice gouge frequency (sometimes used);
- estimation of ice gouge dimensions (used occasionally);
- characterization of ice gouging processes (used occasionally);
- characterization of sub-gouge soil deformations (used occasionally).

**Key**

A	ice keel	J	ice movement direction
B	soil	1	soil zone 1
C	sea floor	2	soil zone 2
D	dead soil wedge	3	soil zone 3
E	passive soil wedge	z	depth below ice keel
F	passive soil frontal mound	F	ice bearing action
G	soil rupture surface	α_k	keel attack angle
H	sub-gouge displacement profile		

Figure A.14-1 — Soil displacements during the gouging process^{[326][327]}

Some common types of models include the following.

- a) Ice gouge depth distribution models — The most common method for predicting the ice gouge depth distribution is to use measurements made during field surveys. Many analyses have used all depths above the resolution of the measurement system, rather than only the tail of the distribution. It should be recognized that this implicitly assumes that extreme and abnormal ice gouges follow the same depth distribution as the whole population. Most commonly, an exponential distribution has been used to describe ice gouge depths, but the most appropriate probability distribution should be investigated on a case-by-case basis for the available data of interest. When data are scarce, the exponential distribution can be used with an appropriate provision for uncertainty. Particular consideration should be given to the use of truncated distributions when the data are limited by the system resolution. When extrapolating ice gouge depth distributions from limited data, consideration should be given to the physical limits discussed in A.14.2.2.6.
- b) Ice gouge frequency models — Phenomenological modelling uses information regarding bathymetry, geotechnical and metocean conditions for ice-gouged seas and also for shoreline locations where tidal-induced ice drift is significant. Where the assessment of ice gouge frequency is uncertain, whether due to lack of survey coverage, infrequent ice gouging rates or difficulty in assessing the age of features, modelling techniques can be useful. The required inputs for this type of modelling include:

- seabed data documenting ice gouge features that can assist with the modelling of ice gouge frequency;
 - speed and direction of ice drift, and/or currents and winds;
 - bathymetry (including sheltering effects of the local bathymetry and shoreline, which can preclude, for example, keels exceeding a given draught, and/or drifting from certain directions);
 - size of drifting ice feature, including mass;
 - sail height and/or keel depth of the ice feature, including sheltering effect of shallower keels within the same ice floe;
 - knowledge about the local ice feature geometry, e.g. spacing between adjacent keels.
- c) Kinetic energy and driving action models — These models are typically used to address circumstances where ice gouging is limited by the kinetic energy of the feature or by the available driving actions. Models developed to analyse kinetic energy-limited ice gouging equate the kinetic energy of the moving ice feature with the work done. Early modelling and assessment efforts were conducted using iceberg gouge data compiled from observations off Canada's east coast. The available models differ in various ways such as
- the energy sinks included,
 - the methods used to compute soil resistance,
 - the slope of the interaction face between ice and seabed,
 - whether vertical displacements and rotations of the ice feature are considered.

Models can be used to assist with the interpretation or extrapolation of ice gouge data. Examples include those dealing with infill and those providing physical limits to ice gouge parameters. Due account should be taken of uncertainties in all models and their parameters, e.g. References [309], [310] and [328].

A.14.2.2.5 Physical models of the ice gouging processes

A number of physical models have been developed to assist with the understanding of ice gouge processes. These include the following:

- a) small-scale testing in a centrifuge: the most extensive centrifuge test series are documented in Reference [328], although others have been performed^{[311][312][313]};
- b) testing in hydraulic basins: small-scale tests have been reported, e.g. in References [329] to [333];
- c) large-scale tests: pulling a 45 t indenter through an outdoor test basin, see Reference [315];
- d) field tests: tests have been performed under actual field conditions near Spitsbergen, see References [334], [335] and [336]

In general, the physical models have been analysed and supported by advanced numerical models for calibration and application in design. References [316] and [317] provide examples.

A.14.2.2.6 Limits to ice gouging parameter distributions

Many factors and processes can limit the ice gouge dimensions that are created on the seabed. Potential limits include the following.

- a) Driving actions — The available environmental driving actions and the ability of the ice cover to transmit them can limit ice gouge length and depth. These are most applicable to the case where a gouging ice keel (typically contained in an ice floe or as part of a rubble/stamukhi field) is being driven by pack ice. In this case, the available kinetic energy is large; effectively infinite. There are several potential limits to the driving action, including the following:
 - the sheet ice containing the gouging ice keel can fail;
 - the sheet ice floe or rubble/stamukhi field can rotate;
 - ridging and rafting can start to form elsewhere in the pack ice.
- b) Kinetic energy — The kinetic energy of the drifting ice mass can also limit ice gouge length and depth. This limit is most applicable to cases where an isolated ice feature (e.g. a ridge within an ice floe or an iceberg) drifts freely into the seabed. Analyses of this type of interaction should include the most significant site-specific energy sinks, which can involve the following:
 - work done on the soil over the length of the ice gouge track, which includes several aspects as work is done in deforming the soil
 - i) in front of the keel,
 - ii) by clearing the soil away from the advancing keel,
 - iii) by soil acting on the bottom of the ice keel;
 - uplift and/or pitch motions of the ice feature;
 - work expended through failure of the gouging ice feature (e.g. a MY or FY ridge in sheet ice).
- c) Ice keel processes — Abrasion or mechanical failure of the ice keel can limit ice gouge depth. Observations on Canada's east coast of iceberg gouging have shown that ice blocks were broken off from the keel during the event^[337]. Although no specific observations are available for ice gouges produced by FY or MY ridges, it is generally assumed that some ablation takes place for a variety of ice keel types.
- d) Strong soils — When the strength of the gouging ice keel is less than that of the seabed soil, this can impose important limits on ice gouge depth, most generally for the case where FY ridges encounter relatively stiff seabed material^[338].
- e) Geography — The local geometry of the shoreline or bay (e.g. for a loading line), or bathymetry (e.g. if a sill were present), can impose limits with respect to the size, number and drift directions of ice features that can enter an area. Gouging ice features can become grounded, thereby preventing further ice movements.

A.14.2.3 Strudel scouring

Soil conditions exert considerable influence on the development of strudel scours. Stiff plastic clay and gravel are resistant to scouring, while silt, sand and soft clay are easily displaced. These soil characteristics should be considered in the analysis.

For pipe laid on the seabed, a potential objective is to estimate the frequency at which free spans occur and a probability distribution for their length.

A.14.2.4 Permafrost

No additional guidance is offered.

A.14.2.5 Geohazards

No additional guidance is offered.

A.14.3 Actions on subsea production systems**A.14.3.1 General action requirements**

No additional guidance is offered.

A.14.3.2 Ice protection structures

Limitations on strength, as well as displacements and rotations of the impacting ice keel, can be used to reduce calculated ice actions on a protection structure. Examples include unconsolidated parts of FY pressure ridge keels and iceberg pitch motions.

A.14.3.3 Mudline cellars

Mudline cellars have been used to protect subsea templates from iceberg contact at the Terra Nova and White Rose subsea developments offshore of Newfoundland. The size and geometry of mudline cellars should consider protection from iceberg interactions, remotely operated vehicle access, flowline connections and stability of side slopes. A key consideration in the above-noted designs is the depth of the hole and, therefore, the clearance between the top of the template and the sea floor. The frequency of interactions was determined from the frequency of iceberg keel incursions into the mudline cellar and the consequent probability of contacting the equipment on the template. The design strategy involved reducing annual interaction frequency to well below 10^{-4} , the threshold for which ice actions would need to be considered in the design. Some general background on the issues is found in Reference [339].

A.14.3.4 Risers and loading/unloading systems

No additional guidance is offered.

A.14.3.5 Flowlines and umbilicals

A.14.3.5.1 Protection of flowlines and umbilicals from ice gouging

Where reliable forecasts of potentially gouging ice features are available, production shutdown and flushing of lines can reduce the risk of damage to acceptable levels. Examples include the subsea facilities at Terra Nova and White Rose on the Grand Banks of Newfoundland. Where the probability of ice contact is less than the probability associated with the EL or AL action, see 7.2.2.3 or 7.2.2.4, it is not necessary that flowlines and umbilicals be verified for the corresponding action combination.

For cohesive soils and rock, steep-walled trenches can be used, thereby minimizing the quantity of excavated material. For granular materials, only shallower slopes can be achieved. A trench can either be left open or be backfilled; the pressures induced by the ice gouge and direct contact should be investigated in this context.

Typically, bending strains resulting from lateral displacements are the most significant design issue for buried lines crossed by gouging ice features. Other processes of concern include ovalization from pressures transmitted through the soil and direct impact from ice keels.

It is generally recognized that a buried pipe can be damaged during the ice gouging process even though it is not contacted by the ice^{[340][341]}. Generally, the strategy used for the protection of pipelines from ice keels is the avoidance of direct ice contact and the burial at sufficient depth to avoid excessive pipe deformations due to soil movements. In practice, burial is required in ice environments for water depths less than the deepest ice keels that can occur.

The most common method considered for the protection of flowlines and umbilicals from ice gouging is burial in a trench on the sea floor. Strategies such as covering the flowlines and umbilicals with concrete, gravel or rock, bundling more than one line, strengthening the pipe or anchoring the pipe can be used in combination with trenching to reduce the risk of ice damage. Such approaches require special analysis procedures.

Connections to a platform and shore crossings require special consideration in the design due to changes in seabed erosion, ice pile-up and permafrost.

A.14.3.5.2 Field experience

It should be noted that because only a few pipelines have been built in ice-covered regions, relatively little experience is available to guide design efforts. Some of these are listed in Table A.14-1.

Table A.14-1 — Summary of reported operational experience with pipelines in ice-covered regions

Location	Reference	General description
Northstar	[342]	—
Oooguruk flowline bundle, offshore of Alaska in the Beaufort Sea	[343], [344], [345]	Bundled, 3-phase flowline started operation in 2008.
Nevelskoi Strait, between Sakhalin Island and mainland Russia	[346]	Although this pipeline has operated without documented damage since 1958, very little quantitative information is available regarding this pipeline.
Melville Island, in the Canadian Arctic	[347]	The Drake F-76 flowline was installed as a demonstration project offshore of Melville Island in the Canadian Arctic. The pipeline was only operated for a very short time in 1978 and has not been monitored since then. Consequently, no information is publicly available regarding its fate.
Water intake line at Hay River, NWT, Canada	[348]	This water intake line in Great Slave Lake, NWT, Canada was damaged by ice ridges in 1979. This line was not buried.
Lake Erie, Canada	[349], [350]	Several gas pipelines are present in Lake Erie. Ice-induced damage has occurred to unburied gas pipelines lying on the lake bed.
NOTE Marine pipelines are currently operating offshore of Sakhalin Island, in the Caspian Sea and in the Kara Sea (Bovanenkovo — Ukhta pipeline in Baidarata Bay). Flowlines are also present at Terra Nova and at White Rose on the Grand Banks. Ice gouging is a potential consideration for each of these cases.		

A.14.3.5.3 Burial strategy in ice gouge environments

For flowlines and umbilicals, ice actions should be considered in the context of non-ice actions such as anchor dropping and dragging, other dropped objects, soil displacements due to seismic actions, ship impacts, corrosion and erosion of seabed soils. Since offshore flowlines in arctic and cold regions should typically be trenched to avoid ice actions, the trench depth and backfill requirements to avoid vertical pipe instability due to upheaval buckling should be considered.

An ice gouge design is required if the expected frequency of contacts for an exposed flowline or umbilical system on the sea floor exceeds the probability associated with the ice action, whether EL (see 7.2.2.3) or AL (see 7.2.2.4). If operational measures are used to purge hydrocarbons from flowlines, thereby changing the consequence category, their effectiveness should be demonstrated and uncertainties accounted for.

Potential burial strategies to calculate required burial depth include:

- consideration of EL and AL ice actions, action factors, pipe response analyses and resistance factors;
- a fully probabilistic approach, in which the pipe response is calculated based on the joint distributions of environmental parameters, pipe characteristics and soil properties to achieve the target reliability (with reference to A.7.2.4);
- a variety of intermediate semi-probabilistic approaches.

Option a) involves the selection of, for example, the ELIE or ALIE ice gouge event followed by a deterministic pipe response analysis. Because sub-gouge deformations depend typically on both ice gouge depth and width, option c) involves the joint distribution of key gouge parameters and a number of deterministic pipe response analyses for representative ranges of ice gouge parameters and burial depths^{[326][351]}. This strategy is illustrated in Figure A.14-2.

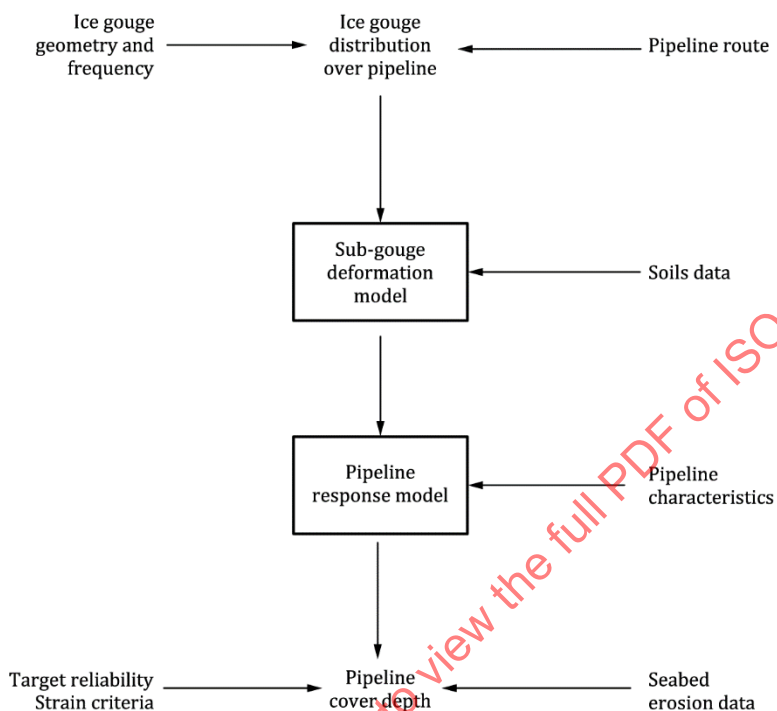


Figure A.14-2 — Strategy for reliability-based design of marine pipelines in ice gouged areas (after Reference [326])

A key aspect of line burial is the identification of potential mechanisms leading to loss of hydrocarbons. These typically involve direct ice contact, tensile stresses, tensile strains, buckling or wrinkling and ovalization. Experience indicates that pipelines in ice gouge environments generally require a greater wall thickness than those in non-ice environments, and that the capability to absorb strains can be more important than high strength in the choice of steel.

Important issues relating to ice and soil actions include:

- the joint distributions of ice gouge depth and width, the associated pressures applied to soil for various pipe burial depths, and potentially the shape of the ice gouge cross-section;
- the sub-gouge soil deformation field, which typically involves the specification of horizontal and vertical displacement fields, both beneath and adjacent to the gouging keel, and their dependence on the parameters specified in the point above;
- the frequency and orientation of pipe crossings by ice gouges.

Another important aspect of pipe burial is the use of an appropriate model of the pipe behaviour based on the specifics of the pipe and trench design, and pipe response to soil movements. Approaches used for pipe/soil interaction include full-scale tests, model tests (including centrifuge) and numerical analyses (analytical, non-linear spring or continuum/FE).

Other factors that should be considered for determining safe burial depths include the state of pipe and trench as a consequence of littoral transport, natural infill, permafrost, upheaval buckling, temperature-induced pipe stresses, coating masses, welds, and operational measures over the design service life of the project such as trench modification.

See References [326] and [351] to [362] for additional information on design approaches for pipeline burial in ice gouge environments.

A.14.3.5.4 Burial strategy in strudel scour environments

When the footprint of a strudel scour encroaches on a flowline, an unsupported length of pipe ("free span") can result if the depth of scour exceeds the design trench depth. An assessment should be considered for pipe behaviour associated with unsupported (or partially supported) span lengths due to EL or AL strudel scour events. The assessment should include the potential for vortex-induced vibration during scour formation and subsequent hydrodynamic or ice actions.

In the case of circular scours, the critical parameters that determine the risk of pipe failure are the maximum horizontal dimension at the sea bottom, the side slope angle and the depth of the scour. In the case of linear scours, the orientation should be taken into consideration as well as the length, side slope and depth.

A.14.3.6 Resistance to ice actions

No additional guidance is offered.

A.14.4 Seismic design

No additional guidance is offered.

A.14.5 Risk reduction

No additional guidance is offered.

A.15 Topsides

A.15.1 Overall considerations

A.15.1.1 Design considerations for topsides facilities

A.15.1.1.1 General

Typical systems and equipment that can require protective heating during start-up, operation and shutdown periods include:

- a) equipment and piping in water service when intermittent operation or minimum flow does not maintain the temperature above freezing;
- b) water seals;
- c) relief valves and their discharge lines;
- d) instrument leads and taps;
- e) field instruments;
- f) auto-refrigeration at control valves and letdown stations;
- g) piping and equipment that can contain significant amounts of moisture during start-up or upsets;
- h) undrained low points in equipment and piping and dead-ended pipes or legs;
- i) drains on flowlines, pumps, tanks, hydraulic power systems and other equipment;
- j) lube and seal oil systems;
- k) closed-system cooling water tanks for compressors in wet gas service;
- l) fuel oil and diesel fuel tanks and lines;
- m) diesel-driven equipment, particularly fire pumps and emergency generators;
- n) drains and traps at low points in compressed air lines;
- o) fuel gas knockout pot drains;
- p) instrument gas;
- q) turbine inlet air systems;
- r) air or water exchangers in condensing service;
- s) natural gas cooler tubes, if hydrate formation is possible;
- t) gas used for cold start;
- u) suction piping to compressors in saturated gas service;

- v) fire foam lines;
- w) pigging operations;
- x) equipment for EER.

A.15.1.1.2 Low temperature

Carbon steel (CS) typically used for pressure vessels and similar equipment can have a lower operating temperature limit of -29 °C, whereas low temperature carbon steel (LTCS) can be used down to -66 °C and lower, subject to their detailed specification. Thus, in most arctic and cold regions, CS should be avoided and LTCS can be utilized if the EL minimum temperature does not fall below the lower operating limit of the selected LTCS.

A.15.1.1.3 Sea and glacial ice — Impact on topsides structures

No additional guidance is offered.

A.15.1.1.4 Ice and snow accumulation

No additional guidance is offered.

A.15.1.2 Operational measures

Restrictions can apply to the use of chemical de-icing measures in some jurisdictions.

Communication technology can include:

- fibre-optic cable;
- microwave;
- UHF;
- VHF;
- VSAT.

A.15.1.3 Sparing philosophy

No additional guidance is offered.

A.15.2 Design and operational requirements

A.15.2.1 General

No additional guidance is offered.

A.15.2.2 HVAC, utilities, and power-generating equipment

No additional guidance is offered.

A.15.2.3 Electrical

An example of cabling rated for offshore use in marine cold weather climates is the IEEE 45 Type P, fine-stranded, highly flexible cable.

Cold temperature reduces battery output. Battery temperature should be kept at 18 °C or higher to allow recharging in a reasonable amount of time.

Electrical isolators are used to separate dissimilar metals such as carbon-steel from stainless steel, or aluminium from carbon-steel.

A.15.2.4 Instrumentation and controls

Heavy trace tubing bundles are fabricated to ensure a close contact between the process tube and tracer. Where heavy trace tubing is not required (freeze protection and general warming), light trace tubing bundles can generally provide sufficient warming. Light trace bundles contain an insulated tracer that protects the process tube(s) from “hot spots” and overheating.

A.15.2.5 Mechanical equipment

No additional guidance is offered.

A.15.2.6 Piping

A.15.2.6.1 Pipe testing and inspection

Piping subjected to simultaneous low temperatures and maximum operating pressures should undergo Charpy testing according to ISO 15649^[8].

A.15.2.6.2 Heat tracing and insulation of piping

Electric tracing components and installation methods for classified areas should comply with Reference [42] or IEC 61892 [13], or with another equivalent standard.

A.15.2.6.3 Circulation of fluids

The combined effect of low ambient temperatures and strong winds can cause more rapid cooling than temperatures alone. This should be addressed with respect to freezing of fluids in exposed pipes.

A.15.2.6.4 System draining and blow down

No additional guidance is offered.

A.15.2.6.5 Deck drains

Typically, insulation to within 750 mm of the module is provided.

A.15.2.7 Safety

A.15.2.7.1 General

No additional guidance is offered.

A.15.2.7.2 Blast protection

Sealed compartments are generally bounded by architecturally insulated cladding and serviced by large volume HVAC ducting. Even following good layout practice and with the use of blow-out panels, it can be expected that sealed compartments can lead to confinement problems not normally encountered in open, naturally ventilated modules. This, in turn, can lead to predicted blast pressures greater than normally encountered in non-arctic regions. The risk of icing effects on blow-out panels should be considered.

A.15.2.7.3 Fire protection

No additional guidance is offered.

A.15.2.7.4 Human factors/ergonomics

No additional guidance is offered.

A.15.2.7.5 Safety showers and eyewash stations

No additional guidance is offered.

A.15.2.7.6 Changing rooms and storage

No additional guidance is offered.

A.15.2.7.7 Safety equipment

No additional guidance is offered.

A.15.2.8 Relief and flare system

Some fluids become quite viscous when cooled appreciably and pressure safety valves (PSVs) should be sized accordingly. As the viscosity of the fluid increases, the required PSV size and inlet/outlet piping pressure drops increase for a given flow rate.

Balance below PSV has been known to freeze (i.e. rain or snow gets inside and subsequently freezes), causing failure. These PSVs have an open vent in the bonnet, which always remains open for the PSV to

work properly. A possible intermediate precaution can be to install a small “street” elbow in the vent and point the outlet downward to minimize the potential for rain/snow to enter. The street elbow should be installed in such a manner that venting gas and/or liquids from the PSV cannot result in a safety hazard to personnel.

The opening pressure of rupture disks, particularly stainless steel, can be strongly influenced by temperature. The opening pressure of the rupture disk should be selected to account for ambient temperature swings (day/night and summer/winter). It can be necessary to select a lower rupture disk opening pressure to take into account the cold temperatures. Using lower rupture disk opening pressures can lead to premature failures in the summer if operating close to the opening pressure. In some cases, it can be necessary to insulate and heat trace the rupture disk holder.

The flare header knock-out drum should be insulated and heat traced. Consideration should be given to installing heating in the flare header knock-out drums/water seal drums. If weep holes are used, hydrocarbon leakage can potentially be avoided by using a system sloping towards the header and knock out drum.

A.15.2.9 Storage tank valves

Water within the channel of a closed ball valve on a production storage tank expands when freezing occurs. This can lead to piping and/or valve failures due to the large forces generated. The resulting failure can cause an environmental spill of produced fluids.

The storage tank relief system should be designed to avoid potential freezing of water accumulation. Relief valves for atmospheric storage tank overpressure and vacuum protection should be designed to avoid any water accumulation that can lead to the seat sticking from freezing.

A.15.2.10 Actions on structure

No additional guidance is offered.

A.15.2.11 Provisions supply and mechanical handling

No additional guidance is offered.

A.15.3 Seismic design

A.15.3.1 General

Because of potential effects of ice-induced vibration, arctic and cold region structures tend to be stiffer than corresponding open water structures. It is often necessary to implement specific seismic measures for such structures.

Topsides structures and systems typically include:

- a) primary structural framing;
- b) deck appurtenances;

- c) fixtures and fittings in living quarters;
- d) fixed equipment for drilling;
- e) production and support;
- f) distributed systems, such as piping, HVAC, electrical, and instrumentation and controls;
- g) equipment/systems supports and attachments; and
- h) topsides systems such as EER and emergency power.

A.15.3.2 Seismic design of the topside structure

Seismic actions on the topsides structure can be calculated using either:

- a) coupled analysis, in which the topsides structure actions can be calculated directly by analysing the topsides structure modelled together with the substructure (more accurate than the uncoupled analysis); or
- b) uncoupled analysis, in which the topsides structure can be modelled separately from the substructure, using appropriate boundary conditions to model the substructure, the seismic action acting on the topsides being based on the substructure analysis.

Dynamic coupling between the topsides and substructure can be assessed by using a screening method such as contained in Reference [20].

Seismic actions from either coupled or uncoupled analysis are applied to the structure using either of the following methods.

- Dynamic analysis: topsides actions from a coupled or uncoupled analysis can be calculated using response spectrum analysis or linear or non-linear time history analysis. This method is more accurate than the equivalent static analysis.
- Equivalent static analysis: the topsides can be analysed using a static analysis by applying appropriate seismic accelerations to the topsides mass. The seismic accelerations should be taken from results of the substructure analysis and the potential for dynamic amplification should be considered.

A.15.3.3 Seismic design of topsides equipment and supports

Reference [16] is an example of a code with recognised seismic provisions for structural connections.

These provisions apply to the design of all structural components and connections required for transferring lateral and vertical actions from the centre of mass of the equipment to their anchorage.

For the purposes of this clause, the following apply.

- Structural damage is a failure of any load-bearing component of the equipment, anchorage failure, or any connection failure. Typical examples of structural damage are bent or buckled support frames, failed anchorage welds or failed fastening hardware.

- Mechanical damage is any dislocation or separation of components. Examples of mechanical damage include disengaged circuit cards and modules and opened doors, drawers and covers.

Actions on equipment, appurtenances and distributed systems can be calculated using either of the following methods.

- a) Equivalent static analysis: actions are calculated by applying the appropriate acceleration to the tributary mass in a static analysis.
- b) Dynamic analysis: actions are calculated directly in a dynamic analysis of a subsystem, using response spectrum or time history methods. The dynamic analysis is considered more appropriate for flexible equipment.

Critical systems, including related equipment and components, are those that are required to function immediately following an earthquake for life-safety, environmental or financial purposes, as defined by the owner or regulator. Examples include fire protection, blowdown, emergency power, certain HVAC, ESD, smoke and fire detection, etc. They are also typically required to perform an active function following the ALE to achieve system functionality. Critical systems should be defined by a systematic risk assessment.

In lieu of explicit structural analysis, critical equipment can be demonstrated to have adequate seismic resistance by analysis, by shake table tests or by the use of historical earthquake performance data.

Certain support details have been demonstrated to perform poorly in shaking actions in past earthquakes. These include C-clamps and vertically oriented friction connections. These supports should not be used for multiple, adjacent supports or any situation where failure of an individual support can cause an unzipping of the system.

Some equipment consists of complex assemblies of mechanical and electrical parts that typically are manufactured in an industrial process that produces similar or identical items. Such equipment can be designed by empirical methods for functional and transportation loads, and can be ruggedly constructed such that it has the ability to survive strong motions without significant loss of function. For such equipment, seismic design is generally not required other than for anchorage and attachments.

It is not intended that all components or parts of equipment, such as shafts, bearings, switches, gears, or similar items, not related to critical systems be designed for seismic actions.

A.15.3.4 Seismic design of component interfaces

An interface check is required since structures and systems can have different structural dynamic properties and can respond differently to earthquakes.

Pipelines and flowlines in arctic and cold regions can be trenched into the soils at the structural interface in order to prevent damage from ice gouging. Differential motion between trenched lines and the structure should be considered in the seismic design.

A.15.3.5 Passive protection systems for seismic design

A seismic passive protection system is a special structural subsystem incorporated into a structure with the aim of reducing the response of the structure to seismic shaking. The passive protection system typically consists of a specific structural configuration coupled with the use of special isolation and/or energy dissipation devices. The term “passive” means that no active control is used to modify the response.

The performance objective of passive protection systems is to decrease the response of a structure to seismic shaking. Typically, a passive protection system is employed in situations where a conventional structural framing solution cannot cost-effectively meet the ALE requirements.

A seismic isolation system introduces an isolation interface between two parts of a structure, effectively decoupling the two parts and, thus, reducing the transmission of seismic shaking from the lower part to the upper part. The isolation system can also include a wind-restraint system, energy dissipation devices and/or displacement restraint system.

A seismic damping system increases the ability of a structure to convert seismically induced kinetic energy to other energy forms, mainly heat, during seismic shaking. This is achieved through the introduction of special damping devices into the structure, which dissipate the energy due to the relative motion between each end of the device.

In rare cases, a passive protection system is also aimed at the reduction of ELE response or at the protection of equipment and systems critical to the post-disaster performance of a structure.

The following should be considered for passive protection systems in arctic offshore structures.

- a) Low temperatures: the performance of passive protection systems in arctic offshore structures can be affected by low temperatures. For example, some components, such as viscous dampers, or friction pendulum bearings, have a proven record of reliable performance in freezing conditions while others, such as rubber bearings, should be protected from freezing.
- b) Wind action: isolated structures need to resist design wind actions at all levels above the isolation interface. If necessary, a wind restraint system should be provided to limit lateral displacement in the isolation system.
- c) Wave and ice action: wave and ice actions can cause a dynamic response of the isolated structure. The isolation system should not introduce adverse effects into the structure's response to these actions.
- d) Restoring force: the isolation system should be configured to produce a restoring force such that the lateral force at the total design displacement is greater than the lateral force at 50 % of the total design displacement by at least 2,5 % of the weight of the isolated structure.
- e) Displacement restraint: the isolation system can be configured to include a displacement restraint that limits lateral displacement to a value that is less than the design displacement due to ALE. If such a restraint requirement is used, it should be explicitly considered in the analysis and the design of both the isolation system and the structures below and above the isolation interface.
- f) Vertical load stability: each component of the isolation system should be designed to be stable under the maximum vertical action effect and the minimum vertical action effect when subjected to the design displacement.

- g) Global overturning of isolation system: the resistance to global structural overturning at the isolation interface should meet the ALS requirements for the required action effect combinations. All gravity and seismic design situations should be investigated.
- h) Uplift of isolator units: local uplift of individual components can be permitted if the resulting deflections do not cause overstress or instability of the isolator units or other components of the structure.
- i) Structure separations: minimum separations between the isolated structure and surrounding fixed obstructions should not be less than the design displacement, unless it can be demonstrated that the system meets the performance criteria with pounding.
- j) Components crossing the isolation interface: components of seismically isolated structures and non-structural components that cross the isolation interface should be designed to withstand the total maximum displacement at the interface. The components should not interfere with the performance of the isolation system. Particular attention should be paid to staircases, wells, risers and piping.
- k) Seismic force-resisting system: structures that contain a damping system should have a basic seismic force-resisting system designed for the reduced seismic action but conforming to recognized seismic structural systems.

A.16 Other ice engineering topics

A.16.1 Ice roads and supplies over ice

A.16.1.1 General

Crossings of lakes and rivers have been achieved using the naturally formed ice cover in winter for centuries. The main requirement to cross safely is to have continuous ice of sufficient thickness to support the intended loadings.

There are numerous examples of the use of floating ice to form roadways over rivers, lakes and oceans for the transportation of heavy loads. This has been done successfully for the support of large-scale loadings, both moving and stationary, including the seasonal deployment of drilling rigs. To support these actions, the natural ice was thickened by flooding or spraying seawater onto the ice surface until the total ice thickness reached a value of approximately 6 m, where the original ice thickness had been as little as 1 m. Long-term loading can induce creep or time-dependent deformation in the ice.

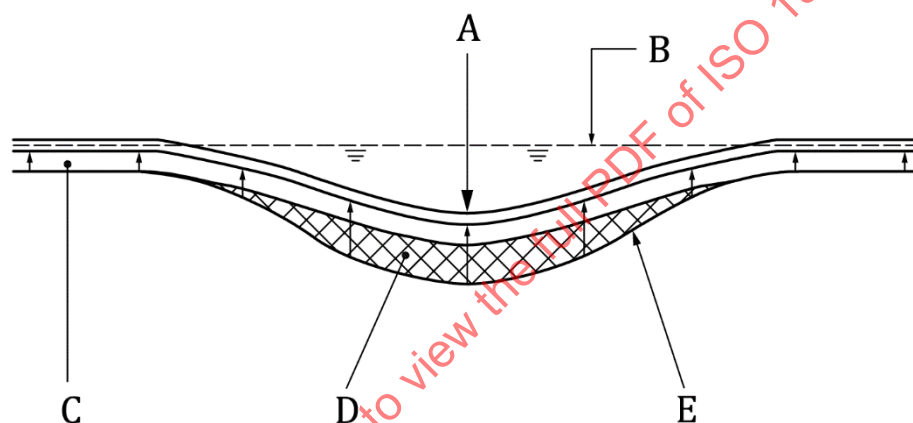
A.16.1.2 Floating ice design criteria

A.16.1.2.1 Background

Ice has a density about 10 % less than that of water, and floats on the water surface unless it is held down by external actions. Because of this difference in density, 90 % of the ice is below water and 10 % is above water. The height of the ice above water is referred to as the freeboard. Under vertical loading, the ice behaves as a plate on an elastic foundation, whereby the ice directly under the action is deflected downward. This deformation results in an increase in water pressure on the bottom of the ice as shown in Figure A.16-1, and the integral of the increased water pressure over the area of the deflected shape

equals the value of the applied action. It should be taken into account that the vertical deflections illustrated in Figure A.16-1 have been exaggerated for illustrative purposes and do not imply that the freeboard is negative.

The bending of the ice under the action imposes a flexural stress on the ice cross-section. If the applied flexural stress does not exceed the maximum flexural stress that can be supported by the ice sheet (i.e. the flexural strength of the ice), the load can be supported. Ice is a material weak in tension and relatively strong in compression. Thus the critical stress is the maximum tensile stress at the bottom of the ice directly under the load. Obviously, it is necessary that the freeboard of the ice remain positive while the load is being applied. If the ice is forced under water and the surface is allowed to flood, the bearing capacity of the ice rapidly diminishes, with potentially dire consequences. In summary, it is necessary to meet two criteria for the static loading of an ice plate, i.e. that the maximum flexural stress does not exceed the flexural strength of the ice and that the freeboard remains positive.



Key

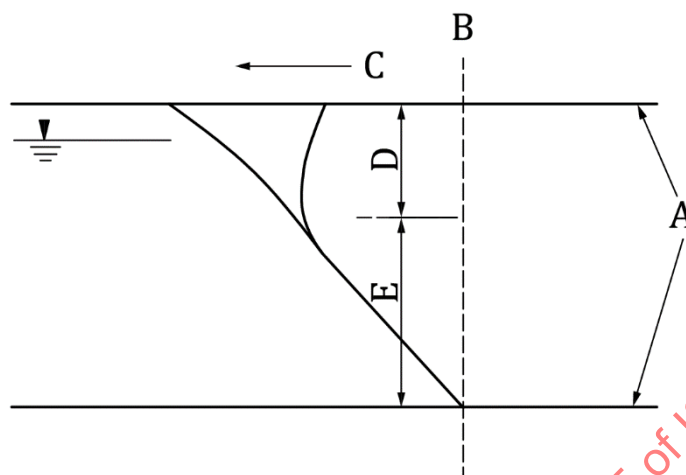
A	applied vertical action	D	additional pressure due to ice deflection
B	waterline	E	total pressure
C	pressure to support ice sheet		

Figure A.16-1 — Floating ice in bending under vertical action

Ice is a material found in nature at a temperature very close to its melting point. It deforms elastically, in a time-independent fashion, and also with significant time-dependent viscoelastic and permanent creep contributions^{[231][232]}. This is why ice can safely support a given load in the short term, but not necessarily for a more extensive time period. As soon as a load is applied, deformation begins to accumulate inside the ice, initially without clear evidence of it, as the ice slowly deflects downward. Ultimately, the ice cover can fail suddenly, without warning. Loss of freeboard (i.e. submergence and surface flooding) should be avoided. When this happens, it is an indication that the load should be removed. Freeboard can be monitored by drilling a hole into the ice cover and checking water level.

A typical natural temperature profile of ice is shown in Figure A.16-2. The cold ice at the surface, where the ice is in compression, experiences large changes in temperature and thus can be strong and brittle or weaker and very ductile. Where snow cover is present, the swings in ice temperature at the surface are dampened due to the insulating properties of snow. As stated previously, ice is relatively strong in compression and, thus, the swings in strength near the upper surface have little effect on the bearing capacity. By contrast, the temperature of the ice at the bottom surface is relatively invariant, and thus the

strength and ductility remain constant^[363]. Since this is the location of the critical stress, one can rely on the basic load-bearing capacity of the ice remaining constant through the main winter season. It is only in the latter part of spring when the ice is isothermal at the melting temperature and it begins to lose latent heat that deformations can become large.



Key

A	upper and lower ice surfaces	D	zone of fluctuating temperature
B	freezing temperature	E	zone of constant temperature gradient over time
C	increasing negative temperature		

Figure A.16-2 — Typical ice-cover temperature profile

Any heat source, such as a warm spring or water discharge from a plant or municipality, deteriorates and melts ice, with a consequent loss of strength. It is not necessary to set complex criteria for the flexural strength and bearing capacity of ice. Using the stress method, an allowable stress can suffice, based on proven experience with loads on ice. It is of paramount importance to ensure that the ice thickness is adequate at all locations on a road or bearing surface and that the actions themselves, and their distribution, are well known. In addition, the ice integrity and presence of major flaws and cracks are important. Even though ice displays surface cracking, this does not mean it is unsuitable for the intended actions. Surface cracks resulting from changes in ambient temperature are common in ice covers. As long as these cracks engage only the upper third or so of the ice thickness, they do not result in diminished strength. Cracks that penetrate the ice and are “wet” are a concern and can result in diminished strength.

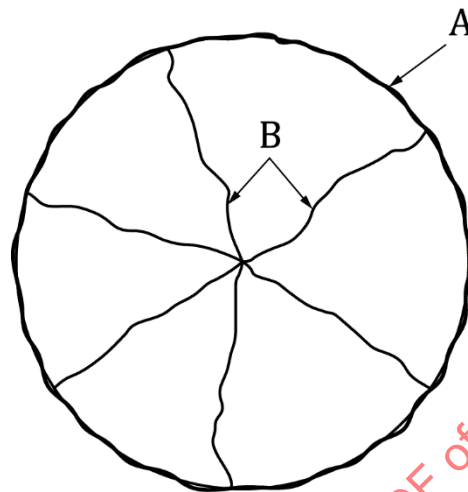
The two design steps for completing a structural analysis of a loaded ice sheet are as follows.

- Ensure that the maximum tensile extreme fibre stress of the ice sheet is less than the allowable flexural stress for ice.
- Ensure that the ice sheet's short-term and long-term deflections are less than the available freeboard.

The flexural strength of a floating ice plate is defined as the allowable maximum tensile extreme fibre stress induced by the action or action combination. This is almost invariably the stress at the bottom of the ice beneath the heaviest action.

A typical failure scenario for a uniformly loaded area on top of an infinite ice sheet is illustrated in Figure A.16-3. As the action is applied, the sheet deflects until the first crack or yielding develops in the

underside of the sheet beneath the centre of the action. Further action results in the propagation of radial cracks through the thickness of the ice to some distance outside the loaded area. Further application of the action results in the development of a circumferential crack pattern. Once this has become fully developed, a complete breakthrough can immediately occur.



Key

- A circumferential crack pattern
B radial crack pattern

Figure A.16-3 — Typical ice-cover failure pattern

When ice fails in bearing, “shear” plugs can form around the loaded area. These are closely related to flexural failure. Flexural failure does not necessarily require the long wedge illustrated above. For yield line type failures, the wedge length is approximately twice the ice thickness, thus supporting the observed shear plug type of failure.

A.16.1.2.2 Theoretical models

These models assume that the ice structure acts as an elastic, homogeneous, isotropic plate on an elastic foundation, to simulate buoyancy. Because the ice in nature is close to its melting point, it also undergoes creep deformation. The models are approximations that are only valid for short loading durations — the shorter the duration, the closer to purely elastic behaviour.

Reference [364] presents a design procedure that can be employed to predict the extreme fibre stress in an ice sheet due to a uniformly distributed action. The extreme fibre stress in the ice sheet, $\sigma_{\max}$, expressed in kilopascals, is predicted by Westergaard as given in Formula (A.16-1):

$$\sigma_{\max} = 0,275(1+\nu) \frac{P}{h^2} \log_{10} \left(\frac{E h^3}{k b^4} \right) \quad (\text{A.16-1})$$

where

- ν is the Poisson ratio;
- P is the magnitude of action, expressed in kilonewtons;
- E is the elastic modulus, expressed in kilopascals;
- h is the ice thickness, expressed in metres;
- k is the sub-grade reaction, expressed in kilopascals per metre, equal to 9,81 kPa/m for freshwater;
- r_c is the radius of loaded area, expressed in metres;
- b is the effective beam length, expressed in metres, equal to $\sqrt{1,6r_c^2 + h^2} - 0,675h$ for $r_c < 1,724h$ and equal to r_c for $r_c \geq 1,724h$.

The Westergaard Formula (A.16-1) is an approximate solution to the plate equations and can lead to errors for loadings with a radius large compared with the characteristic length, L_c , defined in Formula (A.16-2). When Formula (A.16-1) is used to limit the ice sheet stresses to a value that is less than the flexural strength of the ice, cracking in the ice sheet cannot occur. The industry standard is to not allow the occurrence of a “first crack”. Once the “first crack” condition occurs, flooding of the ice surface is possible. The flooded water adds to the imposed action, P , accelerating the deflection, and causes difficulty in clearing equipment from the loaded area. Breakthrough usually does not occur until the formation of the circumferential cracks illustrated in Figure A.16-3. In general, the thinner the ice road, the faster the transition from “first crack” to breakthrough. It is believed that thicker ice sheets allow stress transfer on mechanical levels that are not available to thinner ice sheets. Local crushing of the ice of the thicker ice sheet pieces allows this mechanical stress transfer^[365].

In summary, the “first crack” or first yield condition governs the practical design of ice roads. For applications such as landing a helicopter on ice, a gravity action higher than that causing the first crack can be acceptable, as discussed in A.16.1.8.

When it is necessary to calculate the extreme fibre flexural stress, σ_x , expressed in kilopascals, corresponding to units of P , at distance x from the centre of the action, Formula (A.16-2) is employed^[366]:

$$\sigma_x = 0,249 \left(\frac{P}{h^2/6} \right) \exp \left(\frac{-x}{0,691 L_c} \right) \quad (\text{A.16-2})$$

where

- x is the distance from the centre of the action, expressed in metres;
- L_c is the characteristic length, expressed in metres, equal to

$$\left[\frac{Eh^3}{12k(1-\nu^2)} \right]^{1/4}.$$

The characteristic length, L_c , can in practical cases take on the value $16h^{3/4}$, expressed in metres. Loads placed on a floating ice cover or plate introduce flexural stress into the ice at other locations within relatively close proximity. The net total stress at a point is determined using the principle of stress superposition. The stress analysis performed is elastic and, thus, lends itself to this procedure. If long-term loading and creep occur, with attendant permanent deformation, then the principle of superposition cannot be used.

A.16.1.2.3 Industry experience

For a number of years, industry and government agencies have predicted the load-carrying capacity of ice sheets using P , the ice sheet strength, expressed in tonnes, as given in Formula (A.16-3):

$$P = C_{ir} h^2 \quad (\text{A.16-3})$$

where

C_{ir} is the coefficient for ice road operation, expressed in tonnes per square metre, in the range of $35 \text{ t/m}^2 \leq C_{ir} \leq 70 \text{ t/m}^2$;

h is the ice thickness, expressed in metres.

On the basis of ice failures reported by industry, a curve-fit was made^{[367][368]} as shown in Figure A.16-4.

An important observation from Figure A.16-4 is the location and number of failures with respect to the $P = 35h^2$ and the $P = 70h^2$ lines. Of the 106 failures, 49, or 46 %, occurred when the thickness was greater than the thickness required by the $P = 70h^2$ line. Even when the thickness was greater than the thickness required by the $P = 35h^2$ line, failures still occurred. Nine percent of failures recorded in Figure A.16-4 occurred for ice thicknesses equal to or greater than the thickness required by the $P = 35h^2$ line.

Ice is often distinguished in the field on the basis of a two-fold colour scheme: blue (black or clear) ice and white ice. The latter is white because it contains many small air entrapments, typically produced during surface flooding with or without snow. White ice is therefore less dense than blue ice. Sea ice, while it can have a lower strength than freshwater ice, is a more ductile material, more forgiving and less prone to sudden failure. There is no reason to degrade sea ice bearing capacity relative to freshwater ice.

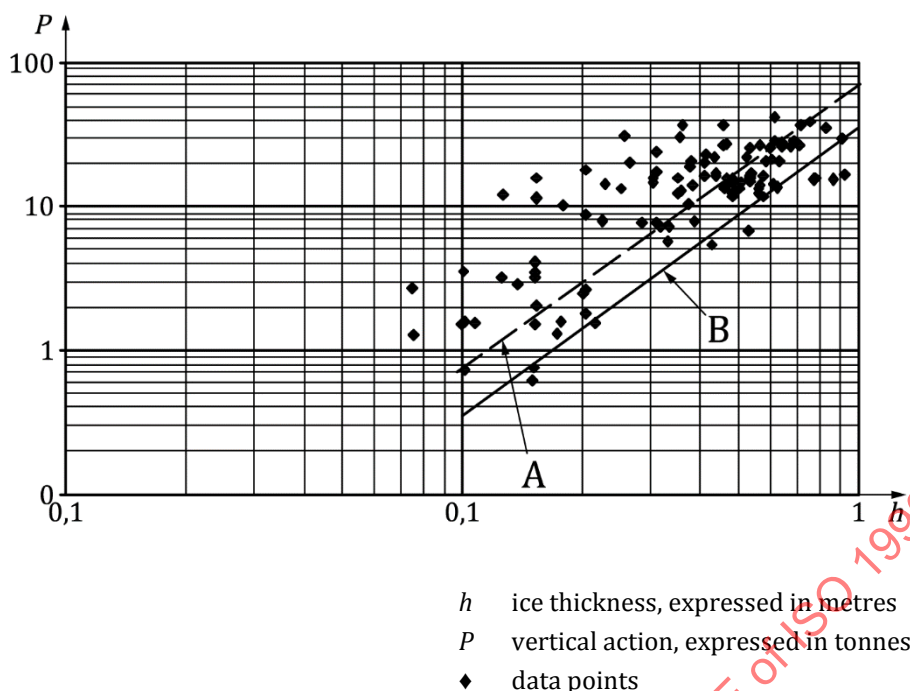


Figure A.16-4 — Ice bearing failure data — Individual failed and safe ice loads^[368]

Ensuring that the actual ice thickness is greater than the ice thickness required, i.e. using the $P = 35h^2$ line, is not a guarantee that ice sheet bearing capacity failure does not occur. While the probability of failure decreases as the value of P decreases, failures at thickness greater than determined from the $P = 35h^2$ line are still statistically significant. In Figure A.16-4, failures at an ice thickness between the $P = 35h^2$ line and the $P = 70h^2$ line are likely to be the result of an operational problem or due to an ice sheet defect. This fact highlights the requirement for proper inspection and safety control measures on an ice road project to ensure that site operation factors such as speed and edge loading are controlled.

A.16.1.2.4 Design recommendations

Industry practice throughout most of Canada has been to employ a load value between $35h^2$ and $50h^2$ for early season operation, especially on ice road opening, and between $60h^2$ and $70h^2$ for later season operation. Ice road openings at a value of $60h^2$ to $70h^2$ are carried out on occasion with diligent monitoring and inspection effort.

Comparing Formulae (A.16-1) and (A.16-3), the flexural stress level associated with a P value of $35h^2$ to $50h^2$ corresponds to a flexural stress level of 500 kPa to 550 kPa at the bottom surface of the ice sheet. It is emphasized that the bearing capacity of ice is calculated in Formula (A.16-1) assuming that the strain and stress vary linearly through the ice thickness and that the ratio of stress to strain is a constant and equal to the modulus of elasticity. Both stress and strain are maximum at the extreme fibres or at the top and bottom and are zero at half the ice thickness, or at the neutral axis. None of this is strictly true. The ice stress-strain relationship is non-linear, especially under creep or time-dependent loading. Also, FE analysis has shown that the compressive stress immediately under the action at the ice upper surface is much higher than predicted by simple linear beam theory and that the tensile stress is lower than predicted by simple beam theory. This behaviour is in conformance with concentrated loads placed on steel and concrete beams and is dealt with accordingly in the respective codes where shear is considered

to govern the design. Web stiffeners are added in rolled steel sections and shear reinforcement is used in concrete design to account for this concentrated load effect.

Linear elastic theory has traditionally been used to calculate the load-bearing capacity of ice sheets and provides reliable, readily calculated stresses and loads. Experience has shown that the recommended allowable stresses accurately predict the ice capacity and that exceeding these stresses results in significantly increased rate of failure. When Formulae (A.16-4) for edge loading and (A.16-1) are applied, flexural stress levels based on the above correspondence should be used. Because of the above reasons, the range of values, 500 kPa to 550 kPa, used to estimate safe loads using these formulae cannot be compared directly with those used for ice actions applied to sloping structures (see A.8.2.4.4 and A.8.2.8.3).

Formula (A.16-3) is a simple empirical formula meant for application in simple load situations. When ice roads are opened early in a winter season, generally the loads are concentrated and of simple foot-print. Long trailer loads should not be used in the early season. The ploughs employed to open the ice roads typically have two axles and the width of the load is approximately equal to its length. These concentrated actions during early season operation require a relatively safe value of A in the range of $35h^2$ to $50h^2$.

Later in the ice road season during rig hauls and trailer moves, when the road is well established, the loads are long and coupled. Heavier total loads are possible on roads with less ice thickness since the trailer axles are further removed from the vehicle drive axle. Stresses superimposed at the point of maximum flexural stress, usually at the drive axle, are relatively small from the secondary trailer loads. The lower flexural stresses from trailer operations and the fact that the ice thickness and other ice road parameters are better monitored on a completed ice road enables the use of $60h^2$ to $70h^2$ in Formula (A.16-3). For these long and coupled loading situations, the methods outlined in Formulae (A.16-1) and (A.16-2) are recommended.

Standard safe operating procedures for equipment involved in an ice road operation should clearly state the limitations assigned in order to allow the use of a particular P value. When limiting conditions such as wet cracks or a sudden change in air temperature are encountered, compensation should be made to ensure safe operation. Safe operating procedures should also state requirements for inspection and monitoring to ensure that defects such as wet cracks are found in a timely fashion.

A.16.1.2.5 Cracked ice sheets

For an action at the edge of an ice sheet, the maximum extreme fibre flexural stress, σ_{edge} , expressed in kilopascals, corresponding to P , is given in Formula (A.16-1)^[369]:

$$\sigma_{\text{edge}} = 0,529(1 + 0,54\nu) \frac{P}{h^2} \left[\log_{10} \left(\frac{Eh^3}{kb^4} \right) - 0,71 \right] \quad (\text{A.16-4})$$

where

- ν is the Poisson ratio;
- E_f is effective elastic modulus, expressed in kilopascals;
- h is a unit ice thickness, expressed in metres;
- k is the foundation modulus;
- b is the coefficient defined in Formula (A.16-1).

An example calculation comparing the stress, $\sigma_{(A.16-4)}$, from Formula (A.16-4) to the stress, $\sigma_{(A.16-1)}$, from Formula (A.16-1) for a continuous ice sheet is outlined for the given ice sheet parameters as follows:

$$\frac{\sigma_{(A.16-4)}}{\sigma_{(A.16-1)}} = \frac{0,529(1+0,54\nu)}{0,275(1+\nu)} \left(\frac{4,5-0,71}{4,5} \right) = 1,43$$

where

- ν is assumed to be 0,33;
- E is assumed as 5 000 000 kPa;
- h is assumed to be 1,0 m;
- k is assumed to be 9,81 kPa/m for freshwater;
- b is assumed to be 2,0 m.

The edge load stresses predicted by Formula (A.16-4) are generally 50 % higher than the values predicted for the centre of the same continuous ice sheet from Formula (A.16-1). As the log term in Formula (A.16-1) and Formula (A.16-4) becomes very large (i.e. the action becomes concentrated), the ratio of stresses becomes

$$\frac{\sigma_{(A.16-4)}}{\sigma_{(A.16-1)}} = \frac{0,529(1+0,54\nu)}{0,275(1+\nu)} = 1,70$$

In the worst case scenario, the stresses increase by 70 % when a wet crack is approached or crossed on an ice road by a very concentrated load. When intersecting wet cracks occur, additional reductions in the capacity of the ice sheet occur^[364].

The deflection of infinite ice sheets due to short-term loading can be determined using the methods given in Reference [370]. When the load is stationary for a period longer than about one day, allowance should be made for creep deflections. Methods using either field measurements from floating platforms or a reduced elastic modulus can be employed. These methods are discussed in A.16.2.2.3.

When a load is located close to a free edge, other methods are available, including that in Reference [371] for rectangular load patches.

A.16.1.3 Ice flexural strength for design

See Clause A.8.2.8.3.

A.16.1.4 Dynamic behaviour and dynamic amplification factor

Moving loads create a pressure wave in the water under the ice that can amplify the deflections and stresses^[372]. Theoretically, the amplification is infinite at resonance but, in practice, measurements indicate the dynamic amplification is about 1,5^[373]. Moving loads can be problematic when approaching a shoreline from the floating ice. The pressure wave created by the moving load reflects off the shallow bottom or off the shoreline and the result can be a rupture of the ice. This phenomenon results in the formation of a hole in the ice, which, while it does not affect the vehicle creating it, can affect vehicles following that are required to cross the same ice and cannot because of the hole created. Also, vehicles travelling a narrow passage or inlet covered by ice set up a wave that can reflect from the nearby shorelines, causing ruptures in the ice. These situations are unique and require careful observation and a consequent limitation on speed. In general, it is desirable to limit the speed of moving loads on ice to avoid dynamic effects. This is particularly important if the loads are close to the maximum allowed for the particular ice plate.

The speed of the water wave is dependent primarily on the depth of the water, the thickness of the ice cover and the elasticity of the ice. In deep water, the greatest deflection and the most severe stresses occur when the vehicle on top of the ice and the wave below it are travelling at the same speed. If the ice sheet is highly stressed because the ice is too thin or cracked, the stress from the wave plus the stress from the action can be enough to cause a sudden failure.

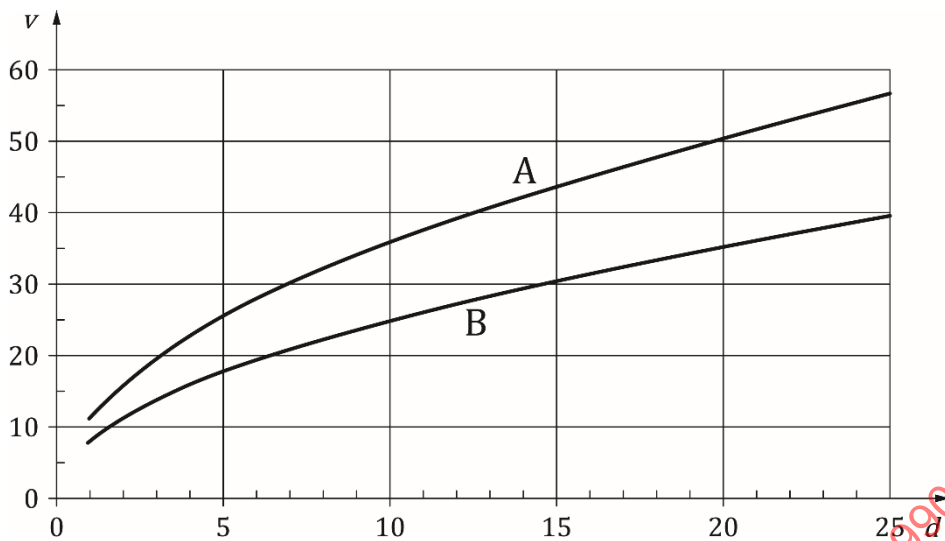
The critical vehicle velocity, v_c , expressed in kilometres per hour, for maximum dynamic magnification is determined principally by the water depth and can be expressed as given in Formula (A.16-5):

$$v_c = 11,3d^{1/2} \quad (\text{A.16-5})$$

where d is the water depth, expressed in metres.

At or near to the critical speed, the ice deflection and the ice stress/strain can be 1,5 times the values when the vehicle is travelling slowly. Field measurements have indicated that the dynamic magnification factor is not significant at a speed of less than 70 % of the critical velocity. These aspects are summarized in Figure A.16-5. From Figure A.16-5, a water depth of greater than 14 m is required for travel at 30 km/h where dynamic effects are completely avoided. Travelling at or close to the critical speed should be avoided.

When a vehicle is travelling parallel to a shoreline, resonant waves reflect back through the ice. The wave pattern is critical when the vehicle weight is close to the load-bearing limit of the ice. Reflected waves are greatest when a vehicle approaches a shoreline at a right angle. If possible, roads and vehicles should meet the shoreline at a 45° angle. It is important that drivers obey the posted speed limit where a road meets the shoreline and when a vehicle's weight is close to the maximum limit for the ice.



- Key**
- | | | | |
|---|---|-----|---|
| A | significant dynamic effect above this speed;
to be avoided | v | vehicle travel speed, expressed in metres per
second |
| B | minimal dynamic effect below this speed;
recommended | d | water depth, expressed in metres |

Figure A.16-5 — Critical speed for dynamic effects

A.16.1.5 Construction procedures

Preparation of the ice surface for flooding, if it is used to thicken the ice, and for traffic, varies according to local practice and experience. If flooding is carried out, then the heavier snow is removed using a mechanical means, such as a blade or snow blower before flooding commences. A thickness of 5 cm to 10 cm of snow can be left on the surface before flooding begins. Some projects do not have the means available to remove the snow, and the deeper snow cover on the ice is soaked with water and allowed to freeze. It is important to ensure that the water-soaked snow has completely frozen before continuing with the application of water. To prepare an ice cover for vehicular traffic, especially for wheeled traffic, the snow can either be removed by blade or blower, or it can be packed down to a relatively high density to ensure the wheeled vehicles do not become stuck. The snow, where possible, should be well removed from the road, with the snow banks along the side being sloped or “feathered” back. This avoids stress concentrations at the road edge and excessive cracking of the ice, plus it discourages the accumulation of further drifting snow.

Thickening of the ice is usually accomplished using low head, high volume pumps that lift water from beneath the ice onto the surface. The water is applied in layers about 3 cm thick and allowed to freeze before another layer is applied. In this way, the accumulation of ice thickness averages about 3 cm per day for most roads as a job average. During very cold periods when the winds are low, the rate can be higher but the average, considering the ability to cover existing ice and delays due to weather and equipment, is as quoted. It is best practice not to dyke or confine the water but to allow it to flow freely and achieve a tapered cross-section of the road or pad. This avoids sharp transitions and the formation of cracks at the edge of the flooded area. It is sometimes necessary to use snow dykes to prevent water from escaping and to achieve the required ice accumulation over a reasonable length of time. Judgment is required at all times.

The equipment used for thickening the ice varies, and locally available equipment is often the most convenient and effective. The pumps should be capable of operating in very cold temperatures. They should be submersible or Archimedes screw-type (augers) that have no hoses to freeze. These types of pumps are self-contained and drain readily when shut down. On road construction, the pumps are moved from (previously drilled) hole to hole as the road is flooded. The crews operating the pumps require means of transportation and of moving the pumps, and they also require a drill or auger to make holes of the required diameter. Spraying techniques can also be used to construct roads, as this accelerates the accumulation of ice thickness. The principles of spraying are described in A.16.2.1.2.

Further information on methods for continuous thickness profiling can be found in References [374] and [375].

A.16.1.6 Safe use of ice roads

No additional guidance is offered.

A.16.1.7 Grounded ice roads

Grounded ice roads are usually roads established in very shallow water whereby the ice is thickened and pushed onto the underlying soil. They are also roads established on-shore where an ice and snow cover is provided to protect the native soil or tundra from damage by wheeled and tracked traffic. Since soil provides a stiffer support or sub-grade for the ice, flexural stress in the ice is very often not a consideration in the design. It is necessary that the ice have sufficient thickness to spread the wheel loads and avoid overstressing of the tundra. In the case of offshore grounded roads, values of the sub-grade modulus, expressed in units of kilopascals per metre or kilonewtons per cubic metre or equivalent, should be high enough to ensure that the ice is not overstressed. Some weak soils have a sub-grade modulus that is little better than that of water (1 t/m^3), while others such as dense sand have a modulus that is orders of magnitude greater than that of water. It is important to know the sub-grade modulus when assessing the load-bearing capacity of grounded ice. The methods outlined in Formulae (A.16-1) and (A.16-2) can be employed to assess the effect of sub-grade modulus on the required ice thickness. Obviously, the consequences of failure are not as severe as they are in deep water, where life can be endangered and equipment lost, but still a failure does render the road unusable until it is repaired.

A.16.1.8 Helicopter landings on ice

For helicopters landing on the ice, the following additional points should be taken into consideration.

- a) A helicopter can keep its rotors running, resulting in an upward lift that can reduce the concentrated vertical action on the ice.
- b) By applying the procedure described in a), the ice thickness can be measured prior to personnel and equipment drop off, thereby ensuring adequate bearing capacity.
- c) Since the helicopter is stationary and not moving across the ice, breakthrough does not occur even if the first crack appears, with reference to Formula (A.16-1). Breakthrough results only from an action that requires the formation of the full pattern of circumferential cracks (see Figure A.16-3). This action is approximately 1,5 to 2 times the action associated with the first crack.

Based on the above considerations and past experience during ice expeditions, the recommended value for C_{ir} in Formula (A.16-3) is 50.

A.16.2 Man-made ice islands

A.16.2.1 Grounded ice islands

A.16.2.1.1 General

For decades, grounded ice islands have been used for oil and gas exploratory drilling in the Canadian Beaufort and US Alaskan Beaufort Sea. As with floating ice platforms, they provide a relatively inexpensive and environmentally sustainable means of supporting drilling operations. Up to 2005, three wells had been drilled in Canada and five had been drilled in Alaska using this technology.

For years, grounded ice rubble formations have been observed in shallower water in polar and sub-polar regions. Grounded rubble masses are stabilized and often remain stationary for the remainder of the winter season. Grounded rubble also serves to stabilize the surrounding pack ice, pushing the active shear zone further offshore. Stable rubble masses, with further artificial stabilizing, can provide a solid base for operations such as exploration drilling, and then melt leaving minimal trace during the summer.

Ice islands should be firmly grounded, with sufficient freeboard to ensure adequate contact with the seabed to resist the design lateral ice actions. The spray ice formed during construction should have adequate density and volume to provide the required weight, which ensures the correct bottom contact at the seabed. The spray ice should also have the required minimum shear strength to ensure that the lateral ice actions cannot produce a shear displacement through a plane of weakness in the island.

A.16.2.1.2 Construction

The water used for the construction of a grounded ice island should be placed and frozen above the water level. Spray operations readily achieve this placement of material due to the fact that the water is nearly frozen and immobile when it falls on the surface. Free-flooding does not readily achieve this placement goal. When free-flooded water is placed on thickened ice, the water tends to flow to low points, which can be the source of the pumped water.

Grounded ice islands have been constructed in the past within the landfast ice zone of the Beaufort Sea. Access has been via a floating ice road from shore to the island. The ice road is established in late November or early December and construction of the island begins shortly thereafter. In addition, the surrounding ice is used as a platform from which to construct the island. It is necessary that the road and the ice around the island be of approximately 1 m thickness in order to support the construction equipment. During the island construction, the road is thickened by flooding to support the transport of the drilling rig and supplies. For the transport of very heavy loads, such as was required for the Pioneer ice islands in 2003^[376], a grounded ice road was used. Currently, grounding of the ice can be accomplished economically only in water depths of up to about 3 m. Grounding can be accomplished by spraying and/or the use of ice chips.

Construction of spray ice-grounded islands occurs during December and January to allow the completion of drilling operations before the spring break-up. The exact duration of construction depends on the

location and year, but usually the latter part of December and most of January constitute the bulk of the construction period. Pumps with a rated capacity of 12 m³/min to 30 m³/min are used. These pumps should have a pressure at the discharge nozzle of 1,5 MPa. Lower pressures are insufficient to achieve the requisite atomization of the water for efficient ice-making. Depending on the water depth and diameter required for lateral stability and operations, an ice island can have a volume of 500 000 m³ to 1 500 000 m³. A pump normally operates for about 20 h/day or 10 h/shift, and its efficiency is 80 % to 90 %. Thus, to build an island with a volume of 1 000 000 m³ of ice, two pumps with a rated output of 20 m³/min can take 25 days to spray the water and construct the island. This calculation assumes no downtime for weather. With downtime for weather included, normally four pumps of this capacity are required to complete an island of this volume in a 30 day to 40 day period. It is not uncommon to have continuous periods of warm, windy weather in which little progress is made. Once the weather turns cold, to take advantage of this period, it is essential to have the equipment and capacity available.

Ambient temperature has the most direct effect on the ability to freeze the sprayed water. If normal seawater is being pumped, experience shows that at temperatures above -18°C little progress is made in ice building. This happens to be near the eutectic point for saltwater freezing, and it can be shown this is a transition for spraying results^[377]. Wind, on the other hand, is a detriment to efficient spraying. A moderate wind of 5 m/s to 7 m/s is desirable for removing heat released from the sprayed water and the avoidance of forming a thermal envelope at the island site, but strong winds hinder spraying. They result in the water droplets being blown downwind from the island and thus lost. Efficiency drops when the winds are strong, and winds in excess of about 12 m/s can bring the spray operation to a halt. In strong winds, there is only the opportunity to spray downwind, whereas in moderate winds one can spray crosswind as well, increasing the coverage and flexibility of any pump. An ideal situation for ice-making is a day with a temperature of -30°C to -35°C and winds of 5 m/s. Pumps with a capacity of 20 m³/min can produce 1 m/day of ice over an island with a diameter of 250 m to 300 m.

If freshwater is used, then there is no transition at -18°C and spraying can continue to the freezing temperature of 0°C . Of course, the rate of freezing decreases with an increase in temperature, and the best results are obtained at low temperatures.

Spraying water into the air using high pressure pumps (1,5 MPa pressure at the nozzle) causes it to be lofted tens of metres into the air and also causes it to be atomized. The air travel results in rapid cooling of the water droplets and, if the spray nozzle is properly sized and aimed, the water droplets are about 80 % frozen when they fall to the existing ice surface. It is desirable not to have the water droplets 100 % frozen at contact with the surface, as this leads to the formation of corn ice or snow, which has very little cohesion and is not a good bearing surface as it lacks shear strength. Also, it is not desirable that the spray be too wet, or the resulting slush that lands on the ice requires a long time to freeze. If the spraying is planned and managed properly, optimum build-up or ice accumulation rates are achieved with maximum density and shear strength. The density of spray ice is usually about 0,6 t/m³ and the shear strength is on the order of 35 kPa to 150 kPa^{[378][379]}. This density and shear strength are very suitable for resisting lateral ice actions from the surrounding moving pack ice and for supporting heavy loads such as a drilling rig on the island.

Spray ice is a very workable material and can be shaped, excavated and moved readily with bulldozers and front-end loaders. The surface of the island at the end of the construction period is usually rolling and never flat. Thus, it is important to be able to level the ice to produce a usable working surface.

Grounded spray-ice islands have been built since 1985 without the benefit of underlying ice rubble, mainly because none was available at the sites where construction took place. Ice was sprayed on top of the level FY ice and, thus, the bulk of the island was formed of spray ice. If grounded or floating rubble is available over the site, then it can be used and the construction time reduced. The rubble forms a good solid base for the island. With larger pumps, more water can be pumped and more ice can be formed in a given time. This applies not only because there is more water pumped, but also because the increased pumping rate results in a higher momentum for the water stream, causing it to be propelled higher and farther. This, in turn, increases the time of exposure to the cold ambient air and results in more freezing, which is required for the increased water supply. Larger pumps produce a volume of ice in a day that is proportionally more than for a smaller pump. Thus a pump with a capacity of 20 m³/min produces more than 20/12, or 1,7, times the ice per day than a pump with a capacity of 12 m³/min, all other factors being equal. It is, therefore, desirable to use the largest pumps practical when building a spray ice island.

At present, the maximum water depth for which grounded spray-ice islands can be used realistically is 12 m to 15 m. The maximum depth depends on the mobility of the ice pack and on the timing of the start of construction. If the local geography results in the ice becoming landfast early, then it is possible to access the site early and to complete the construction in time for the intended operation. Water depth itself is not so much the issue as the fact that with increasing water depth the ice pack remains mobile for longer periods during the winter. Generally, it is necessary for the ice to become landfast and stable by about 1 January for a project to be successful. This, of course, applies to operations where the construction is supported from the ice. If a ship is used to support the construction, then there is more tolerance for ice movement later in the year. While spraying can be used to help ground the ice locally to stabilize the pack, most practical applications involve construction using the existing ice as a support.

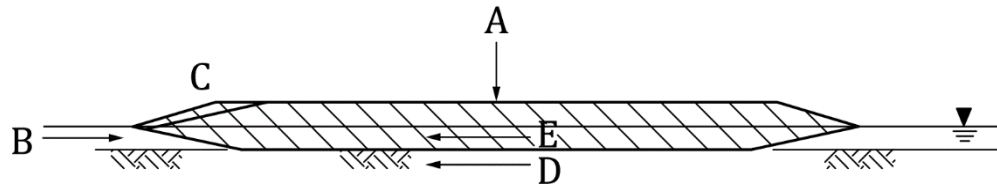
Once constructed, the grounded portion of the island forms the core of the island beyond which there is the sacrificial edge which, in the event of a major ice movement, can be subjected to shear-type failure. All critical, non-relocatable facilities, such as the drilling rig and any camp, should be located within the core radius.

The shape of the ice island edge is very different from that of gravel or other earth edges. Since, unlike soil or gravel, the ice is buoyant and since the natural ice sheet is bent and submerged during spraying of the island, the underwater part of the edge naturally takes on the reverse taper shown in Figure A.16-6. Profiles taken after the completion of construction have generally confirmed this as the shape of the island edge. The taper can run further than shown in Figure A.16-6 due mainly to overspray. This overspray can be removed during construction and placed on the island proper.

A.16.2.1.3 Material properties of the ice

A.16.2.1.3.1 General

The material properties of the grounded ice island determine the ability of the ice island to resist lateral action and to support the surface load in bearing. A.16.2.1.3 focuses on spray ice since it is the primary material employed in the construction of grounded ice islands.

**Key**

A weight of ice
B ice action
C edge failure plane

D shear resistance at ice/seabed interface
E internal shear resistance

Figure A.16-6 — Ice action and resistance of an ice island

A.16.2.1.3.2 Material properties of spray ice below waterline

In determining the sliding resistance of spray ice islands, the shear strength of the spray ice underwater should also be considered since, depending on the bottom soil conditions, a shear failure can develop on a plane through the island itself.

While there are limited data on the shear strength of spray ice below the waterline, available data suggest that the spray ice below the waterline is a low friction material (when considered as a granular material) and one can assume that the shear strength of the ice below the waterline equals the cohesion of the submerged ice material. Table A.16-1 lists upper and lower bounds on the submerged ice material or shear strength of saturated spray ice as indicated by various test methods.

Table A.16-1 — Underwater spray-ice strength

Test method	Shear strength kPa
Pressure meter	$99 < \tau_{ice,bw} < 145$
Borehole jack	$147 < \tau_{ice,bw} < 217$
Flat jack	$55 < \tau_{ice,bw} < 77$
Cone penetrometer	$40 < \tau_{ice,bw} < 50$

The shear strength of spray ice below the waterline was assumed to be the lowest recorded strength and a shear strength of 40 kPa was chosen for designs in the 1980s.

An extensive series of cone penetrometer tests was conducted at the Karluk Spray Ice Island during the verification programme^[378]. The average bearing pressure below the waterline was 3,8 MPa. The following range of bearing pressure was noted:

$$1,6 \text{ MPa} < \text{bearing capacity} < 6,3 \text{ MPa}$$

Assuming, as is standard practice, that the shear strength is 1/6 of the bearing capacity^[380], then the Karluk Spray Ice Island had the following bounds on shear strength below the waterline.

$$267 \text{ kPa} < \tau_{ice,bw} < 1\,050 \text{ kPa}$$

The lack of voids and general continuity of the ice at Karluk, plus the high cone test results, indicate high shear strength. A weighted mean shear strength using all of the above data is 56 kPa.

The spray ice has considerably higher shear strength than the sand of the seabed. For a shear strength of 56 kPa, an ice island with a core radius of 100 m has an internal shear resistance of 439 MN. Generally, shear failure through the sea bottom material governs in any sliding stability calculation.

A.16.2.1.3.3 Spray ice properties above waterline

Data from spray ice platforms and islands suggest that spray ice above water behaves as a Mohr-Coulomb material such that the shear strength, $\tau_{ice,aw}$, is given by Formula (A.16-6):

$$\tau_{ice,aw} = c_{ice,aw} + \sigma \tan \phi_{ice,aw} \quad (A.16-6)$$

where

- $c_{ice,aw}$ is the cohesion for the spray ice above water, assumed to be equal to 283 kPa;
- $\tan \phi_{ice,aw}$ is the tangent of the friction angle for spray ice above water, assumed to be equal to 0,85;
- σ is the normal stress, expressed in kilopascals.

The normal stress, σ , is the vertical stress component in the ice at the point where $\tau_{ice,aw}$ occurs. Suggested cohesion values are 283 kPa for the above water spray ice material and 56 kPa for the underwater material^[376]. Note, however, that spray-ice strength properties can depend on many parameters (temperature, salinity, density, strain rate, stress condition, etc.) and it is advised that the spray ice properties used for design be verified.

A.16.2.1.3.4 Ice and soil interface

By grounding the ice island through the surcharging of the existing ice surface with successive layers of spray ice, the bottom of the ice island comes into contact with the seabed. This interface between the ice and the seabed soils is an important consideration in assessing the stability of the grounded island against lateral ice actions. If the seabed is a granular material, then the shear resistance of the interface is given by Formula (A.16-7).

$$\tau_{is} = \sigma_{is} \tan \phi_{is} \quad (A.16-7)$$

where

- τ_{is} is the shear strength of the ice/soil interface, expressed in kilopascals;
- σ_{is} is the normal stress due to the weight of ice, expressed in kilopascals;
- ϕ_{is} is the friction angle at the ice/soil interface, expressed in degrees.

For a frictional material, the shear strength of the interface increases with increasing weight of ice on the bottom. Since the ice below water is slightly buoyant, all of the weight on the bottom results from the freeboard of ice above the waterline.

The on-bottom weight, W_{ii} , of an ice island with a circular plan shape is determined using Formula (A.16-8):

$$W_{ii} = \frac{\pi D_c^2}{4} \{ [\gamma_i h_{fb} + (\gamma_{is} - \gamma_w) d] \} \quad (A.16-8)$$

where

D_c is the core diameter, expressed in metres;

γ_i is the above-water spray ice density, expressed in kilonewtons per cubic metre;

γ_{is} is the below-water spray ice density, expressed in kilonewtons per cubic metre;

γ_w is the seawater density, expressed in kilonewtons per cubic metre;

h_{fb} is the island freeboard, expressed in metres;

d is the water depth, expressed in metres.

The on-bottom weight calculated from Formula (A.16-8) is a force, expressed in kilonewtons, with the parameter units as stated. The density of the spray ice above water and below water is approximately 0,6 t/m³.

If the seabed is cohesive, then the shear strength at the interface is determined by Formula (A.16-9).

$$\tau_{is} = c_{soil} \quad (A.16-9)$$

where c_{soil} is the cohesion of the soil, expressed in kilopascals.

In this case, the shear strength at the interface is not dependent on the weight on bottom, or at least it does not appear to be. Once the island is set on bottom, any loose seabed material can be consolidated by the weight of the ice; this, in turn, increases its shear strength. The degree to which the shear strength is enhanced depends on the initial density of the soil, its permeability and the physical structure of the soil.

The seabed can also be a Mohr-Coulomb material, in which case both cohesion and friction are considered in the resistance calculation.

A.16.2.1.4 Lateral stability against ice action

The lateral stability of a grounded ice island should consider the actions shown in Figure A.16-6. Lateral ice actions are resisted by the shear resistance of the island.

The island is first considered as a rigid body, and its resistance, R_{ii} , to the ice actions is determined by Formula (A.16-10).

$$R_{ii} = \frac{\pi D_c^2}{4} \{ c + [\gamma_i h_{fb} + (\gamma_{is} - \gamma_w) d] \tan \phi \} \quad (A.16-10)$$

where

- D_c is the core diameter, expressed in metres;
- ϕ is the bottom friction angle, expressed in degrees;
- c is the bottom cohesion, expressed in kilopascals;
- γ_i is the above-water spray ice density, expressed in kilonewtons per cubic metre;
- γ_{is} is the below-water spray ice density, expressed in kilonewtons per cubic metre;
- γ_w is the seawater density, expressed in kilonewtons per cubic metre;
- h_{fb} is the island freeboard, expressed in metres;
- d is the water depth, expressed in metres.

The resistance calculated from Formula (A.16-10) is expressed in units of kilonewtons with the parameter units as stated.

As shown in Figure A.16-6, edge failures can occur that can alter the actions applied to the island. Generally though, edge failures require about the same level of action as is required to crush the oncoming ice.

Lateral actions on the island due to movement of the surrounding pack ice are calculated in the same manner as those on other offshore structures. Activities on the ice island only take place during the winter and, thus, are during a time when the surrounding ice is relatively stationary. Usually the thickness of FY ice is used to determine the action effect, with the contact width being the waterline diameter of the structure. The ice action imposed on the ice island due to the pack ice, F_{ii} , is determined from Formula (A.16-11).

$$F_{ii} = p w h \quad (\text{A.16-11})$$

where

- p is the effective ice crushing pressure, expressed in kilopascals;
- w is the contact width of the grounded structure, expressed in metres;
- h is the average ice thickness, expressed in metres.

When MY ice is in contact with the island, it is necessary to calculate the action considering the thickness of the MY ice and its width of contact with the surrounding pack ice. In cases when the MY ice, because of its thickness, can be grounded, it can become a stabilizing agent against ice motion in the area. Each situation should be evaluated prior to the time of construction and use of the particular island.

A.16.2.1.5 Load-bearing capacity

A.16.2.1.5.1 Assurance of load-bearing capacity

Spray ice has proven to be a material very capable of supporting its own weight when set down on the seabed and of supporting heavy surface loads such as drilling rigs. This is accomplished by the

construction method whereby the sprayed seawater droplets are not totally frozen and the freezing process is completed on the island surface. By doing this, the development of good cohesion in the spray ice is assured. This is in contrast to materials, such as man-made snow, that have low cohesion and provide a weak bearing surface.

The combination of the rig load plus the weight of the spray ice can cause vertical creep settlement during drilling of the well. Creep settlements on the order of 200 mm are common.

A.16.2.1.5.2 Below-water capacity

Tests and observed behaviour indicate spray ice to generally be a cohesive material. From foundation theory for a circular plate^[380], the bearing capacity, q , expressed in kilopascals, is determined from Formula (A.16-12):

$$q = 1,2\tau_{ice,bw}N_c \quad (A.16-12)$$

where

$\tau_{ice,bw}$ is the shear strength of spray ice below waterline, expressed in kilopascals;
 N_c is equal to 5,14.

A.16.2.1.5.3 Above-water capacity

For Formula (A.16-6), the shear strength of the above-water ice is at least 283 kPa. Using the previous formulations for bearing capacity from Timoshenko, given as Formula (A.16-12), the bearing capacity for the above-water ice is at least 1 747 kPa. Since the shear strength is dominated by the cohesion term, the total shear strength can be estimated as 283 kPa.

A.16.2.1.6 Thermal considerations at the well

For drilling a well, it is necessary to analyse carefully the heat transfer to the ice during drilling. Failure to do this in the past has resulted in significant melting of the ice under the main rig loads and near collapse of the rig. Insulation, either passive or active, should be used for any drilling programme lasting more than a week. Passive systems use insulation, and active systems use a saline solution continuously pumped through the annulus between the conductor pipe and the surface casing (see Figure A.16-7)^[379]. The insulation system chosen should be capable of maintaining the ice adjacent to the conductor pipe below the thaw temperature.

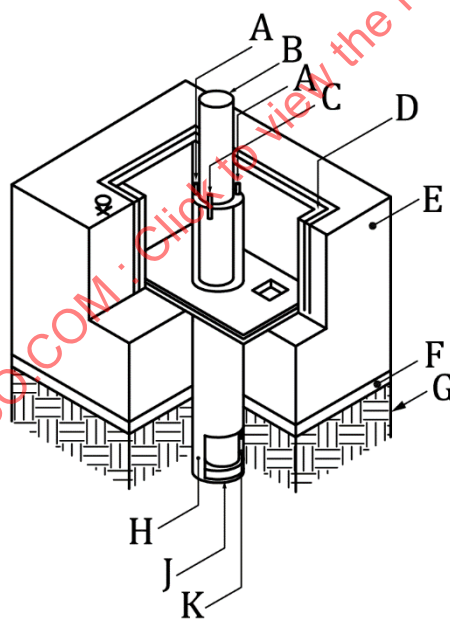
A.16.2.1.7 Verifications and monitoring during construction and drilling

No additional guidance is offered.

A.16.2.1.8 Safety measures

Safety measures covering a wide range of activities on floating ice and on the island are of prime importance during construction and drilling. Issues to be considered include the following.

- Will there be significant ice movement during construction?
- What will be the effect of ice movement, both on the access road and the island?
- What measurements can be taken and what data obtained to predict movement?
- What response is required to movement?
- What movement of ice is likely during drilling or operations on the island?
- Is the safety of the well compromised?
- Will critical access to the island be denied?
- Will emergency planning for the well be compromised?
- What mitigative measures are available?



Key

A	brine injector tube	F	sea ice
B	conductor	G	seabed
C	brine return tube	H	outer casing
D	well cellar	J	cement plug
E	spray ice	K	brine outlet

Figure A.16-7 — Cut-away of a refrigerated conductor

A.16.2.1.9 Construction quality control (QC) and monitoring

Monitoring of the surrounding ice cover during construction is vital to the success of an offshore programme. This monitoring should include:

- daily visual observations by the personnel on site;
- satellite imagery;
- continuous monitoring of ice motion.

Reasonable ice alert procedures should be in place and carefully planned to provide critical information without undue alarms.

During the construction phase of the island, the QC tasks verify material quantity and material quality as required by the design, and consist of measurements of ice volume, ice temperature and ice density from samples in situ (see A.8.2.8.10) plus the recording of key pump-operating parameters. A key activity during the construction consists of visual inspection of the spraying process and of the island itself.

The ice thickness and the related constructed volume can be measured at predetermined locations using marked tubing installed in the ice at the start of construction. The tubing should be extended during spraying to ensure access for measurement. Ice temperature can be measured using “strings” of thermistors.

A.16.2.1.10 Post-construction verification

At the completion of the island construction, a programme is generally conducted to verify that the design conditions for the island have been met or exceeded. The activities associated with this phase are as follows:

- review information on geometry, density (see A.8.2.8.10) and temperature obtained during construction;
- perform spot checks on the island's total thickness at select thickness-monitoring stations (approximately 10 % of the thickness-monitoring stations should be checked in this manner);
- conduct cone penetrometer tests (CPTs).

A.16.2.1.11 Monitoring during drilling

The principal activities are the measurement of settlement of the ice surface, measurement of ice temperature near the cellar and conductor, and ice movement monitoring.

The position of the island, measured at a predetermined location, should be established at least daily. Also, any movement of the surrounding ice relative to the island should be determined.

A.16.2.2 Floating ice islands

A.16.2.2.1 General

Both the mining and the oil and gas industries have employed floating ice platforms to carry out drilling programmes over bodies of water. In the oil industry, loads up to 1 500 t have been placed on these platforms for periods of 100 days or longer. A typical thickness of such a platform is 6 m, and the diameter is on the order of 150 m. Mining exploration programmes tend to employ lighter-weight core-sampling drills on thinner ice platforms. The references and points noted on ice roads in A.16.1 apply to ice platforms.

A.16.2.2.2 Construction

When spraying is employed to construct a floating ice island, the same procedures and safety precautions given in A.16.2.1.2 for spraying on a grounded ice island apply.

A major difference for constructing a floating ice platform relative to a grounded platform is that it is necessary to ensure that the ice in the platform flexural tension zone is of sufficient strength to safely carry the design (typically 550 kPa) flexural stress. Free-flooded ice platforms have consistently strong ice top to bottom. Sprayed floating-ice platforms are typically formed by spraying onto a layer of natural ice to commence the flooding operation. For this reason, the bottom tension zone is in the stronger natural ice area. This is a convenient occurrence that adds to the structural integrity of sprayed platforms.

Free-flooding operations on an ice platform can be carried out with electric submersible pumps when thicknesses of over approximately 3 m are required. This is especially useful in very cold climates where the operation of smaller gas- or diesel-powered pumps can be a problem. Smaller gas- or diesel-powered pumps are employed typically to free-flood, especially for smaller ice platform programmes. Often the gas-powered pumps are moved about by hand. Mobile pumps, especially when employing diesel power, are often mounted on a wheeled or tracked chassis.

A.16.2.2.3 Design for short-term and long-term load-bearing capacity

When designing an ice platform, both the short-term stress and long-term deflection, or creep, should be considered^{[381][382][383]}.

The same principles of stress analysis given in A.16.1.2 for floating ice road design apply for the stress analysis of stationary loads on an ice platform. Creep of the ice in the platform results in relaxation of stress over time.

Safe ice platform design requires that the deflection resulting from the loading does not exceed the available freeboard. The available freeboard with both freshwater and seawater ice equates to approximately 10 % of the platform ice thickness. The design case deflection, δ , expressed in units consistent with δ_0 , can be calculated as given in Formula (A.16-13)^[383]:

$$\delta = \delta_0 \left(\frac{h_0}{h} \right)^3 \left(\frac{P}{P_0} \right)^{1,5} \quad (\text{A.16-13})$$

where

- δ_0 is the previous-case known deflection, in any units of length;
- h is the design-case ice thickness calculated to satisfy flexural stress limitations, in units consistent with h_0 ;
- h_0 is the previous-case known ice thickness, in any units of length;
- P is the design-case known applied load, in units consistent with P_0 ;
- P_0 is the previous-case known applied load, in any units of force.

Formula (A.16-13) can be employed only when the area of distribution for the two load cases and duration of loading are similar. Drill rigs placed on an ice sheet generally have similar equipment layout patterns and similar durations of loading for comparable rig weights.

A.16.2.2.4 Thermal design

The same conditions and recommendations of A.16.2.1.6 apply.

A.16.2.2.5 Monitoring during construction and drilling

Monitoring requirements during the drilling phase should ensure that all areas of the ice platform remain above the water level. Water that floods onto the surface acts as a further load on the platform and accelerates deflection. In addition, water on the surface results in an unsafe work area, which makes it difficult to retrieve the rig or other equipment and material.

Ice strength measurements, using a borehole jack through the ice profile, are a good indicator of the flexural tensile strength. The flexural strength of the ice is approximately 1/9 of the confined borehole compressive strength.

A.16.3 Protection barriers

A.16.3.1 General

Ice rubble fields are accumulations of fragmented ice that form from moving ice sheets around wide offshore structures, islands or sloping beaches in shallow waters. Depending on the water depth, the rubble can be embedded in a moving ice sheet or can be grounded on the sea floor. When moving ice rubble interacts with a structure, the ice actions on the structure can increase compared with interactions with level ice. This should be considered when designing a structure. On the other hand, grounded ice rubble around a structure can reduce the ice actions on the structure due to transfer of actions to the seabed or by change of failure mode.

A.16.3.2 Ice protection structure

A.16.3.2.1 Grounded ice as a protection barrier

Natural ice rubble formation results normally from thin-ice interactions in the freeze-up and early winter periods. Also, the installation of man-made ice protection structures in shallow waters can initiate the ice rubble formation process in order to protect offshore exploration and production structures.

For a structure sitting on an underwater soil/gravel berm, rubble can become grounded on the underwater berm and move the active failure zone to the outside of the ice rubble^[384]. A berm can also cause thick ice features (floes) to be slowed or stopped by grounding. The reaction created by deformation of the soil berm and uplift of the floe dissipates the floe's kinetic energy and thereby reduces the potential action on the structure^[26].

Ice interaction mechanisms are governed by structure shape and structure geometry, interaction speed and the geometry of the ice feature. Thus, the effect of ice rubble is an important consideration in ice action calculations^[385].

If the grounded ice rubble is significantly larger than the structure it surrounds, the effective structural cross-section to global ice actions is increased. The potential action increase is counterbalanced by the sliding resistance of the grounded rubble and the manner in which actions are transferred through the rubble pile. The ice failure mode changes experienced at the rubble boundaries can result in lower effective ice failure pressures and, consequently, lower global ice actions^[386].

Since it has been observed that most grounded ice rubble remains stable during a winter season, it affords a degree of protection to offshore structures. Ice rubble can also protect a structure from the potential for ice ride-up and ice overtopping, and it tends to mitigate the effect of dynamic ice actions^[386].

If the structural design relies on ice defence and barriers to reduce actions, the barrier's effectiveness should be qualified by theoretical calculations, full-scale experience or model tests where the ice rubble and pile-up process is simulated correctly.

A.16.3.2.2 Rubble generation

The mechanism of rubble-pile formation is quite complex and not well understood. In some cases, the rubble forms a ramp for the oncoming ice sheet and fails in bending, particularly for thin-ice sheets. In other cases, the moving ice sheet penetrates existing ice rubble and also fails in bending due to the difference of buoyancy and gravitational actions.

When ice rubble forms, the ice sheet is usually thin compared to the width of the island or offshore structure. If the broken ice pieces cannot clear around the structure/island during ice movements, the fractured ice pieces accumulate as a rubble field^[387]. Data on rubble pile heights for the Beaufort, Baltic and Caspian Seas are summarized in Reference [388].

For wide structures in a sea ice environment, the accumulation of ice rubble can significantly affect the ice failure mode and the resulting ice actions. When the ice becomes too thick to fail in bending or the oncoming ice sheet is constrained, the ice begins to fail in crushing at higher ice stresses. The crushing

stress in the active zone is difficult to predict, and it is likely to be lower than can be experienced by narrow, gravity-based structures^[389]. Experience from field measurements should be used in such cases.

A.16.3.2.3 Ice barriers

Grounded ice rubble can be used as a protective ice barrier for offshore exploration and production structures. Ice barriers can be constructed using existing grounded ice rubble, or augmented by flooding and spray techniques^[386]. These techniques are well proven in the Beaufort Sea, especially in terms of building protective ice pads (see A.16.2).

One important issue with ice barrier construction is the quality of the ice/seabed contact. If the seabed consists of frictional material (e.g. sand), then the ice barrier should be built with smaller cross-sections and a high freeboard to minimize the lateral ice action. If the seabed is cohesive, larger barriers with low freeboard become more attractive^[386].

In the case where a barrier is built on a smooth level ice sheet, the ice sheet can impede the drainage and consolidation of the cohesive soil. In addition, the influence of smooth ice on the ice/soil interface shear strength should be considered.

When the ice barrier is built on top of a smooth ice sheet, it can slide a small amount under actions from the surrounding ice sheet, depending on the compressibility of the rubble surcharging it and the nature of the ice surface.

Water depth and water level fluctuations are important factors in assessing ice rubble sliding resistance. Experience in the Beaufort Sea indicates that a grounded ice rubble field usually forms around a structure when the berm is set at 15 m or less, and the rubble extends to a water depth of about 18 m to 20 m down the flanks of the berm^[386]. Permanent grounding of ice rubble is more likely for shallower water depths.

In general, the ice rubble formed early in winter from thin ice sheets does not create sails as high as those created from thicker ice sheets later in the season. Its topography (i.e. the relationship between sail height and thickness of grounded ice rubble) is not as well understood as that for sea ice pressure ridges.

Grounded ice protection barriers should be designed to resist lateral ice actions. Such actions tend to cause failure in one of four ways:

- a) sliding along a weak plane through the ice;
- b) sliding along the bottom at the ice-soil interface;
- c) sliding along a weak plane through the soil;
- d) passive edge failures.

The sliding resistance of the rubble depends on the strength of the interface between the ice blocks and the sea floor. This is reasonably well defined if the rubble sits on a sand berm. When the ice rubble pile is grounded on the natural sea floor, the interface strength is often uncertain and the designer should perform careful geotechnical investigation and assessment.

A.16.3.2.4 Ice actions and ice/barrier interaction

A knowledge of ice rubble properties is important for characterizing ice action transmission. Ice rubble generally consists of a sail (portion above sea level), a refrozen layer and the keel. In areas of low sail height and minimal snow, the heat flux usually is large and the refrozen layer can attain thicknesses that are double the normal level-ice growth for the region. The continuity of the refrozen layer is also important in this respect. Because of difficulties of drilling through high sails, few data have been gathered to date for this condition^[386].

The ice strength and elastic modulus of the refrozen layer are best deduced from in situ strength measurements. Measuring salinity and temperature is not a reliable means of determining the strength of rubble ice. The properties of the grounded keels are key to how the ice actions are transmitted to the sea floor or the underwater berm. Based on gross measurements of rubble field behaviour, it is assumed that the keels have sufficient strength and stiffness to effectively transfer most of the ice actions to the sea floor or berm. It is believed that low temperatures during the rubble formation processes and high grounding stresses can initiate the bonding of fragmented ice blocks to form a cohesive mass. There is evidence to indicate that strength increases do occur. Sea floor “pock marks” have been observed where FY ice rubble fields have been grounded, indicating that significant stress can be applied.

While laboratory measurements of the strength of ice rubble have led to its description as a linear Mohr-Coulomb material, there is no agreement on ice rubble parameters to be used in models for ice actions on structures. Since grounded ice rubble is compressed, it is reasonable to believe that it is stronger than floating ice rubble.

The majority of the field measurements and observations in the Beaufort Sea support the finding that once a grounded ice rubble field is established around an offshore structure, the action transmitted to the structure is often zero and, even when there is transmission, it is usually less than about 30 % of the applied ice action. There have been cases where greater than 50 % of the applied action appears to have been transmitted^[386]. It is assumed that in these cases the refrozen layer is probably more continuous than usual.

There are some instances in the spring with warm ice when the action transmitted is higher than 50 %. This situation matches the model test results, which generally show higher levels of action transmission than in normal winter field situations.

Experiences from the field indicate that grounded ice rubble dissipates or eliminates the transmission of significant dynamic ice actions. The mitigation of ice-induced dynamics can be related to the change in ice failure mode, but the additional mass and damping of ice rubble are also presumed to be a beneficial influence.

Ice rubble deforms with time and under ice actions. The most significant deformations are vertical settlements (creep behaviour) after formation, which can be greater than 1 m. Lateral deformations are often associated with vertical settlement, but also with sustained lateral actions.

Field measurements of ice action transmission through ice rubble fields are difficult. Theoretical calculations of ice rubble field resistance and effectiveness in protecting structures from ice actions can be subject to considerable uncertainty. Consequently, model testing can be performed if it is clear the processes in the pile-up and rubble formation are modelled correctly. Attention should also be given to a suitable scaling of the structure, the ice environment and ice failure processes.

A.16.3.3 Methods for mitigating the effects of ice

A.16.3.3.1 Ice control and defence

Passive ice control and defence methods can be used for lowering the risk or safety class associated with a given structure. They can be implemented at the design stage, or operationally during the design service life of the structure.

Ice control and defence methods can also be used to reduce the ice actions on the structure. The following approaches have been attempted:

- a) cutting a trench or moat in the ice around an island or structure. This approach can only be effective if
 - the trench is kept dry or prevented from refreezing,
 - the trench precipitates out-of-plane ice movements.

This technique suffers from the limitations that

- i) it is a one-time solution,
- ii) the ice can crack, causing the trench to fill and refreeze.

The trench approach can have a negative effect in that it can induce ice over-ride onto the working surface of the drilling platform it was designed to protect;

- b) placing barriers in front of the structure to initiate the formation of a grounded rubble pile; see A.16.3.2;
- c) using satellite structures to relieve the ice actions on the drilling platform itself. An ice protection system was put in place around Sunkar, a drilling platform in the Caspian Sea, with the dual purposes of
 - adding more sliding resistance,
 - forming grounded ice rubble, if ice movements occur,
 - spraying ice on the satellite structures^[390];
 - helping to provide relatively ice-free access to the Sunkar structure for supply vessels.

Various concepts have been used or designed for the satellite structures, including barges and rock-mound breakwaters^{[391][392]}.

- d) using spray ice to augment the sliding resistance, e.g. for barges deployed at Sunkar, to augment their sliding resistance^[390];
- e) placing piles in front of the structure to augment its sliding resistance and to control ice rubble build-up at the structure. This has also been done at the Sunkar drilling barge ^{[393][394][395]}. More general model tests of this concept have been performed^[396]. If model tests are used in design of pile structures, attention should be given so that the ice failure is modelled correctly at the piles.

- f) including local variations in the structure's perimeter. The GBS at Hibernia was built with local indentations around its perimeter. These were intended to reduce the global action by lengthening the time taken to decelerate an impacting iceberg.
- g) using explosives, which have been considered for large ice masses (i.e. icebergs and ice islands) for many years, dating back to about 1926. This approach has never been used operationally for ice defence, owing to a number of limitations and concerns.

A.16.3.3.2 Mitigation of ice encroachment

The ice control and defence methods listed in A.16.3.3.1 can also be used to protect the structure against ice encroachment.

Ice ride-up is complex, as many factors affect the interaction, and only a rough understanding is currently available. Reference [397] offers the following guidelines.

- Shallow slopes are more susceptible to ice ride-up.
- Smooth slopes with few irregularities are more susceptible to ice ride-up.
- Ice ride-up is more likely to occur in combination with tidal fluctuations, storm surges or gravity waves, which act to break the ice-shoreline bond and elevate the ice sheet.

Reference [397] further indicates that “rough, irregular or steeply sloping shores will tend to initiate ice pile-up when onshore ice movement occurs”.

The following ice control methods are available to protect against ice encroachment.

- a) Layout of facilities on the island: this includes laying out islands such that they have a perimeter road, and putting the least critical items closest to the island's perimeter. This approach is most applicable to gravel or man-made islands. The perimeter road provides general access around the island as well as protection against ice encroachment onto the island, which can put the facilities at risk.
- b) Constructing caisson-type drilling structures with sufficient freeboard that the facilities on them are protected from potential ice encroachments: e.g. some structures such as the Molikpaq and the caisson-retained island were constructed with steel ice deflectors around the full perimeter at the top of the caisson^{[398][385]}.
- c) Designing the slopes and faces of drilling islands such that they cause ice pieces in an encroaching ice sheet to become unstable, leading to rubble formation, thereby preventing further encroachment onto the island. The approaches for achieving this include:
 - using slopes with a variable elevation profile, such as
 - i) a “bump” in the slope which produces an instability in the advancing ice pieces,
 - ii) having a steep section that can bring about a change in ice failure mode;
 - placing obstacles along the face, such as steel piles, to inhibit ice ride-up, (the “tank traps” used at Challenge Island^[399] are a variation of this concept, as the tank traps are intended to initiate rubble formation, thus preventing ice ride-up onto the island).

Since encroachment is a local design issue, the exposure level (see 7.1.4) for facilities potentially affected by ice encroachment can be designated individually. For example, it is not necessary that unmanned storage areas of non-hazardous materials be protected from ice ride-up or pile-up. Hydrocarbon storage, production wells and manned areas require design according to the provisions of Clauses 7 and 8.

A.16.4 Measurements of ice pressure and actions

A.16.4.1 General

Ice action measurements have provided the basis for many important advances in ice engineering with respect to offshore structures, and current design codes state that empirical treatment of full-scale data is often the best approach for determining design ice actions^[26]. Fundamentally, ice action measurements are undertaken to meet the two general objectives listed in Table A.16-2.

Table A.16-2 — Overview of ice action measurement objectives and requirements

Key requirements of the measuring system	General application and objective	
	Safety assurance of an existing structure ^a	Improved design criteria for future structures
Real-time data	Essential	Not required
Algorithms to interpret the data	Essential, and required in real time	Required, but not in real time
Frequency of data acquisition and ice alert levels	Real-time data more important than high-frequency data, if a compromise is necessary Alert levels required	Depends on the ice failure mode: high-frequency data (>10 Hz per channel) required, if ice failure occurs by crushing Alert levels not required
Measurement of global versus local actions	Global actions typically most important	Depends on application; data can be required for either one or both
^a Many failure modes are possible, such as sliding along various failure planes and overturning.		

A.16.4.2 Measurement techniques

A wide range of approaches for the measurement of ice actions has been used to date. See Reference [400] for a description of some of them. Comprehensive systems have been used at the following locations:

- measurement system on the SSDC^[401];
- measurement system on the Molikpaq while deployed in the Beaufort Sea^[398];
- measurement system on the Molikpaq while deployed in the Okhotsk Sea^[402];
- monitoring system used at the Confederation Bridge^[403];
- monitoring system at the Hondo Bridge Pier^{[404][405]};
- monitoring system at the Yamachiche Light Pier^[405];
- measurement system at a structure in the Pechora Sea^[406];
- LOLEIF/STRICE^[407];

- measurement system on the Kulluk in the Beaufort Sea^[170];
- measurement system on the USCGC Polar Sea in the Beaufort and Chukchi Seas^[408];
- details of measurement systems on ships^[409].

Ice measuring systems should be designed to operate in conjunction with other monitoring systems that are in place, such as for structure and foundation response, taking into account the possible failure modes. The most appropriate system should be selected based on the structure, the environmental conditions at the site, and the objectives of the project. Generally, the available field techniques can be classified as either:

- a) measurements of the stress or strain in the ice: many instruments have been developed to accomplish this^{[410][411][400]};
- b) measurements of structural response, which, in general, can be accomplished by
 - measuring the strains, deformations or movements of the structure, including its foundation,
 - placing load-sensing, or pressure-sensing, panels on the structure,
 - measuring the accelerations of the structure in cases of dynamic loading.

A.16.4.3 Limitations and requirements for different techniques

The most appropriate technique for measurement of ice actions depends on factors such as the type of structure, the objectives of the measurement project and the ice-structure interactions of concern. Broadly, these can be classified as either of the following.

- a) Structures in relatively static ice;

In this case, ice movements that occur while the structure is frozen-in are likely to generate the highest ice actions. The man-made islands used for exploration in shallow water in the Beaufort Sea are an example. In situ ice stress meters are typically used to measure and determine ice actions for this case.

- b) Structures in mobile ice;

Examples include

- caisson drilling structures in the Beaufort Sea, which were deployed relatively far offshore compared to the man-made islands. See Reference [405] for a catalogue of these data,
- multi-leg and GBS type structures in other locations, such as Cook Inlet^[412], the Bohai Sea^[413] and Okhotsk Sea^[402],
- bridge piers: for most highway bridges, the design actions are produced during break-up, which produces ice runs^{[404][414]}, while the Confederation Bridge is exposed to moving ice over the full winter^[403],
- light piers and lighthouses^{[407][415]},

- ice control booms placed in Lac St Pierre^[416] and Lake Erie^[417],
- research projects, such as those done to
 - i) measure MY ice impact actions at Hans Island^{[418][419]},
 - ii) measure pack ice driving actions (e.g. at Katie's Floeberg, in the Canadian arctic, in Labrador, and near Svalbard^[420],
 - iii) measure iceberg impact actions^[421],
 - iv) measure indentation pressures at Hokkaido, Japan^{[422][423]}, and at various locations in the Canadian arctic^{[424][425][426]}.

Ice action data were obtained for almost all of the above cases using measurements of structural response. The methods used to measure structural response for these cases have included panels or load cells on the structure, tiltmeters, accelerometers and strain gauges on the structure.

The use of in situ ice stress and strain meters is generally inappropriate for applications involving significant ice movements. Furthermore, in some cases involving moving ice (e.g. caisson-type structures in the Beaufort Sea and some lighthouses), a grounded rubble field has formed around the structure, which affects the actions exerted on the structure itself.

The pack-ice driving action measurements are somewhat unique, since in situ ice stress meters were used to determine the effects within the ice.

The requirements for an ice action measurement system also depend on the type of ice failure that is expected. The type of ice failure can include crushing, flexure, buckling, ride-up, splitting and mixed-mode. Systems with the highest frequency response and data acquisition rates are required for crushing failures where the effect can cycle at frequencies greater than 10 Hz.

Furthermore, for wide structures, ice failure can alternate from being simultaneous across the full structure width to being non-simultaneous, which affects the actions developed^[398].

The requirements for ice action measurement systems also depend on whether they are intended to measure global or local actions. Some systems, such as accelerometers, tiltmeters and large-scale load panels, are capable of measuring only global actions. Others, such as panels and strain gauges (depending on the type of structure), measure local actions and pressures, and these should be integrated to determine the total action effect.

For all systems, there is a requirement for calibration. The most appropriate calibration approach depends on the type of measurement system and the objectives of the measurements.

The time-stability of the instrumentation is another factor that it is necessary to consider. Drift is of most concern in cases where the structure can be in contact with ice for long periods, such as caisson structures in the Beaufort Sea, with the result that true zero levels are difficult to establish and check regularly.

A.16.4.4 Documentation of environmental conditions

Ice action or pressure measurements should be complemented with data-gathering efforts to quantify the associated ice and environmental conditions. This is especially important for measurement projects performed to develop improved design criteria for future structures, although these data also help to provide a reality check for monitoring performed to assure the safety of an existing structure.

The key contributing factors, particularly those that are random such as the ice thickness, should be measured. This is especially important for subsequent probabilistic treatment of the data and for calculating ice actions or pressures for a site.

A.16.4.5 Observations of the ice-structure interaction process

A knowledge of what happened is a fundamental requirement for understanding any ice action data that are collected. Because the required environmental data vary from case-to-case, only general suggestions are made here.

It is essential that the collected data should identify and describe the loading scenario that occurred. The key issues include:

- the ice feature and type (e.g. FY, second-year or MY ice sheets, ice ridges, rafted ice, ice jams, etc.);
- the morphology of the ice feature (e.g. thickness, floe size, feature dimensions, shape);
- the ice failure mode(s) that occur (e.g. crushing, flexure, buckling, splitting, simultaneous versus non-simultaneous failure, ride-up, mixed-mode, etc.);
- the ice movement.

A.16.4.6 Ice action databases and synopses

Ice action databases are useful for estimating the expected actions and pressures on a structure. In addition to the usual requirements for a database (e.g. accuracy, extensiveness, ability to search and output information, ability to add new data, user-friendliness, compatibility of computer software in relation to common operating systems), an ice action database should contain the following:

- a) quantitative ice action and/or pressure data, including
 - the measured actions and/or pressures,
 - the areas of the structure over which they were measured, or to which they apply,
 - the time histories, and/or the frequency content of the measured data;
- b) information describing the structure or site where the data were obtained;
- c) description of the loading scenario;
- d) information defining the environmental conditions that produced the actions and/or pressures.

Various ice action and pressure databases have been developed to meet the above general requirements. Reference [427] documents one of the first publicly available databases. It contains information for:

- drilling structures and other sites in the Beaufort Sea and the Arctic;
- drilling platforms and structures in other locations (e.g. Cook Inlet, Bohai Bay);
- ship trials in the Beaufort Sea;
- lighthouses in the St Lawrence and the Baltic;
- bridge piers.

Recently, a comprehensive database that contains information for a wide range of structures has been assembled^[405]. A detailed hard-copy report is publicly available describing the information in this database.

In addition to electronic databases, several summary reports have been produced documenting measured ice action and pressure data. While these synopses are not as extensive as an electronic database, they nevertheless provide useful information for subsets of the overall ice action problem. References [428] and [429] present summary information for caisson drilling structures used in the Beaufort Sea. Reference [430] presents an overview of ice actions for some slender structures (i.e. piles, bridge piers and lighthouses). Reference [431] presents a synopsis of information regarding local ice pressures.

A.16.5 Ice model tests

A.16.5.1 General

Ice tank modelling can be used to investigate various ice-structure interactions, and offers the advantage that relatively complex problems (that can be difficult to analyse using other methods) can be studied and visualized at a small scale (i.e. smaller than full scale). Scale modelling of ships has been studied most, and thus tests where ice is level ice and ice failure is bending down are modelled adequately. If other types of structures or ice failure modes are studied, close attention is to be given to adequate scaling.

Generally, ice model tests have been used to investigate global ice actions resulting from moving ice, such as the expected ice actions and/or the expected ice interaction modes (e.g. ice failure modes, ice ride-up, the build-up of ice rubble around a structure, clearing of ice around a structure, ice blockage, etc.). Ice model tests have not been used to investigate static ice actions, e.g. resulting from thermal effects. Also, ice model tests have generally not been used to investigate local effects, such as local ice pressures as the compressive to flexural strength ratio is in general lower in model scale than in full scale. Model tests in which the temporal and spatial local pressures on the model are measured with tactile sensors are becoming more common, but it is not clear how well compressive failure of ice can be modelled.

Ice tank modelling is a flexible tool that has been applied to many ice-structure interaction cases such as:

- a) various structure types; the types tested include
 - large vertical or multi-faceted caissons,

- upward-breaking and downward-breaking cones,
 - narrow versus wide structures,
 - multi-leg structures,
 - berms,
 - moored versus bottom-founded structures,
 - satellite structures placed near a drilling structure to provide ice protection, and access for EER craft or protection for quay areas;
- b) various ice features interacting with a structure, such as
- sheet ice,
 - FY ridges,
 - MY ridges,
 - broken ice, and floe ice conditions,
 - icebergs.

Table A.16-3 lists common ice processes treated by means of physical modelling and indicates the important variables influencing them. Model reliability depends on the accuracy with which the model replicates those variables. Note that some modelling situations can involve a combination of processes. Consequently, the variables can be grouped differently, as shown in Table A.16-3.

In modelling broken ice, attention should be given to both the local floe-floe interaction and more global floe assembly interaction with the structure. It is not clear how to model broken ice, especially as there is a wide variation in observed cohesion values. At least a qualitative validation with full-scale observations is recommended.

In modelling ice ridges, attention should be given to modelling the consolidated layer. The growth and mechanical properties of the consolidated layer have not been well established in model scale.

Only a limited number of comparisons have been made between model scale and full-scale results for structures, although several correlation studies have been done for icebreaking ships. Ice model tests have been conducted at different scales for fixed icebreaking conical structures. Comparisons are made for the Kulluk (a large downward breaking floating conical structure) between model tests conducted at different ice tanks and field data collected while it was on station in the Beaufort Sea.

A problem of major concern in planning a model test programme is the type of ice. Not all ice problems can be investigated reliably using present-day ice tank modelling techniques. An ice model test programme should be targeted to investigate the specific ice interaction problem of interest. Sometimes, it is preferable to test a simplified, basic problem in the ice tank, and then use these results to assess an overall problem that is more complex.

Previous investigations of ice ride-up and ridge building are examples where the gradual approach of making more and more complicated models has been used. Initially, simple model tests were done to

investigate ice ride-up and ridge-building processes. These basic data are part of the information set that is used to address more complex issues such as:

- designing islands and structures to avoid ice ride-up problems;
- quantifying pack-ice driving actions and developing satellite structures designed to form protective rubble around drilling structures such as man-made islands.

Scaling uncertainties and modelling artefacts are another important issue that should be considered in planning an ice model test programme. These can arise from imperfections in the ice modelling material being used. Some model ices are better able to simulate some types of ice interactions than others. The model ice should, at minimum, model adequately the major ice failure processes in the tests.

Table A.16-3 — Ice processes and variables that it is important to model

Ice process	Variables of importance
Ice sheet deflection	Ice flexural strength Modulus of elasticity Loading rate Ice thickness
Ice ridging	Velocity of parent ice sheet Ice thickness of parent ice sheet Ice-ice friction Level ice strength (flexural, crushing, shear) Keel depth Sail height Ridge cross-section Consolidated layer
Ice-structure interaction	Structure stiffness Dynamic characteristics of structure/mooring system Velocity of ice sheet Ice thickness Ice drift direction Ice sheet strength (crushing, flexural, shear) Ice-ice and ice-structure friction Mode of breaking (crushing, flexure, shear) Ridge properties and dimensions
Icebreaker modelling	Vessel speed Ice-ice and ice-hull friction Ice thickness Ice sheet strength (crushing, flexural, shear) Ice piece size Piece movement around hull and propeller Mode of breaking (crushing, flexure, shear) Ridge properties and dimensions

A.16.5.2 Scaling

When ice model testing is used to study ice-structure interaction, appropriate scaling relationships should be selected to represent the mechanisms or processes that dominate the ice actions or response to ice actions. The basic starting point in all model testing is the geometrical scale, i.e. the ratio of lengths in model and full scale. In the physical modelling of ice and structure interactions, Froude similarity (the ratio of inertial to gravitational actions) and Cauchy similarity (the ratio of inertial to elastic forces) can be maintained between the prototype and the model.

Other scaling possibilities exist, particularly with respect to ice strength. It should be noted that neither Froude nor Cauchy scaling implies anything directly with respect to ice strength properties. Also, if inertial effects are not important, neither of these similarities is particularly relevant. Scaling rules are not universally agreed, and are the subject of some debate. Although scaling theory is well known, practical applications have focused mainly on Froude scaling. To date, other scaling relationships have not been verified by full scale observations.

Considerable effort has been expended on the development of model ice with mechanical properties scaled to prototype ice and with analogous failure behaviour. There can also be rigorous modelling of the structure shape, stiffness, and surface characteristics. As long as the failure modes expected in the prototype are correctly simulated, model tests can provide an important input into the design process. Model ice can provide optimum simulation of ice interactions only over a certain range of geometric scale factors, generally within about 10 to 40. Tests done at scale factors that are outside this range are likely to produce results that are subject to modelling distortions.

The scaling approach typically adopted by ice tanks is described in the following. Scaling is accomplished by observing the Froude scaling law, as given in Formula (A.16-14), and the Cauchy scaling law, as given in Formula (A.16-15):

$$Fr = \frac{v}{gL} \quad (\text{A.16-14})$$

$$Ca = \frac{v^2 \rho_w}{E} \quad (\text{A.16-15})$$

where

Fr is the Froude number, the ratio of inertial to gravitational forces;

Ca is the Cauchy number, the ratio of inertial to elastic forces;

v is the relative speed between ice and the structure, expressed in metres per second;

g is the acceleration of gravity, expressed in metres per second squared;

L is the length dimension, expressed in metres;

ρ_w is the density of water, expressed in kilograms per cubic metre;

E_f is the effective modulus of elasticity of ice, expressed in megapascals.

The Froude number is generally used as the similitude criterion for ice basin modelling, especially in ship testing. The Cauchy number, then, provides the necessary scaling for material stiffness parameters. Other

possibilities exist for scaling of time, and the adequate scaling system chosen should reflect the most important forces present. It is not possible in model tests to simultaneously satisfy the requirements of Reynolds law, which governs viscous effects, with those of Froude/Cauchy scaling. Since viscous effects are relatively small for ice model tests at low speeds, Reynolds law is usually neglected.

In order to satisfy the Froude and Cauchy laws, the various geometrical and physical quantities of the tested objects should be scaled according to Table A.16-4.

Table A.16-4 — Scale relations

Physical values	Model scale	Full scale
Ice thickness	h'	$h = \lambda h'$
Flexural strength of ice	σ'_f	$\sigma_f = \lambda \sigma'_f$
Elastic modulus of ice	E'	$E = \lambda E'$
Density of water	ρ_w'	$\rho_w = \rho_w'$
Density of ice	ρ'_i	$\rho_i = \rho'_i$
Time	t'	$t = \lambda^{1/2} t'$
Velocity	v'	$v = \lambda^{1/2} v'$
Force	F'	$F = \lambda^3 F'$
Friction coefficient	μ'	$\mu = \mu'$
NOTE λ is the geometric scale factor.		

A.16.5.3 Test methods

A.16.5.3.1 Model ice types

Natural sea ice behaves as a brittle or ductile material depending primarily on its temperature, salinity and strain rate. Basic mechanical properties of the natural ice, such as strength and deformation, also depend mainly on the strain rate, ice temperature and salinity content in the ice. Flexural strength is conventionally considered to be independent of strain rate. Ideally, model ice should behave in the same manner when applying the selected scaling law, i.e. the strengths should be related by a linear scale factor, λ .

Currently, model ice used in test basins is formed from a refrigerated water solution. To scale the ice properties correctly, the water used to form the ice is doped with sodium chloride or other chemical dopants, such as ethylene glycol, detergent, alcohol or ethanol. Two fundamental approaches can be used to produce the model ice.

- The ice is formed directly from the water solution in the basin. A water mist is sprayed to initiate growth of a fine, crystalline, columnar-structure. Air bubbles can be introduced during the freezing process. A warming or tempering process is used to adjust the model ice properties.
- The ice is formed by spraying a water solution that freezes in the air, falling on the surface to produce a fine-grained granular ice sheet. A cooling or hardening process is used to adjust the model ice properties.

It is important to note that a standard “model ice” has not yet been established, and judgment is required to ensure that the model ice used is appropriate for the ice-structure interaction of interest, in combination with other factors such as the size and capabilities of the ice tank.

A.16.5.3.2 Testing technique

In general, two testing options are used in ice model tanks. The first method is to push or pull the model through a stationary ice sheet; the second is to have a moving ice sheet pushed against a fixed or moored model. The selected option should be consistent with the test objectives. Parameters measured and the configuration of the measurement systems should be primarily dictated by the test objectives and the characteristics of the structure and its operational conditions.

Model tests in various ice basins can lead to different results. These differences can be illustrated in benchmark tests to get an understanding for how the differences manifest themselves. A simple test structure can be designed for the benchmark test and the test procedures will typically specify at least model scale, dimensions and angles of the model, configuration (fixed or floating) and ice conditions. Hydrodynamic effects associated with the testing techniques should be considered.

The objective of ice model testing is often to quantify the global ice action on a model. If the model is pushed through a stationary ice sheet the measured force also contains a contribution from the hydrodynamic effect, i.e. equivalent current force acting on the model. In this case the measurements can be corrected regarding this hydrodynamic effect.

In the case of pushing the model through the stationary ice sheet, hydrodynamic effects are usually evaluated (e.g. by open water test run) and their influence on the measured global ice action is assessed and compensated for.

Differences in the dimensions and layout of the ice tank facility can have some influence on the tests. An important factor is the effect of the basin size (length and width) on the number of tests that can be carried out with one ice sheet. The required actual test length depends on the type of test. As an example, for ice rubble formation tests or ice pile-up tests, the model should be able to proceed until a steady state is reached. The other factor that can restrict the test programme is the proximity of the basin walls. For the case when a model is pulled through ice, the level ice sheet can be considered to have infinite extent if the shortest distance from the point of application of any actions to the nearest tank wall is more than three times the characteristic length of the ice sheet.

The choice of testing technique depends strongly on the type of test. In particular, it should be appreciated that when pushing the ice sheet against a model of a fixed or moored structure, unrealistic cracks can often propagate from the model towards the sidewalls of the tank. In addition, the ice sheet can fail along the pushing plate instead of on the model; this happens especially for thin and brittle ice. As well as for the testing technique option, the most practical way to minimize negative consequences of the boundary condition deviation is to conduct tests with an ice sheet sufficiently wide relative to the model width. Ice model tests of a stationary (i.e. moored) floating system call for special considerations in test preparation compared to model tests of fixed structures.

Visualizing the ice failure and flow of broken ice around the model is often essential for interpreting the test results. Underwater video of the tests is to be used to record the tests (synchronized with the force and motion data, so that action events can be identified and visually inspected. If a mooring system is used, then tension forces can be measured in each mooring line. Tension force and line angle can be used to resolve the forces into global actions acting on the floating system. In all cases data should be recorded as time histories at a sampling rate sufficiently high to capture peak action events at model scale.

A.16.5.3.3 Ice conditions

Model tests can be performed in ice conditions such as level ice, rafted ice, a newly broken channel, brash ice (old channel), broken ice, rubble ice fields and ridges. The proper documentation of the tests should include the method by which the ice conditions are simulated. It is recommended to document the ice conditions prior to and after the test by still photographs and video records, preferably from some elevation. The number, time and location of ice thickness and property measurements should also be documented. Visible cracks in the ice extending from the broken channel towards the basin walls or towards open water areas should be included in the report.

The thickness of the model ice should be measured after each level ice test and the number of measurements should be sufficient to adequately evaluate variations in ice thickness along the track of the model through the ice. In cases where test runs are performed close to the sidewalls of the ice tank, measurements should be taken on both sides of the broken channel.

In an old channel or rubble field, the thickness should be measured along two or more lines within the model track. Underwater sonar for scanning the lower surface of model ice and laser profiles for evaluation of ice upper surface or similar remote sensing devices is particularly advantageous for tests with ice rubbles/ridges or brash ice. Such measuring systems allow for the non-destructive acquisition of the ice thickness profiles or a 3D picture before running the test.

Ice ridges and rubble can contribute, in many cases, to the design action on a structure, and conducting model tests for such conditions is of particular importance. Producing model ridges and rubble in compliance with the requirements of similitude theory is one of the most challenging tasks in ice/structure interaction modelling. The conventional method of creating a FY ice ridge/rubble is to grow level ice with a thickness equal to the thickness of ice blocks constituting a model ridge/rubble, break this ice sheet into irregular pieces and then collect these pieces into a pile. The resulting pile of ice is normally left exposed for some period of time to negative ambient air temperature in order to create a consolidated layer of the ridge/rubble.

For pressure ridge tests, the following parameters should be recorded and assessed:

- a) ice temperature in level ice sheet immediately before ridge production process;
- b) thickness of parent ice sheet;
- c) thickness of consolidated layer;
- d) size of ice blocks in ridge;
- e) ridge profile (sail and keel);
- f) maximum sail height;
- g) maximum keel depth;
- h) ridge shear strength (typically obtained by “punch” tests);
- i) ridge porosity (calculated from the profiled volume and the volume of ice used for ridge production).

In the course of ice ridge/rubble modelling, particular attention should be paid to modelling the effects of the interaction within the unconsolidated part of the ice feature and to the mechanical properties of its refrozen part. The mechanical properties of the consolidated layer can be evaluated in the same way as for level ice, assuming that both sail and keel are carefully removed. For the measurements of the mechanical properties of the unconsolidated part, pull-up, punch and/or shear tests can be employed.

Model tests in managed ice conditions are often carried out. Managed ice conditions can be achieved by systematically breaking up the parental ice sheet into pieces with a specified edge length or overall dimension. In order to replicate natural managed ice conditions, partial concentrations can be utilized in which the distribution of ice floes and the coverage scales with sea ice conditions in nature. For managed ice tests the following parameters should be recorded and assessed:

- initial ice floe distribution and initial ice concentration;
- evolution of the ice floes during the test;
- constraint of external boundaries on the managed ice test.

A.16.5.4 Model ice properties

A.16.5.4.1 General

Different model testing facilities use different types of model ice materials. None of the existing model ice materials is perfect. Thus, ice properties measured for one type of material cannot be directly compared with another material. The geometrical parameters and mechanical properties of the model ice should be determined accurately, regardless of the material composition.

To maintain reliable results, it is recommended to perform property measurements in situ in the tank and, whenever possible, without lifting the samples out of the natural environment. The timing and location of the measurements are important. The measurements should be done as close as possible to the actual test area and test time. All measurement procedures should be as simple as possible and measure the desired parameter directly. The test procedures and measurements should be performed by competent personnel and should be clearly documented. The equipment used in all measurements should be calibrated at the ambient temperatures of the ice tank. Location within the tank and number of tests should be carefully selected considering the type of ice action, model arrangement and programme.

Properties of FY and MY ridges are very difficult to control in ice basins. Samples should be taken from parts of the ridge to document both consolidation and other internal properties. The ice conditions adjacent to the ridge should be documented. For instance, broken level ice surrounding a ridge reduces the actions substantially compared to intact level ice.

A.16.5.4.2 Flexural strength and modulus of elasticity

The flexural strength is commonly determined by cantilever beam tests. A floating cantilever beam having length L and width B is cut in situ. The recommended dimensions of a beam ($L \times B \times h$) are $6h \times 2h \times h$, where h is the ice thickness. The tip of the beam is loaded up or down at a constant speed until the beam fails. It is recommended to use an electrically driven loading device. The applied load as well as the deflection of the beam should be recorded. The determination of the deflection is required only for the

determination of the elastic modulus. Strength measurements should be carried out several times during the tempering phase and after each ice test has been performed. Tempering is a process of increasing or decreasing the ice temperature to attain the target strength. Whenever possible, the strength should be measured at different locations distributed over the tank length. The flexural strength can be calculated from the failure load and the measured beam dimensions as given in Formula (A.16-16):

$$\sigma_f = \frac{6F_b L}{B h^2} \quad (\text{A.16-16})$$

where

- σ_f is the flexural strength in bending;
- F_b is the failure load;
- L is the length of the beam (load point to support);
- B is the width of the beam (at the support)
- h is the thickness of the ice.

The method to measure the modulus of elasticity in bending is to measure the deflection of an infinite floating ice sheet under a given load. The elastic modulus is defined as given in Formula (A.16-17):

$$E_f = \frac{3(1-\nu^2)}{16\rho_w g h^3} \left(\frac{F}{\Delta} \right)^2 \quad (\text{A.16-17})$$

where

- F is the applied load;
- σ_f is the effective elastic modulus in bending;
- ν is the Poisson ratio for ice;
- Δ is the deflection of the ice sheet;
- ρ_w is the water density;
- g is acceleration due to gravity.

Other designations are as for Formula (A.16-17).

A.16.5.4.3 Compressive ice strength

The compressive strength of model ice can be measured using any of the following three methods:

- a uniaxial test is performed in the water;
- an ice block is cut and lifted from the water to perform a uniaxial test;
- an indenter is used to load the ice sheet horizontally.

The compressive strength of model ice is the most difficult to measure with high accuracy, and the structure of the model ice does not always allow the use of all of the above methods. The indenter test is easiest to carry out and this should be done as a minimum, with due regard to length and location of indentation.

A.16.5.4.4 Friction coefficient

Friction between ice and the hull of the structure is important. When the structure begins to move with respect to the ice, or vice versa, it has to overcome static friction. Once the structure is moving, it then overcomes dynamic friction. Dynamic friction is usually the mode of interest.

The friction coefficient is determined through measurements of the tangential action when either a piece of model ice is slid along a plate, painted identically to the model structure, or such a plate slides over a piece of model ice. In both cases, the ice and the plate should be pressed together by a given normal action. The friction between two ice pieces can be determined using the same testing arrangements. The contact surfaces of the ice and the plate should be moistened, since wet and dry friction coefficients differ significantly. The friction tests should be performed at a speed corresponding to the ice-structure interaction velocity expected in the tests.

The following parameters should be reported:

- horizontal towing forces, F_T ;
- total normal force, F_N (specimen weight plus ballast weight);
- dimensions of the ice sample (length, width, thickness);
- velocity, v (speed of the carriage of friction apparatus);
- ice temperature, T_i .

The dynamic friction coefficient, μ , is calculated according to Coulomb friction, as given in Formula (A.16-18):

$$\mu = \frac{F_T}{F_N} \quad (\text{A.16-18})$$

where

F_T is the mean measured tangential (friction) load during steady motion;

F_N is the normal load on the contact surface.

A.16.6 Offloading in ice

A.16.6.1 General

An offloading system for hydrocarbons generally consists of a tanker and an offloading unit. For decades, tankers have been a reliable method for exporting hydrocarbons from offshore platforms. Shipping is an

attractive solution for hydrocarbon transportation in arctic and cold regions, with the loading operation being the most vulnerable marine operation.

A number of offloading concepts have been proposed, including the DeKastri and the Aniva Bay offloading systems, and the Pechora Sea loading tower. The tanker can load directly from the production platform or from a narrower loading tower. These concepts can suffer from a high risk of collision between the tanker and the structure in variable ice drift conditions. The tanker can, alternatively, moor on the loading hose via a single-anchor loading system, but effective IM using icebreakers is required to protect this system in heavy ice conditions. Another option for arctic and cold regions is to offload from a submerged turret where the hose system is protected by armour from moving ice.

Depending on the design, a full concept for offloading in ice is likely to include a moored tanker connected to a moored storage vessel, a moored production storage vessel or another type of floating system. Alternatively, the moored tanker can be connected to a fixed bottom-supported platform or to a subsea production system.

The loading of a tanker at a production platform, loading tower or subsea buoy (the offloading unit) can include the following phases^[432]:

- initial approach;
- final approach;
- stationkeeping;
- departure.

Operational measures such as IM can be used in all these phases to reduce global or local ice actions, provided it can be shown that the intended level of safety, in combination with structural resistance, is achieved.

A.16.6.2 System reliability

Typically, risk analyses for offloading systems should include:

- a) a description of ice and associated metocean conditions, and appropriate statistical distributions for key parameters;
- b) a description of system components and details of their operation, which should include particulars of the disconnection system, see 13.7;
- c) a realistic representation of tanker capabilities and operation, if available, supported by data from actual offloading operations in ice;
- d) where appropriate, a description of the IM capability, including demonstrated effectiveness in the ice conditions to be encountered;
- e) a definition of acceptance criteria, consistent with the provisions of this document, for the release of hydrocarbons and loss to life, and potentially for contact frequency between tanker and floating system, damage to the vessel, damage to the floating system, and downtime.

Where significant uncertainties exist in the physical environment, the efficiency with which IM, tanker operations and disconnection can be conducted should be considered in the analysis.

It should be possible to disconnect a tanker connected to an offshore loading terminal even in the case when moving ice becomes stationary. In such circumstances, the ice can start drifting again with any heading, and the ice actions and consequent collision risks with a loading structure can rapidly increase. A threshold ice-drift speed should, therefore, be defined for disconnection. Disconnection can potentially be avoided in the following situations:

- when the ice-cover has a limited impact on the system (low ice actions and no impediments to manoeuvrability), as can be the case for thin ice or low ice concentrations;
- when reliable ice-drift forecasting can be performed at the site, disconnection can be performed only just before the ice starts drifting in a dangerous direction. This type of event can also be assessed as critical only when the drift change is large. In areas where the ice can be landfast, it is important to detect these events so that offshore loading operations can continue. Nevertheless, it is necessary that the ice-drift forecasting be extremely reliable so that safety is not compromised;
- when the ice stops drifting, it can start drifting again slowly. For example, when the wind and the current act suddenly in the same direction, the ice cover can move around 200 m in a 15 min period (for a 1 m thick ice cover and wind and water stresses on the order of 0,1 N/m²). If the tanker is moored on a submerged turret loading buoy in deep water (and requires 15 min to disconnect), and an icebreaker is assisting, the IM and the flexibility of the mooring normally prevent the development of excessive action effects before a disconnection is required.

A.16.6.3 Requirements for the offloading terminal

A.16.6.3.1 Types of offloading terminal

The offloading terminal should be designed for the physical environment in which it is planned to operate. This applies especially to moving ice. In principle, there are several potential categories for such offloading terminals (see Figure A.16-8).

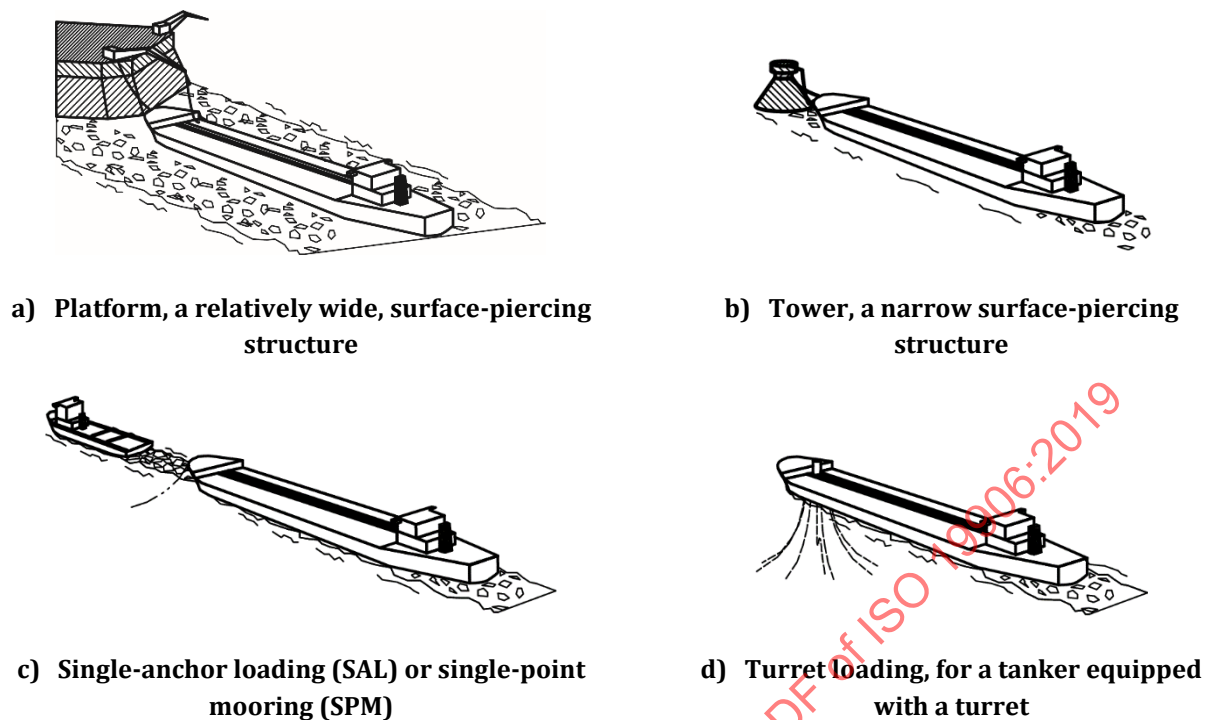


Figure A.16-8 — Potential arctic and cold region offshore loading concepts

A.16.6.3.2 Platform

A platform is generally a relatively wide, surface-piercing structure that should be capable of resisting large global or local actions as well as mooring actions from the loading tanker. This can be the production platform itself, which is normally equipped with one or more loading arms. For a GBS that is square in plan, the loading arms can be located at the corners as shown in Figure A.16-8. Since the tanker is moored to a fixed point on the periphery of the structure, it has a limited capability to remain in the lee of the platform without disconnecting for significant changes in ice drift direction.

The structure should be designed to maintain integrity under impact from the tanker, whether by accident or the result of ice drift.

A.16.6.3.3 Tower

The tower concept is a narrow structure that can be located some distance away from the production platform or storage vessel. The tower is normally equipped with a loading arm. This adaptation of the tower mooring system should be designed to resist ice actions. A rigid mooring system (a wishbone or a yoke) can be stronger than a flexible mooring system and guarantee a minimum distance between the structure and the tanker bow. Model tests show that collision risks due to a sudden change in the ice drift direction are still present with a rigid arm^[433].

A.16.6.3.4 Single-anchor loading

A single anchor loading (SAL) or SPM system is designed so that the tanker moors on a single line coupled with the loading hose and connected to a single anchor on the seabed. In the idle position, the line and

the hose can rest on the seabed. The SAL system can be designed so that the hawser for bow loading is protected in a lobster (a segmented, interlocking shield over a hydrocarbon-loading line used for protection from ice impact)^{[434][435]}. There are also designs where a non-protected reinforced hawser is used.

Because of limited capacity to resist ice actions, the SAL system can be operated only when effective IM is available^[436].

A.16.6.3.5 Turret

For turret loading, the tanker is equipped with a turret that can be internal or external to the hull; for offshore loading purposes, a releasable mooring solution with an internal turret such as the submerged turret loading system can be used. The internal turret loading concept is a fully subsea system. The system should be designed so that it is capable of transferring the action to the mooring system for all conditions, including pressure ridges. The riser system should be sufficiently protected to avoid damage caused by floes and broken ice pieces pushed under the hull of the tanker.

A.16.6.4 Requirements for the tanker

Tankers that are loaded in ice should comply with the applicable ice class requirements.

A.17 Ice-specific operations

A.17.1 Operational measures for ice hazards

A.17.1.1 Mitigation of ice actions

No further guidance is offered.

A.17.1.2 Ice alert system

The ice alert system enables the use of successive operational measures to mitigate risks arising from ice hazards in arctic and cold regions environments. The requirement for an ice alert system acknowledges the need for additional safety in these remote ecosystems, the uncertainty in knowledge for ice and metocean processes, a lack of readily available support infrastructure, and the distances involved with the transfer of personnel and equipment in the event of adverse consequences which require a rapid response.

Contingency measures to increase availability of an ice alert system can involve backup systems and equipment, backup personnel, and reliance on multiple barriers in the alert system. From a design perspective, resources should always be available to achieve availability and success rates consistent with the planned decrease in values of ice actions or reduction in frequency of ice events.

Particular consideration should be given to hazards which could result in ice events beyond the capability of the structure, both for fixed structures, and for floating systems without rapid disconnection capability. In such cases where this barrier (disconnection) is impossible, more conservatism should be included in

the operating envelope, and increased provision should be made for securing hydrocarbons and the safety of personnel by means of the emergency response plan for ice hazards (see 18.1), which can include EER plans (see 18.3). See also A.7.2.2.

For sea ice, the quantification of IM success in the absence of actual performance data is uncertain, and the requirement for an effective emergency response plan is important if the design relies on IM capability.

Failure of the ice alert and monitoring systems can potentially result from undetected ice features, underestimation of ice hazard severity, unanticipated ice events, underperformance of the IM fleet, equipment failure, human error, or underperformance of the stationkeeping system.

A.17.2 IM system

A.17.2.1 IM scope

Structures in ice-covered waters can be supported by highly capable IM vessels, with the intended role of modifying the local ice environment, reducing ice actions on the structures, and enhancing ice clearance around them. The requirement to identify potentially hazardous ice features or conditions requiring IM, and then to deal with them in a timely manner, increases the range of environmental considerations that are normally associated with these structures. Offshore structures can also rely on IM to ensure access to re-supply and offloading facilities, and to clear potential escape routes for EER systems.

The type of IM system that is employed can have a significant influence on the design approach taken for any particular offshore system. This depends upon expected level of IM reliability, for example, the ability to consistently detect potentially adverse ice conditions and, in turn, to manage them successfully before they interact with the structure (e.g. by towing icebergs, clearing grounded ice from EER access points, fragmenting thick sea ice features).

A.17.2.2 Characterization of IM performance

In the case of iceberg management, success can be measured by means of demonstrated deflection capability within a specified time frame.

Sea IM success can be difficult to characterize, since the benefit depends on the level of IM used (e.g. managed ice piece size, amount of effort spent on ice clearance around a platform). Full-scale data^[437] show that ice actions can be reduced significantly in certain situations, depending on the “amount of IM” used. However, experience also shows that not every adverse ice scenario can be managed with 100 % reliability in a timely manner, even with highly capable IM systems.

Various analytic methods have been, and can be, developed to characterize the performance of any IM system across a range of ice conditions. However, the actual full-scale field experience that is available to calibrate and verify these methods remains quite limited.

In this regard, it is important to note that systematic documentation of actual experience is highly recommended to improve future IM activities. Full-scale demonstration projects can be beneficial,

particularly when uncertainties about the effectiveness of IM systems are both high and very consequential.

Given the current state-of-the-art and sometimes incomplete quantitative information about IM effectiveness (particularly for sea ice), it is recommended that experienced IM personnel be used to provide judgments on probable IM effectiveness for the types of quantitative assessments addressed in this document. In this regard, even undocumented input from experienced operational people is a key factor to recognize, and should be solicited as a key input to any evaluations about IM approaches and their effectiveness, at least to the extent possible.

Sea ice or iceberg management performance assessment should involve:

- the characterization of the relevant ice and metocean environments;
- a quantification of the capabilities for icebreaking, towing, and other IM functions of these vessels in the above ice and metocean conditions;
- a description of the IM strategies, such as icebreaking patterns or towing protocols, in terms of times to complete various stages of the operations, number of vessels involved, vessel speeds, manoeuvres, distances covered, ice concentration changes, floe size reduction, ice clearing, ice feature deflection, and ice feature destruction;
- the characterization of uncertainties in the ice and metocean environments and the operational measures that can have an impact on IM success;
- an evaluation of progress toward the stated objective in the context of the ice alert system or other defined objectives; and
- documentation of ice alert status.

Sea IM assessment can involve:

- a) ice cover characterization, ice pressure, and drift speed/direction;
- b) associated metocean conditions and visibility;
- c) icebreaker fleet performance, subject to a) and b);
- d) forward speed, including ramming, subject to a), b), and c);
- e) managed swath width as a function of distance from the platform or facility based on forecast drift direction uncertainty (and likely also as a function of drift speed), and other measures in the case of large drift direction changes; and
- f) IM fleet progress in the updrift direction relative to the encroaching sea ice.

The updrift progress of a sea IM vessel can be estimated from the average forward speed times the managed area divided by the icebreaker track length times the swath width. The composite performance of the IM fleet, where applicable, should be characterized in a way that considers the respective roles of the different vessels.

When the objective involves floe size reduction, the measure of floe size used in the assessment of IM performance should be consistent with the ice action calculations used to develop the operating envelope.

Ice concentrations used in the IM performance assessment should reflect contributions from all ice types present, including brash ice and its state of consolidation.

Iceberg towing performance can involve:

- 1) iceberg tow assessment, including size, shape and sea state;
- 2) transit time, hook-up time and time under tow;
- 3) method used for tow;
- 4) speed and direction of tow;
- 5) deflection distance, or angle from original trajectory; and
- 6) reason for termination of tow or tow attempt.

Whether the threat is from sea ice or from icebergs, the region of interest (see ISO 35106) to be managed can be defined based on drift forecast uncertainties, with due account for the attributes of the performance forecast system and the drift speed of the ice.

The ice alert status recorded continuously over the design service life can be used to assist with the verification of IM performance.

A.17.3 Particular measures for floating systems

A.17.3.1 All systems

The safe-learning process outlined in ISO 35104 involves the demonstration that the IM system can deal with increasingly severe ice conditions. Only when successful demonstration of capability in particular ice conditions is achieved can IM be used to alter the ice conditions, within the context of 8.2.7, or to involve it in meeting or expanding operational limits.

A.17.3.2 Specific requirements for different types of floating systems

In addition to the IM system, active systems include shut-in, down-manning, disconnection and move-off provisions in the ice alert system.

Semi-active systems include shut-in, down-manning, disconnection and move-off provisions in the ice alert system.

In addition to the IM system, semi-passive systems include shut-in and down-manning provisions in the ice alert system.

Passive systems typically include shut-in and down-manning provisions in the ice alert system.

A.18 Emergency response

A.18.1 Emergency response plans

No additional guidance is offered.

A.18.2 Emergency response measures

No additional guidance is offered.

A.18.3 Escape, evacuation and rescue

EER performance requirements, see ISO 35102, can be specified in terms of reliability, functionality, availability, survivability, independence, time or distance. They should contribute to the overall goal of reducing the life-safety risk of harm to platform personnel and others involved in EER operations.

A distinction is made in Clause 18 between structural reliability and overall reliability with respect to life-safety consequences. Structural reliability is related to exposure level, as explained in Clauses 7 and A.7. Overall reliability includes structural reliability, the consequences of further risk mitigation measures, and includes consideration of the performance of the EER system. For example, if the platform is normally manned and the exposure level is L2, further risk mitigation is needed to ensure life-safety. This can be achieved by evacuation of personnel, in which case the performance of the evacuation system in combination with the structural reliability needs to provide adequate overall reliability with respect to life-safety.

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Annex B (informative)

Regional information

B.1 Introduction to regional information

Regional descriptions of the physical environment are provided in this annex for ice-covered regions of the northern hemisphere. The regional descriptions are meant to provide interested parties with an overview of the region but are not meant to provide parameter values appropriate for the design of offshore structures. While it is necessary to consider the parameters described in the design, some might not be important for the design of particular facilities. A full description of the appropriate parameters requires review and analysis of available data, collection of new data, interpretation of parameters found in nearby regions or similar ice regimes, and statistical evaluation of the data. Appropriate specialists should be consulted in the determination of parameters relating to the physical environment for use in the design of offshore facilities.

Each regional subclause starts with an overview text describing the general meteorological, oceanographic and ice environments that can be found in the region. This is followed by tables listing estimates of the highest (or lowest) values that are exceeded on average every year. Some parameters, such as wave period, are values that are associated with other parameters, such as significant wave height. When data to determine the parameter are unavailable, “ND” (for “No Data”) is shown for the parameter. In some cases, sufficient data are available to determine an average annual value, but not to determine a meaningful range of average annual values. In this case, “ND” is also used. The definition of “a meaningful range” is somewhat subjective. The higher end of this range will typically relate to values that occur with return periods more frequent than 100 years. Similarly, “range of water depths, metres” refers to the general range of water depths potentially applicable to oil and gas activities.

Several of the tables in Annex B refer to the length of ice-covered season, the length of the open water season, as well as the lengths of winter and summer seasons. An ice season or winter season is the period during the year where sea ice is present typically within the region. Ice incursions can take place within an open water season and periods of open water can occur within the ice season. Spring season can be used to describe the period over which the transition from ice-covered to ice-free waters takes place.

Not all ice parameters are shown in every region. If an ice parameter is not listed in the table, it is not found in that region. For example, since MY ice is not found in Cook Inlet in Alaska nor in the Okhotsk Sea off Russia, parameters related to MY ice are omitted from the accompanying table for these regions. In certain cases, NA (for “Not Applicable”) is used to signify that the parameter is not relevant for a portion of a larger geographical region.

For some regions, there are sufficient data to provide additional detailed information on the parameters listed and these data are provided. An example is the number of ridges per kilometre, which is provided only for the offshore Russia regions.

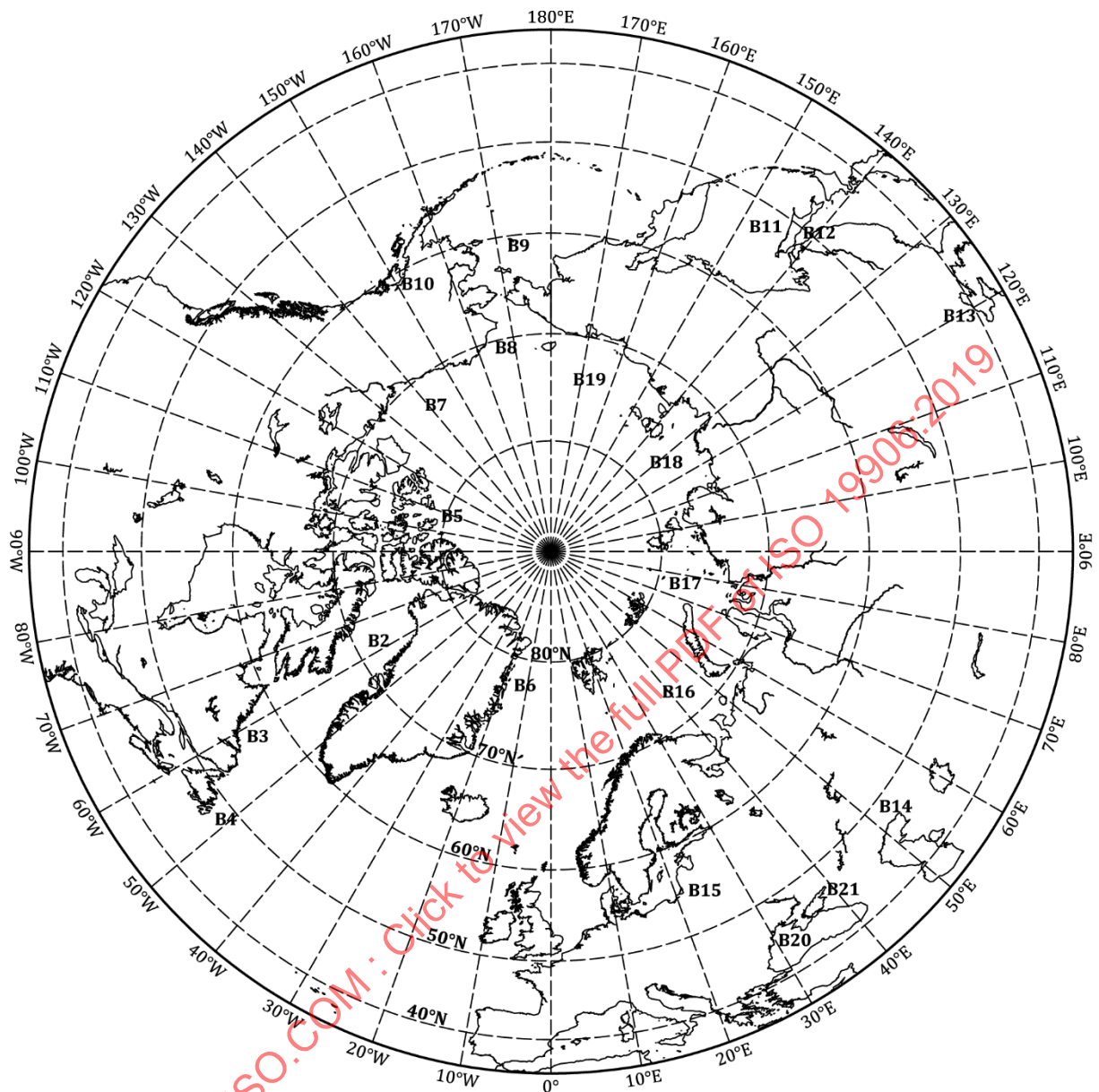
Definitions for column headings in the regional descriptions are the following:

- a) “Average annual value”: the annual maximum or minimum parameter values averaged over several years;
- b) “Range of annual values”: the range of values of the parameter over the time period of available data.

ISO 19901-1 contains more specific metocean information for a small number of regions of the world where adequate data are available. ISO 35106 contains information for Arctic metocean, ice, and seabed data requirements for design and operations.

Figure B.1-1 gives an overview of the regions specified in Annex B.

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Key

B2	Baffin Bay and Davis Strait	B12	Tatar Strait
B3	Labrador	B13	Bohai Sea
B4	Newfoundland	B14	North Caspian Sea
B5	Canadian Arctic Archipelago	B15	Baltic Sea
B6	North East Greenland	B16	Barents Sea
B7	Beaufort Sea	B17	Kara Sea
B8	Chukchi Sea	B18	Laptev Sea
B9	Bering Sea	B19	East Siberian Sea
B10	Cook Inlet	B20	Black Sea
B11	Okhotsk Sea	B21	Sea of Azov

Figure B.1-1 — Map of arctic and cold regions; the key identifiers correspond to the subclauses in Annex B where the regional description is found

B.2 Baffin Bay and Davis Strait

B.2.1 Description of region

This region contains Canadian and Greenland waters of Baffin Bay and Davis Strait.

A map of the region is shown in Figure B.2-1.

Table B.2-1 — General information for Baffin Bay and Davis Strait

Area of coverage	61° N to 77° N, 55° W to 80° W
Length of ice covered season	late October to July
Length of open water season	late July to mid-October
Range of water depths, metres	100 to greater than 2000

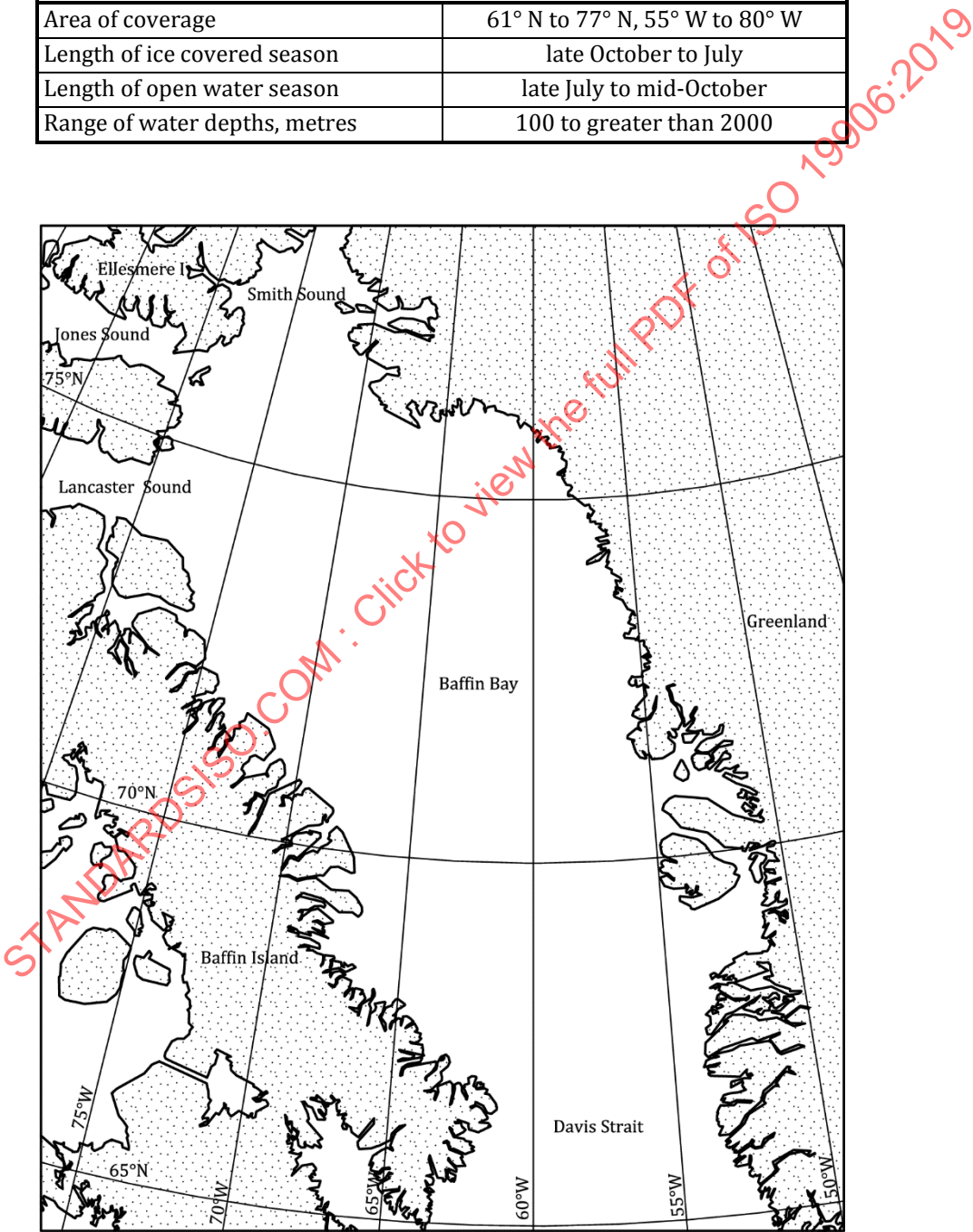


Figure B.2-1 — Map of the Baffin Bay and Davis Strait region

B.2.2 Baffin Bay and Davis Strait technical information

B.2.2.1 General

References [438], [439], [440], [441] and [442] are good sources of information regarding the ice conditions in the Canadian waters of this region. Reference [443] provides information on the conditions in the Greenland portion of the region.

B.2.2.2 Air temperatures

This region has an arctic climate with mean temperatures of approximately 4 °C in August and –24 °C in February

B.2.2.3 Visibility

Fog (visibility less than 1 km) is primarily a summer phenomenon. Its frequency increases during May, has its peak value in June/July and reduces in late August. The estimated frequency of fog in July is 20 % to 30 % of the total time over the coldest parts of the sea area. Fog is less frequent in the coastal region.

Temperatures within fog are often 1 °C to 2 °C below that of the sea surface. Freezing temperatures within the fog over a cold water surface are not unusual, and icing with rime ice or clear ice can occur. In winter, fog can form occasionally within a warm and moist air mass advected from the south. Sea smoke forms within cold air flowing from drift ice or from cold land out over open water. The occurrence is often very local but in a very cold air mass it can be more widespread.

In winter, snow showers are present much of the time over open water, causing moderate or poor visibility.

B.2.2.4 Precipitation

Precipitation varies from 10 mm/month to 80 mm/month with higher values in the summer months and in the southern regions. Precipitation is low in the north, particularly in winter and spring.

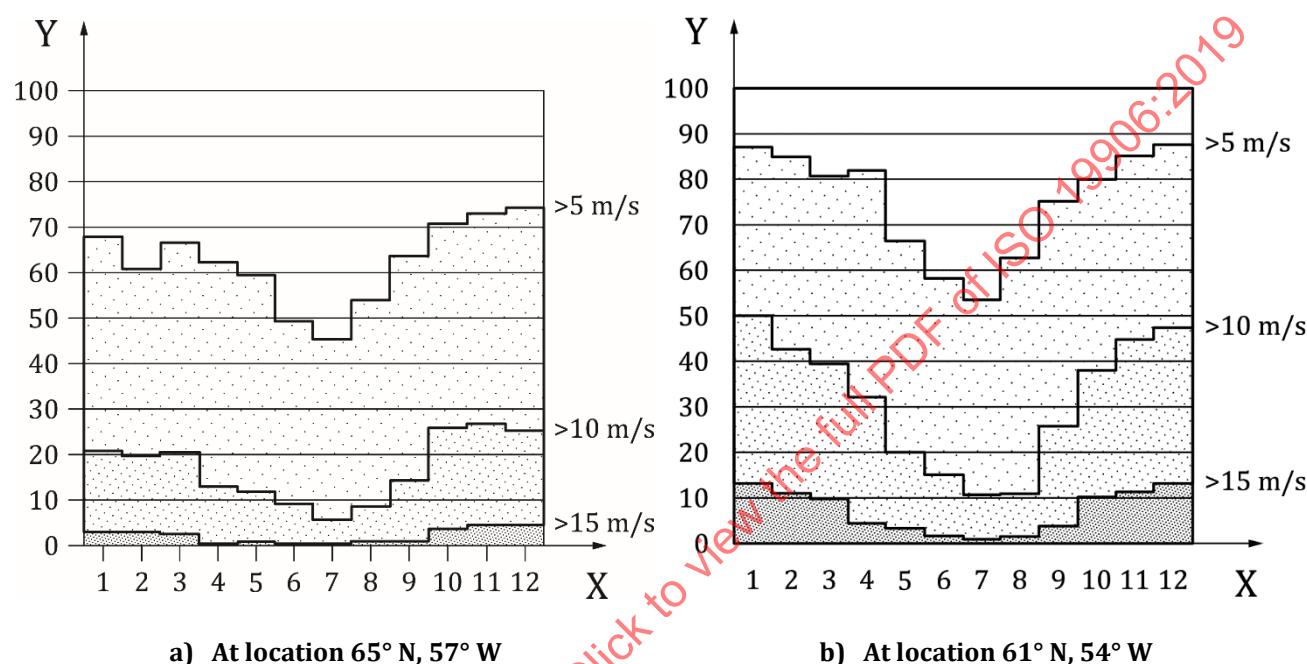
The amount of precipitation is high in the south due to open water and frequent cyclonic activity. The annual amount of precipitation ranges from 200 mm to 300 mm in the Disko area to more than 1 000 mm in southernmost Greenland. In Nuuk (Godthåb), it is about 600 mm. Most of the precipitation falls in late summer or in autumn. In winter, precipitation usually is in the form of snow. In summer, light snow (or freezing drizzle) can fall from stratus clouds over drift ice or seawater with temperatures close to the freezing point. Otherwise, snowfall is limited to short spells of cold weather in the northern part of the area. Generally, October and June are the rain/snow transition months in the north, November and May are the transition months in the south

B.2.2.5 Wind

The annual mean wind speed ranges from 5 m/s in the northern regions to up to 10 m/s in the southern regions. The frequency by month of wind speeds exceeding 5 m/s, 10 m/s and 15 m/s for selected positions is shown in Figure B.2-2. The maximum speed in the northernmost part of the area occurs in

October to November, elsewhere in midwinter. Gale-force winds (above 13,8 m/s) are relatively rare in the northern part of the area, less than 5 % in winter and less than 1 % in summer, increasing southward to a maximum of 30 % in winter and 4 % in summer in the southernmost part.

Figure B.2-3 shows wind roses for winter (November to March) and summer (June to August), based on European Centre for Medium-Range Weather Forecasts (ECMWF) data. Winds of gale force in the Davis Strait in winter are mainly from northerly directions. In summer, there is a small predominance of southerly directions.



Key
X month
Y percentage of observations

Figure B.2-2 — Frequency by month of wind speeds exceeding 5 m/s, 10 m/s and 15 m/s
(based on ECMWF data for 1980-1993^[444])

B.2.2.6 Oceanography

The pattern of water circulation in Baffin Bay and Davis Strait is cyclonic or anti-clockwise. A strong southward flow, the Baffin Island Current, exists along the west side, with a weaker northward flow, the West Greenland Current, along the east side. A large part of the West Greenland Current turns westward about latitude 63 °N and then southwestward to join with the Baffin Island Current. The remaining West Greenland Current flows northward in Baffin Bay, turning northwestward at the northern extremity of the bay. The Baffin Island Current consists of polar water from Lancaster Sound, Jones Sound and Smith Sound, plus an additional source from West Greenland. The mean velocity of these currents varies from 8 km/day to 20 km/day.

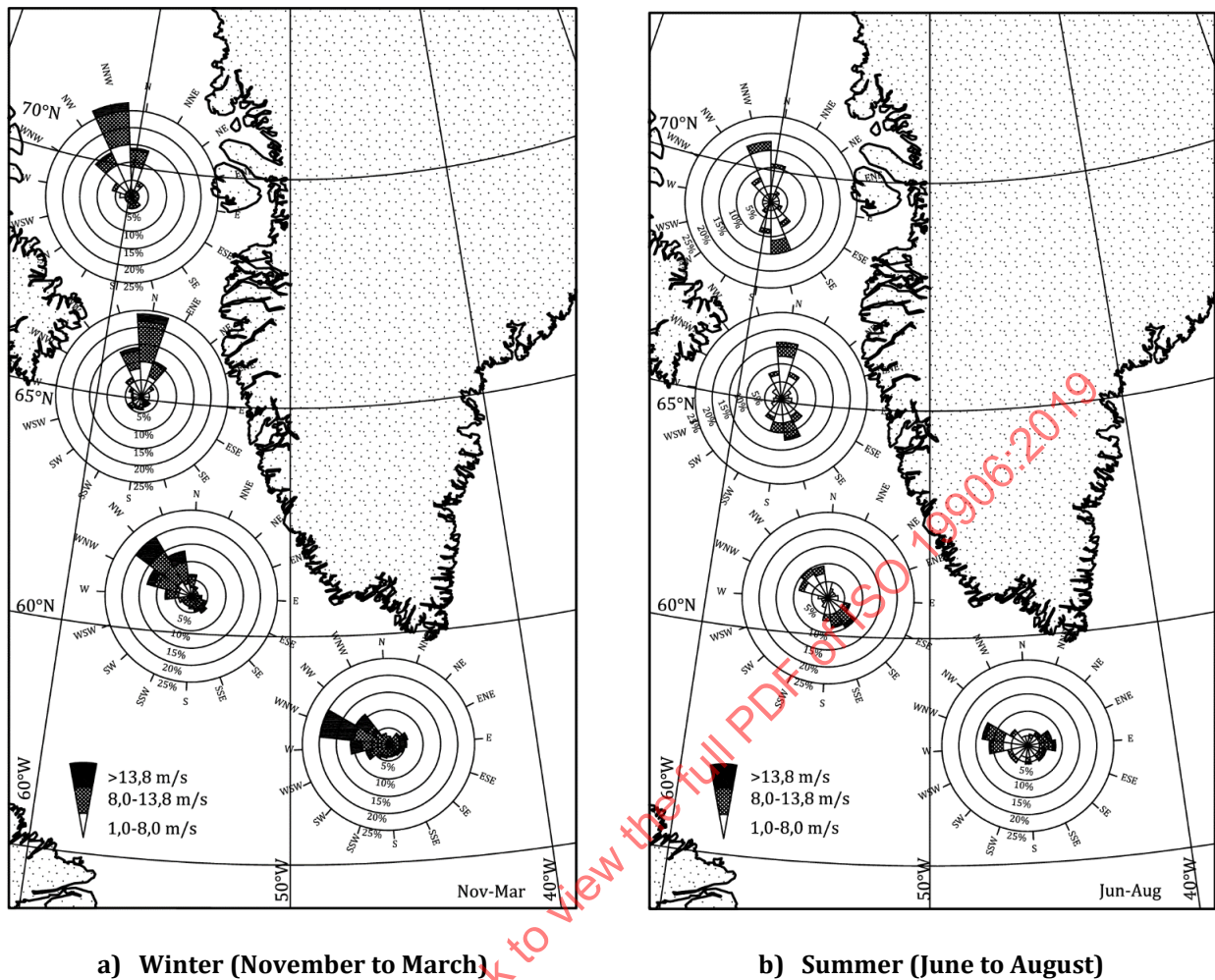


Figure B.2-3 — Wind roses showing direction and speed
(based on ECMWF data for 1980-1993 [444])

Along the West Greenland banks, two current components dominate. Closer to the shore, the East Greenland Current component is diluted by run-off water from the various fjord systems. West and south of the polar water, currents include contributions from the Irminger Sea and the North Atlantic. Current velocities are generally weak ($<0,10$ m/s) except for areas close to the coast and the area just west of the West Greenland Banks. In this zone, the current velocities are generally above $0,25$ m/s and values of $0,4$ m/s to $0,5$ m/s are not unusual.

The mean tidal range along the West Greenland coast is $1,9$ m to $3,2$ m. Along the Baffin Island coast, the range is $0,7$ m to $7,3$ m. The most important tidal constituent in the Davis Strait/Baffin Bay area is the semi-diurnal (M2) tide with an amphidromic point (i.e. point with no tidal amplitude around which cotidal lines rotate anti-clockwise) at about 70°N , almost in the middle of Baffin Bay. Along West Greenland, the greatest amplitude (120 cm) is found in the Nuuk area, decreasing to around 40 cm north of Disko Island.

A map illustrating the general current patterns in the Baffin Bay and Davis Strait can be found in Reference [445].

B.2.2.7 Waves

Observations of wave heights are scarce and little is known for this region. Estimated average wave heights range from 1,5 m to over 3 m, with higher values in the autumn months prior to complete ice freeze-up.

B.2.2.8 Icing

In a 10 year period, freezing rain at the coastal stations occurred most frequently in Nuuk in 0,2 % of the observations in winter. Persistent freezing fog is typically a summer phenomenon occurring over vast ice fields and is not likely to occur over open water with a water temperature above +1 °C.

In open water, icing caused by sea spray is frequent from November to April and rare in October and May. Heavy icing can occur with persistent, strong northerly and northwesterly winds. Strong winds from other directions (particularly southwest) can cause heavy icing as well, though of short duration.

B.2.2.9 Ice conditions

Baffin Bay and Davis Strait have severe ice conditions with thick FY ice and MY floes that can be highly ridged and rubbled. Sea ice can be relatively dynamic and drift speeds exceeding 0,4 m/s are not unusual.

A large polynya often forms between November and March in the northern section of Baffin Bay as a result of an ice bridge that forms in Smith Sound, between Greenland and Ellesmere Island^[442].

The waters of the eastern Davis Strait are normally free from sea ice from April/May until November/December. The easternmost waters have a significantly longer sea ice-free period.

The West Greenland Current retards the time of sea ice formation in the eastern Davis Strait and results in a break-up earlier than in the western parts of the Davis Strait. During the winter and early spring months, sea ice normally covers most of the Davis Strait north of 65 °N, except close to the Greenland coast, where a flaw lead of varying width often appears as far north as latitude 67 °N between the shore and the drift-ice offshore. South of 65 °N to 67 °N, sea ice-free areas dominate throughout the year and the sea ice edge is normally oriented to the southwest towards Hudson Strait or the Labrador Coast.

At the end of the freeze-up season in March/April, the sea ice reaches its maximum thickness of about 50 cm to 90 cm in eastern parts (up to about 100 km from the Greenland coast). The western and central parts of Davis Strait are dominated by medium and thick FY ice categories mixed with small amounts (1/10 to 3/10) of MY ice. The dominant size of the ice floes ranges from large floes about 1 km wide to vast floes larger than 10 km.

Low pressure systems can cause MY ice in the East Greenland Current to drift northwestwards along the Southwest Greenland coast and into the West Greenland Current. The width, concentration and position of this ice belt vary from year to year. Some years, the ice never passes Nunarsuit, while in other years it passes Nuuk and the Fyllas Banke area, but normally the northernmost position of the MY ice on the west coast is near Paamiut at 62 °N. The waters near or south of Paamiut are normally free from MY sea ice beginning in early August. The size of the MY ice floes is usually less than 100 m, and normally about 5 m to 20 m. When MY ice occurs off southwest Greenland, it is normally characterized by low or medium

concentrations averaged over large areas, but long, narrow belts of high concentrations are common. In Greenland, this ice regime is known as the “Storis” or “Great Ice”, mainly because of the thickness of the ice.

If sea ice is present close to the Greenland coast, it is very sensitive to easterly winds and break-up happens quickly. When sea ice covers the entire strait, a narrow lead normally occurs close to the Greenland coast, just off the fast ice edge. The normal ice type in the area is young ice or thin FY ice in varying floe sizes. Wide belts of small floes normally occur near the ice edge.

B.2.2.10 Icebergs

Icebergs can occur everywhere in Baffin Bay and Davis Strait. The highest concentrations are found in the waters off West Greenland. In some areas they occur only rarely, e.g. off Sisimiut, while in other areas, e.g. in Disko Bay, icebergs are always present. A major source of icebergs is eastern Baffin Bay (the west coast of Greenland), north of latitude 73 °N, where over 10 000 icebergs are calved every year from 19 major Greenland glaciers. Nine of these are more than 8 km wide across their front and produce icebergs up to about 1 km long. South of 73 °N, the glaciers in Uummannaq Fjord and Disko Bay are the major source of 10 000 to 15 000 icebergs per year, and these glacial outlets are very important for the iceberg input to the northern Davis Strait and Baffin Bay.

The most active glacier is Ilulissat (Jakobshavn). This glacier produces over 20 km³ of ice each year in varying types and sizes of icebergs. Almost no icebergs are produced south of Disko Bay.

The majority of icebergs from Disko Bay are carried northward into eastern Baffin Bay before heading westward and then southward along the Baffin Island coast. Most of the icebergs from Baffin Bay drift southward into the western Davis Strait, joining the Labrador Current further south, while some of them can enter the eastern Davis Strait area, west of Disko Bay and Kangaatsiaq. Due to the dominant currents and the distribution of the major glacier outlets, the icebergs observed in the northern and western parts of the Davis Strait (north of Sisimiut) are expected to originate from the glaciers in Disko Bay and eastern Baffin Bay. In the southeastern Davis Strait, most of the observed icebergs are of East Greenland origin.

The seasonal maximum of icebergs in the southeastern Davis Strait is normally in July and August, closely related to the actual distribution of the “Storis” in the South Greenland waters. Off the ice edge of the “Storis”, the melt of glacial ice increases significantly and, therefore, the seasonal minimum of glacial ice near the Fyllas Banke area is normally during the autumn and early winter months of September to December.

An important factor controlling the iceberg environment off southwest Greenland is the input of icebergs to the East Greenland Current at high latitudes during the summer. Thousands of large icebergs are calved every year from several glacier outlets on the Greenland east coast. The icebergs drift southward in the East Greenland Current, which contains large amounts of sea ice from the Arctic Ocean most of the year. Large variations in the number and size of icebergs passing Cape Farewell can be expected because of the variability of the currents, the amounts of protecting sea ice, and the extreme weather conditions here during the winter.

The maximum iceberg density off southwest Greenland is expected in early and mid-summer.

Most of the icebergs drifting southward from Baffin Bay in the western part of the Davis Strait occur within 100 km to 150 km of the Baffin Island shore. The large-scale drift of icebergs is often related to the presence and drift of the surrounding sea ice cover.

Based on observations^[446], the largest icebergs are most frequently found in separate areas: south of 64 °N and north of 66 °N. South of 64 °N, the mass near the 200 m depth contour varies between $1,4 \times 10^6$ tonnes (t) and $4,1 \times 10^6$ t with a maximum mass of $8,0 \times 10^6$ t. The mean draught is 60 m to 80 m and maximum draught is 138 m. Between 64 °N and 66 °N, masses are between $0,3 \times 10^6$ t and $0,7 \times 10^6$ t. The maximum mass is $2,8 \times 10^6$ t. Mean draught is 50 m to 70 m and maximum draught 125 m. North of 66 °N, the largest icebergs are found north and west of Store Hellefiske Banke, where the mean iceberg mass is about 2×10^6 t and maximum mass 15×10^6 t. In Disko Bay, the masses are in the range of 5×10^6 t to 11×10^6 t with a maximum recorded mass of 32×10^6 t. Mean draught is 80 m to 125 m and maximum draught is 187 m.

It is worth noting that many icebergs have a deep draught and, due to the bathymetry, large icebergs cannot drift into the shallow water regions, e.g. at Fyllas Banke, where the water depth over large areas is only about 100 m. The measurements of iceberg draughts north of 62°N indicate that an upper limit for a draught of 230 m is exceeded only very rarely. Several submarine cable damage incidents or breaks have occurred at water depths of about 150 m to 200 m with a maximum depth of 208 m southwest of Cape Farewell.

Atlantic ice islands have been defined as very large, low, flat-topped icebergs with length exceeding 500 m if north of latitude 50°N, or exceeding 300 m if south of that latitude, and emanating from the ice shelves of Northern Ellesmere Island or the east coast of Greenland^[447]. Maximum lengths in northern regions can exceed 10 km. Since 2000, ice island occurrence in Baffin Bay and offshore Newfoundland and Labrador has been primarily due to calving of the Petermann glacier. A review of historical ice island observations shows a high incidence of ice island sightings in the late nineteenth and early twentieth centuries, with peaks occurring afterwards approximately every couple of decades. While smaller ice islands have been successfully towed, many ice islands are too large and cannot be dealt with using current IM technology. Additional information on ice islands can be found in References [448] and [449].

Table B.2-2 — Baffin Bay and Davis Strait meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	18	17 to 22
	Minimum, degrees Celsius	–39	–38 to –41
	Freezing degree days	5 000	4 000 to 6 000
Wind speed at 10 m elevation	10 min average, metres per second	18 (BB) ^a 24 (DS) ^b	14 to 24 (BB) 20 to 29 (DS)
Wind direction	Dominant winter direction	280° (BB) 335° (DS)	ND
	Dominant summer direction	154° (BB)	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	ND	ND
^a “BB” indicates Baffin Bay. ^b “DS” indicates Davis Strait.			

Table B.2-3 — Baffin Bay and Davis Strait oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, offshore (>100 m water depth)	Significant wave height, metres, annual maximum	4,1 (BB) ^a 7,9 (DS) ^b	1,8 to 6,8 (BB) 4,8 to 12,6 (DS)
	Range of zero-crossing periods, seconds	7,2 (BB) 9,8 (DS)	5,6 to 8,7 (BB) 8,6 to 11,3 (DS)
Current	Near-surface maximum speed, centimetres per second	10	ND
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Tide	Tidal range (total), metres	1,9 to 3,2 (G) ^c 0,7 to 7,3 (BI) ^d	ND
Wind-induced surge	Water depth increase range total, metres	ND	ND
Water salinity	Average surface salinity, g/kg	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	ND	ND
Seabed geotechnical — Ice-induced gouge	Ice gouge depth, metres	<2	ND
	Water depth range, metres	~220	ND
Seismic	Magnitude	ND	ND

^a “BB” indicates Baffin Bay.
^b “DS” indicates Davis Strait.
^c “G” indicates Greenland.
^d “BI” indicates Baffin Island.

Table B.2-4 — Baffin Bay and Davis Strait sea ice and iceberg conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	mid-November (South) early October (North)	October to November
	Last ice	July (South) late August (North)	July to September
Level ice (FY)	Landfast ice thickness, metres	1,6	1,5 to 2,0
	Floe thickness, metres	1,6	1,5 to 2,0
Rafted ice	Rafted ice thickness, metres	ND	ND
Rubble fields	Sail height, metres	ND	ND
	Length, metres	ND	ND
Ridges (FY)	Sail height, metres	≈0,5 to 1,5	0,5 to 6
	Keel depth, metres	≈5 to 8	5 to 20
Level ice (second- and MY)	Floe thickness, metres	2,5 to 5	2,5 to 10
Ridges (second- and MY)	Sail height, metres	ND	ND
	Keel depth, metres	10	10 to 25
Rubble fields (second- and MY)	Average sail height, metres	ND	ND
	Length, metres	ND	ND

Parameter		Average annual value	Range of annual values
Ice movement	Speed in nearshore, metres per second	0,15	0,1 to 0,4
	Speed in offshore, metres per second	0,20	0,2 to 0,4
Icebergs			
Size	Mass, million tonnes	20	10 to 50
Frequency	Months present	12	12
	Number per year	>2 000	ND
	Maximum number per month	ND	ND

B.3 Labrador

B.3.1 Description of region

Offshore exploration took place in this region in the 1970s and reasonable-sized gas fields were discovered. The information from this exploration phase is very much in the “grey literature” and is not generally publicly available. Detailed descriptions of metocean and ice conditions can be found in References [449] through [454].

Table B.3-1 — General information for Labrador

Area of coverage	52° N to 60° N, 51° W to 65° W
Length of winter season	November to April
Length of summer season	June to October
Range of water depths, metres	20 to greater than 1 000

A map of the offshore Labrador region is shown in Figure B.3-1.

B.3.2 Labrador technical information

B.3.2.1 Climate

The air temperature in this region ranges from approximately 30 °C in summer to –40 °C in winter, based on coastal sites. Wind speeds can range up to 30 m/s to 40 m/s (1 min average).

B.3.2.2 Hydrology

Waves in this region have significant heights up to 12,5 m with associated zero-crossing periods of 8,4 s to 11,8 s in the offshore region based on hindcast data.

Because of the intricacies of the coastline, currents nearshore are quite variable. The main Labrador Current has two branches: the cold Baffin Island Current, which is fresher and close to shore, and the West Greenland Current. There is a net southerly drift due to the Labrador Current (see Figure B.3-1). The mean tidal range along the Labrador coast varies from 0,4 m in Lake Melville to 4,6 m at Cape Chidley.

B.3.2.3 Ice conditions

Offshore Labrador has a harsh environmental climate with heavy pack ice, large icebergs and relatively high wave conditions in the summer months. As one moves further offshore to the east, the amount of ice is reduced, with conditions more similar to the Grand Banks. The region is characterized by heavy pack ice that contains both FY and MY floes. Sea ice can be quite dynamic with speeds up to 0,4 m/s. In sheltered harbours and bays, shore-fast ice grows to a thickness of about 120 cm during a normal winter. Offshore, level pack ice can reach thicknesses greater than this because of the southward drift of the ice from more northern areas. Ice thicknesses can significantly increase under conditions of pressure. Ice ridge sails of up to 3 m to 5 m high can easily develop in these circumstances but 1 m to 2 m is normal. Also, a considerable number of icebergs can be present year-round, including ice islands and ice island fragments, see B.2.2.10.

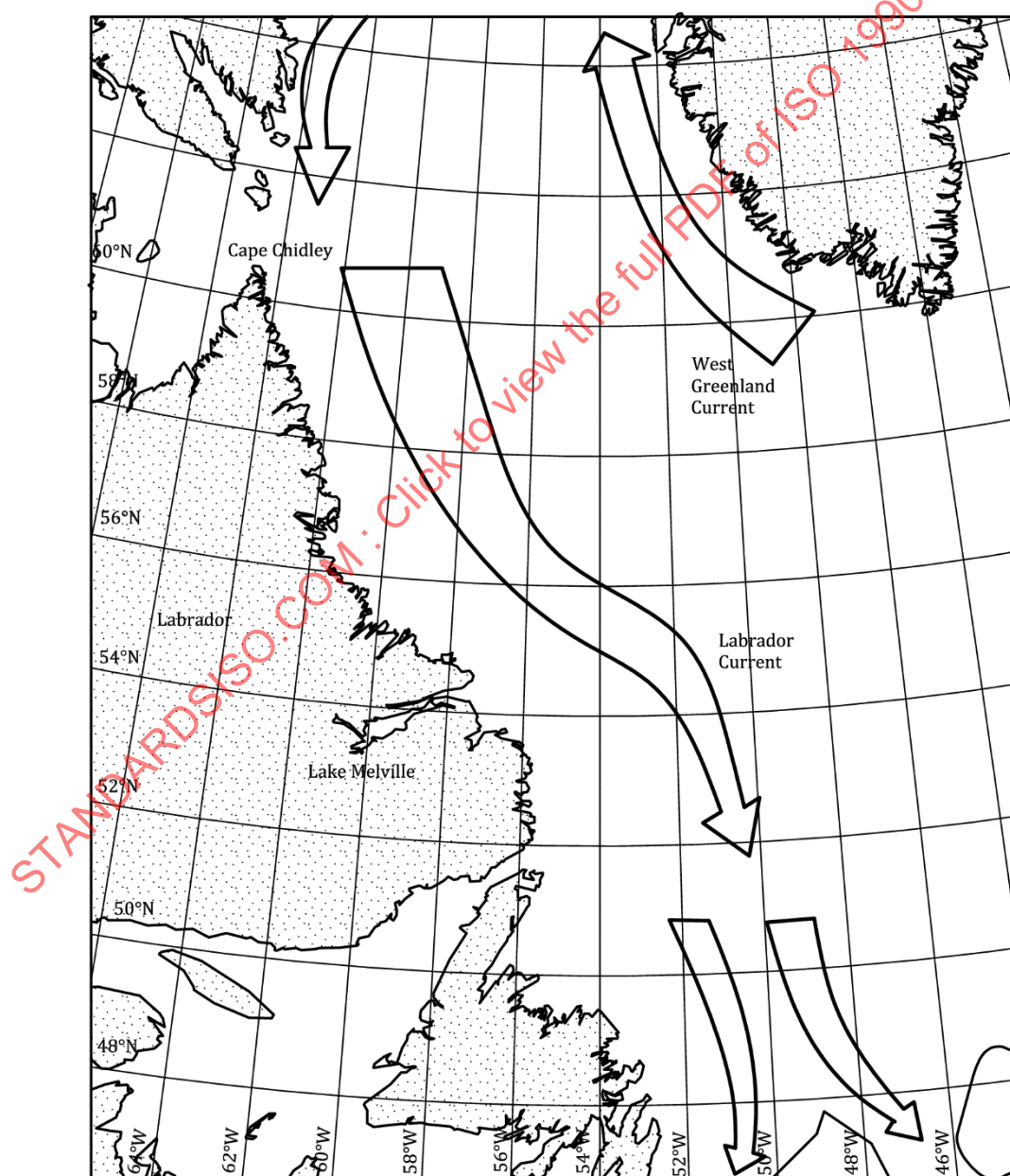


Figure B.3-1 — Map of offshore Labrador

Table B.3-2 — Labrador meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	25	20 to 27
	Minimum, degrees Celsius	-26	-25 to -40
	Freezing Degree Days	1 600	1 000 to 2 000
Wind speed at 10 m elevation	10 min average, metres per second	30	26 to 38
Wind direction	Dominant winter direction, degrees	300	ND
	Dominant summer direction, degrees	210	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	90	ND

Table B.3-3 — Labrador oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, offshore (>100 m water depth)	Significant wave height annual maximum, metres	11,4	8,2 to 14,0
	Range of zero-crossing periods, seconds	10,4	8,4 to 11,8
Current	Near-surface maximum speed, centimetres per second	20	15 to 40
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Tide	Tidal range (total), metres	0,4 to 4,6	ND
Wind-induced surge	Water depth increase range total, metres	ND	ND
Water salinity	Average surface salinity, g/kg	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	5	ND
Seabed geotechnical — Ice-induced gouge	Ice gouge depth, metres	<2	ND
	Water depth range, metres	≈ 220	ND
Seismic	Magnitude	ND	ND

Table B.3-4 — Labrador sea ice and iceberg conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	December	November to January
	Last ice	July	July to August
Level ice (FY)	Landfast ice thickness, metres	1	0,8 to 1,2
	Floe thickness, metres	1,5	1 to 2
Rafted ice	Rafted ice thickness, metres	4	ND
Rubble fields	Sail height, metres	1,5	ND
	Length, metres	—	ND
Ridges (FY)	Sail height, metres	2	1 to 5
	Keel depth, metres	8	3 to 15
Level ice (second- and MY)	Floe thickness, metres	5	2 to 8
Ridges (second- and MY)	Sail height, metres	2	1 to 5
	Keel depth, metres	10	5 to 32
Rubble fields (second- and MY)	Average sail height, metres	ND	ND
	Length, metres	ND	ND
Ice movement	Speed in nearshore, metres per second	0,1	0,1 to 0,3
	Speed in offshore, metres per second	0,2	0,2 to 0,4
Icebergs			
Size	Mass, million tonnes	5 to 10 (maximum)	1 to >20
Frequency	Months present	12	12
	Number per year	1 000	500 to 5 000
	Maximum number per month (number per month)	numerous	ND

B.4 Newfoundland

B.4.1 Description of region

The Grand Banks region offshore of Newfoundland is considered to be a harsh environment due to the possibility of intense storms and the potential for ice (sea ice and icebergs). Superstructure icing can also occur between December and March because of the temperature and wind and wave conditions. Restricted visibility due to fog is also common, especially in the spring and summer months, when warm air masses overlie the cold ocean surface. The worst visibility conditions are experienced in July. During the winter months, restricted visibility can also be caused by snow in addition to fog and mist. Additional information can be found in ISO 19901-1 and References [455] through [459].

There has been significant exploration and development of the petroleum resources on the Grand Banks of Canada off the east coast of Newfoundland. Several companies are involved. Information on this area can be obtained from the Canada-Newfoundland Offshore Petroleum Board (C-NLOPB)^[456]. Additional information on the ice environment on the Grand Banks is provided in Reference [458].

Table B.4-1 — General information for Newfoundland

Area of coverage	45° N to 52° N, 48° W to 56° W
Length of winter season	December to April
Length of summer season	May to November
Range of water depths, metres	75 to 1 200

A map of the offshore Newfoundland region is shown as Figure B.4-1.

B.4.2 Newfoundland technical information

B.4.2.1 Climate

High winds and storms are common in eastern Canada during the winter months. Spring and summer months have fewer, less intense storms and moderate winds, and precipitation is usually in the form of fog, drizzle or rain showers. Hurricanes and tropical storms from the south can threaten the region in the autumn. The wind fields associated with extra-tropical and tropical cyclones excite a wide range of sea states. Extreme wave heights, with maximum individual waves up to 30 m, have been recorded in the region during previous severe storms (e.g. Hurricane Luis in 1995).

B.4.2.2 Hydrology

The Labrador Current is perhaps the most dominant current regime in the region. It plays a major role in the transport of colder water to the region, and the regional current pattern is a function not only of this large current but also of tides, encounters with the warmer eddies and meanders of the Gulf Stream and storm winds. The Labrador Current is also responsible for the transport of icebergs from northern areas to offshore Newfoundland.

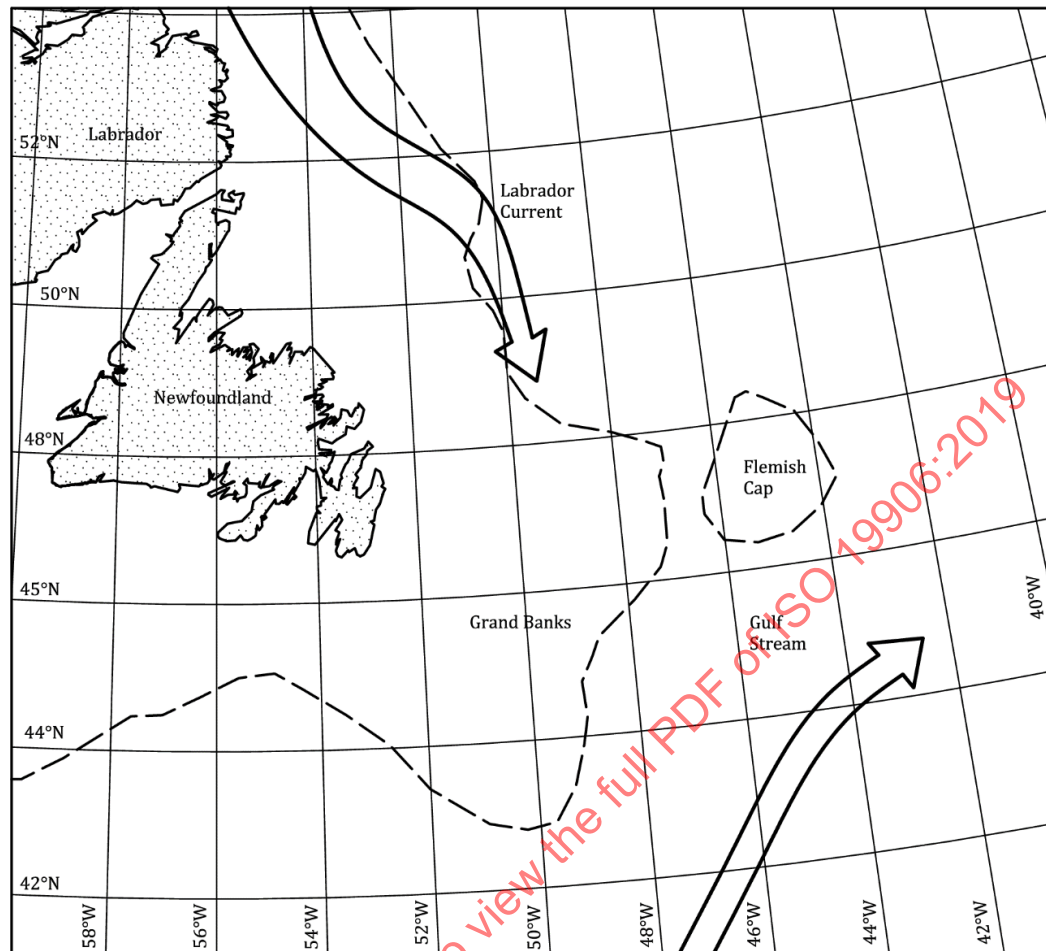


Figure B.4-1 — Map of Newfoundland and offshore regions

B.4.2.3 Sea ice

Sea ice on the Grand Banks is mostly comprised of loose (typically 5/10 to 7/10) pack ice. It drifts in from the Labrador region under the influence of the Labrador Current. In a typical year, the ice edge reaches the northern tip of Newfoundland by early January and the northern Grand Banks by mid-February. The pack ice off Newfoundland generally reaches annual peak coverage in March but can remain at high levels until May. The amount of pack ice varies over the Grand Banks regions and it can vary widely from one year to the next. An offshore structure on the Grand Banks is expected to encounter pack ice several times during its design service life.

B.4.2.4 Icebergs

The Grand Banks has a relatively large population of icebergs that can vary considerably from year to year. The icebergs that travel past the east coast of Canada originate primarily from Greenland glaciers. After calving, the icebergs move north with the West Greenland Current, then south with the Baffin and Labrador Currents until they finally melt in the warmer waters of the southern Grand Banks and the Gulf Stream. While ice islands and ice island fragments have drifted on or near the Grand Banks in recent years, see B.2.2.10, they have not adversely affected oil and gas operations.

According to the International Ice Patrol, the number of icebergs crossing 48° N each year has varied from a low of 0 in 1966 to a high of 2 202 in 1984, with the average of around 800 icebergs (based on data from the period 1995-2004). Some of these icebergs can drift into the vicinity of the various existing oil production operations and require active iceberg management to reduce the probability of encounter. Iceberg speeds and drift directions on the Grand Banks, as measured over 1 h to 3 h time intervals, are less than 35 km/day and 47 % move toward the southwest.

Icebergs are characterized according to their height, length and mass estimate. Site-specific or project-specific studies to develop appropriate iceberg-related criteria are required, as these criteria change according to the region. Data on iceberg numbers can be found in IIP data^[459] and geometrical information can be found in the PERD iceberg sightings database^[460]. Data on IM operations can be found in the PERD Iceberg management database^[461].

A large iceberg can drift into a region where its draught exceeds the water depth, resulting in scours and/or pit features. Iceberg scours occur in various locations on the Grand Banks and have been mapped with side scan and multi-beam sonar. The Grand Banks Scour Catalogue^[462] is a compilation of data from previous seabed surveys. The average scouring frequency is approximately 1×10^{-4} to 1×10^{-3} scours/km²/year depending on the region. The average scour length is approximately 650 m and the average scour width is approximately 25 m. The average depth of scour depends on the type of soil conditions present at the scour location. Stiff or compacted sediments can limit the scour depth. For a typical location on the Grand Banks, the average scour depth is about 0,3 m.

Table B.4-2 — Newfoundland meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	16	14 to 18
	Minimum, degrees Celsius	-10	-6 to -16
	Freezing Degree Days	110	35 to 225
Wind speed at 10 m elevation	10 min average, metres per second	32	24 to 38
Wind direction	Dominant winter direction, degrees	260	ND
	Dominant summer direction, degrees	225	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 nautical miles	40 % April to August 11 % September to March	ND

Table B.4-3 — Newfoundland oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves (>100 m water depth)	Significant wave height annual maximum, metres	11,7	7,4 to 15,6
	Range of zero-crossing periods, seconds	10,6	8,3 to 12,3
Current	Near-surface maximum speed, centimetres per second	90	90 to 130
	Mid-layer maximum speed, centimetres per second	70	50 to 100
	Bottom maximum speed, centimetres per second	60	50 to 80
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Tide	Tidal range (total), metres	ND	ND
Wind-induced surge	Water depth increase range total, metres	0,5	0,46 to 0,6
Water salinity	Average surface salinity, g/kg	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	17	15 to 19
Seabed geotechnical — Ice-induced gouge	Ice gouge depth, metres	0,3	0,1 to 1,5
	Water depth range, metres	≈ 220	ND

Table B.4-4 — Newfoundland ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	January	December to January
	Last ice	May	May to June
Level ice (FY)	Landfast ice thickness, metres	0,8	0,6 to 1
	Floe thickness, metres	1	0,7 to 1,2
Rafted ice	Rafted ice thickness, metres	2	ND
Rubble fields	Sail height, metres	1,1	ND
	Length, metres	ND	ND
Ridges (FY)	Sail height, metres	1,5	1 to 2
	Keel depth, metres	5	3 to 8
Level ice (second- and MY)	Landfast ice thickness, metres	0	0
	Floe thickness, metres	1,5	1 to 2
Ice movement	Speed in nearshore, metres per second	ND	ND
	Speed in offshore, metres per second	ND	ND
Icebergs			
Size	Mass, million tonnes	0,1 to 0,2 (mean)	0,05 to 6
Frequency	Months present	April to July	January to December
	Number per year	450	0 to 2 200
	Maximum number per month	ND	ND

B.5 Canadian Arctic Archipelago

B.5.1 Description of region

Panarctic Oils Limited and its partners drilled in the High Arctic Islands in the Sverdrup Basin for approximately 20 years from the late 1960s to the mid-1980s, and a considerable amount of industry experience and technology was gained in this region^[463]. More information regarding the High Arctic physical environment based on experiences from drilling operations can be found in various papers published at the Offshore Technology conferences in the 1970s.

There is a known earthquake epicentre northwest of Melville Island. Facilities designed for the Melville Island region of the Arctic Islands should consider the seismic risk.

Reference [464] is the best source of information on ice conditions in this region. The region is not as well characterized as other areas of the Canadian Arctic since there is very little shipping here.

A map of the Canadian Arctic Archipelago is shown in Figure B.5-1.

Table B.5-1 — General information for Canadian Arctic Archipelago

Area of coverage	68° N to 80° N, 80° W to 125° W
Length of winter season	September to May
Length of summer season	July to August
Range of water depths, metres	100 to 500

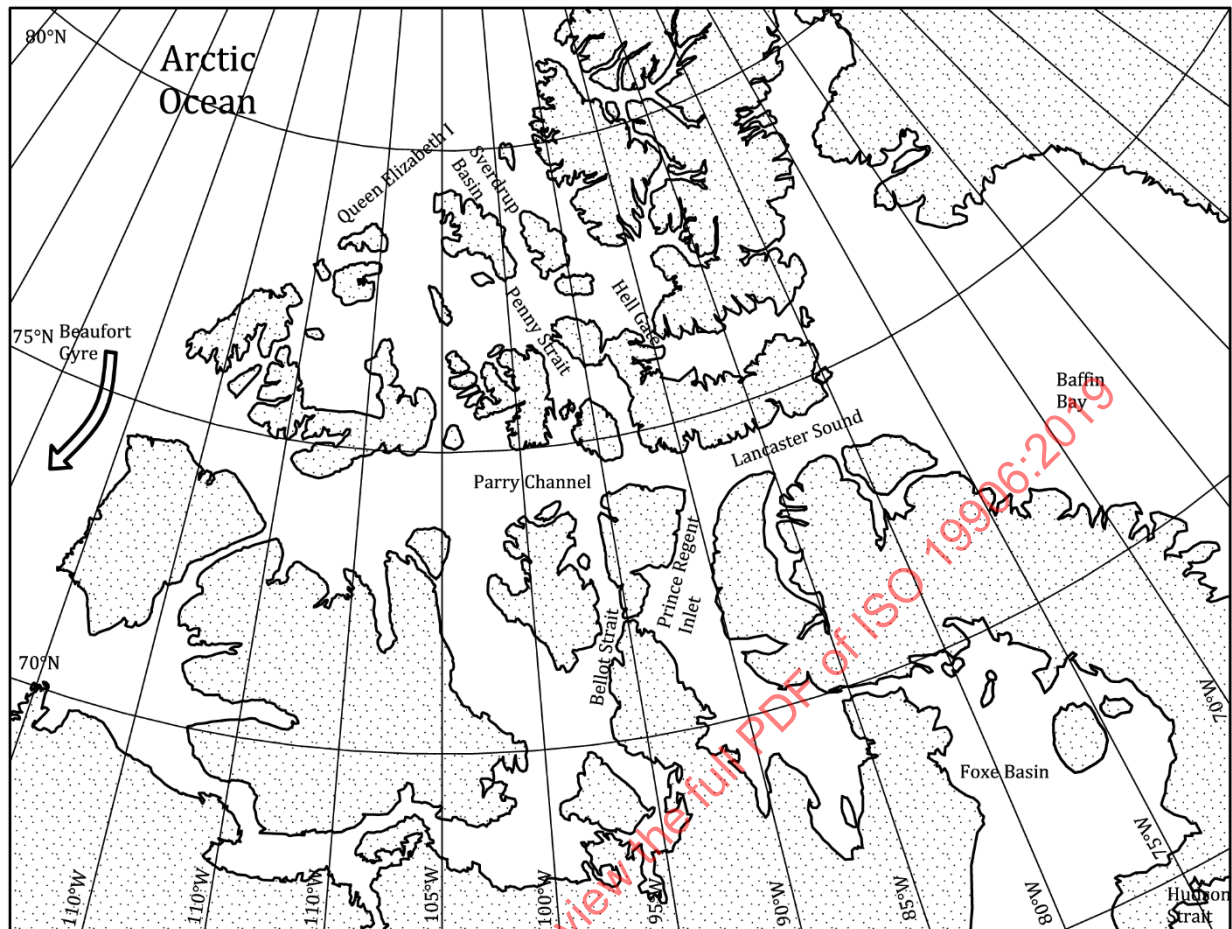


Figure B.5-1 — Map of the Canadian Arctic Archipelago

B.5.2 Canadian Arctic Archipelago technical information

B.5.2.1 Climate

The Canadian Arctic Archipelago has a very extreme climate with winter temperatures in the range of $-30\text{ }^{\circ}\text{C}$ to $-40\text{ }^{\circ}\text{C}$ and summer mean daily temperatures averaging approximately $10\text{ }^{\circ}\text{C}$. There are typically 7 000 Freezing Degree Days in this region each year. Older data for the “ND” entries of Table B.5-1 can be found in Reference [465].

B.5.2.2 Hydrology

Water currents in the Arctic Archipelago are primarily the result of the outflow of water from the Arctic Basin. Some of this water emerges into Baffin Bay and some goes through the Foxe Basin and Hudson Strait into the Labrador Sea. The mean tidal range is generally from near 0 m in Slidre Fiord to 2,9 m in Smith Sound.

In many areas, tides are the principal contributor to current speed in the narrow passages between basins. The most extreme tidal flows occur in Bellot Strait (4 m/s), Hell Gate (3 m/s), Fury and Hecla Strait (2,5 m/s), Cardigan Strait (2,5 m/s) and Penny Strait (1,5 m/s). Further data can be obtained in Reference [45].

B.5.2.3 Sea ice

Most of the waterways of the Arctic Archipelago are dominated by a consolidated ice sheet during the winter months. The main exceptions are Lancaster Sound and central Prince Regent Inlet, where the ice remains in restricted motion. Small tidal openings are common in Penny Strait and Bellot Strait, while a significant open-water polynya exists in Hell Gate all winter. During the first week of September, new ice usually begins to form among the old floes in the Queen Elizabeth Islands area. By the middle of September, it begins to spread from the northern and western sections, covering many of the waterways by the end of the month. Lancaster Sound is the last area to become ice-covered, and this usually occurs by the middle of October. By the end of October, ice in many of the waterways has already consolidated. Knowledge of the ice regime of the Canadian Archipelago is based heavily on data acquired during the 1970s and early 1980s. Present conditions, particularly in relation to ice thickness, are poorly known. One can anticipate that conditions will change dramatically if the adjacent area of the Arctic Ocean does indeed lose all its MY ice, as some experts predict.

Reference [466] summarizes the existing information concerning the pack ice and relevant climate variables of the Canadian Arctic Archipelago north of Parry Channel. Pack ice in this area is a mix of MY, second-year, and FY ice types, with the latter subordinate except in the southeast. Ice remains landfast for more than half the year, and summertime ice concentration is high (7/10 to 9/10). In a typical year, less than 20 % of the old ice and 50 % of the FY ice melt. Figure B.5-2 shows the median concentration, expressed in tenths of ice coverage, in the Sverdrup Basin at the time of minimum extent (3 September). The chart is based on a 30 year climatology prepared by the Canadian Ice Service for 1970 to 1999.

There are large inter-annual fluctuations in ice coverage and some suggestion of a decadal cycle. The average ice thickness in late winter is 3,4 m but sub-regional means reach 5,5 m. References [467] and [468] document MY sea ice conditions in this area. The pack is a mix of two populations: one consisting largely of MY ice imported from the zone of heavy ridging along the periphery of the Beaufort gyre, and the other consisting of a mix of relatively undeformed first-year, second-year, and MY ice types that grow and age within the basin. The ice of the Sverdrup Basin is strongly influenced by a flux of heat that originates in the Atlantic-derived waters of the Arctic Ocean. The drift of ice through the basin is controlled in the present climate by the formation of stable ice bridges across connecting channels. The drift is episodic. Relaxation of these controls in a warmer climate can cause deterioration in ice conditions in Canadian Arctic waters^{[466][469]}.

Table B.5-2 — Canadian Arctic Archipelago meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	9	8 to 11
	Minimum, degrees Celsius	-40	-35 to -45
	Freezing Degree Days	7 000	5 500 to 8 000
Wind speed at 10 m elevation	10 min average, metres per second	ND	ND
Wind direction	Dominant winter direction	NW	ND
	Dominant summer direction	ND	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	ND	ND

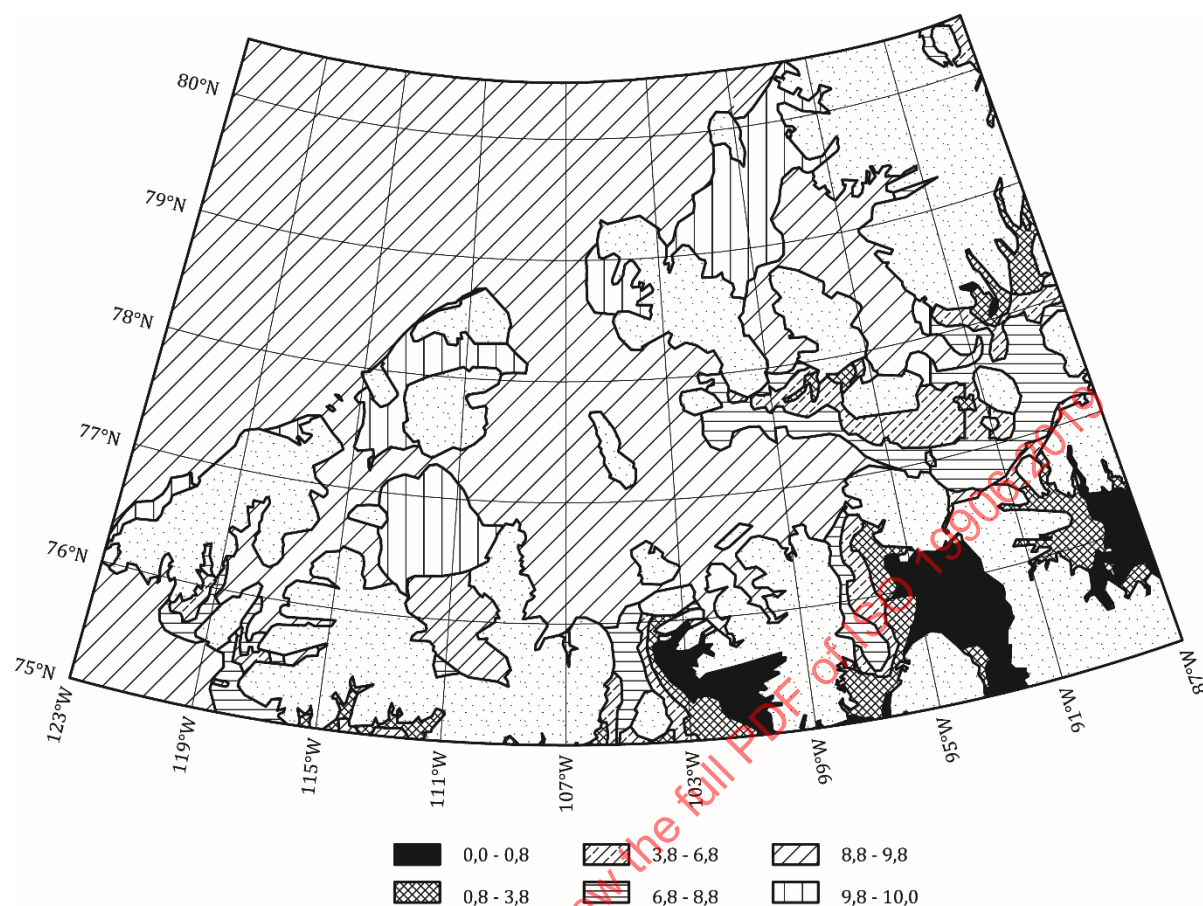


Figure B.5-2 — Median concentration, in tenths, of ice in the Sverdrup Basin at the time of minimum extent (3 September), based on a 30 year climatology for 1970 to 1999^{[463][466]}

Table B.5-3 — Canadian Arctic Archipelago oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, nearshore (<100 m water depth)	Significant wave height, metres	ND	ND
	Range of zero-crossing periods, seconds	ND	ND
Current	Near-surface maximum speed, centimetres per second	10	400 (in narrow channels)
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	10	400 (in narrow channels)
Tide	Tidal range (total), metres	2,2	ND
Wind-induced surge	Water depth increase range total, metres	ND	ND
Water salinity	Average surface salinity, g/kg	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	ND	ND
Seabed geotechnical — Ice-induced gouge	Ice gouge depth, metres	ND	ND
	Water depth range, metres	ND	ND
Seismic	Magnitude	5	3 to 7

Table B.5-4 — Canadian Arctic Archipelago sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	end August	—
	Last ice	August	August to September
Level ice (FY)	Landfast ice thickness, metres	2,2	1,8 to 2,6
	Floe thickness, metres	2,2	1,8 to 2,6
Rafted ice	Rafted ice thickness, metres	ND	ND
Rubble fields	Sail height, metres	5	3 to 6
	Length, metres	ND	ND
Ridges (FY)	Sail height, metres	4	4 to 5
	Keel depth, metres	20	20 to 25
Stamukhi	Water depth range, metres	20	15 to 30
	Sail height, metres	ND	ND
Level ice (second- and MY)	Landfast ice thickness, metres	3,5	2 to 11,3
	Floe thickness, metres	3,5	3 to 5
Ridges (second- and MY)	Sail height, metres	ND	ND
	Keel depth, metres	15	5 to 25
Rubble fields (second- and MY)	Average sail height, metres	ND	ND
	Length, metres	6	3 to 20
Ice movement	Speed in nearshore, metres per second	0,1	0,05 to 0,2
	Speed in offshore, metres per second	0,15	0,1 to 0,3
Icebergs/ice islands			
Size	Mass, million tonnes	400	10 to 600
Frequency	Months present	12, northern half only	ND
	Number per year	few	ND
	Maximum number per month	few	ND

B.6 North East Greenland

B.6.1 Description of region

This region consists of the waters off the east coast of Greenland from Iceland in the south to Svalbard in the east, see Figure B.6-1. The water depth is typically within the range 100 m to 1 000 m.

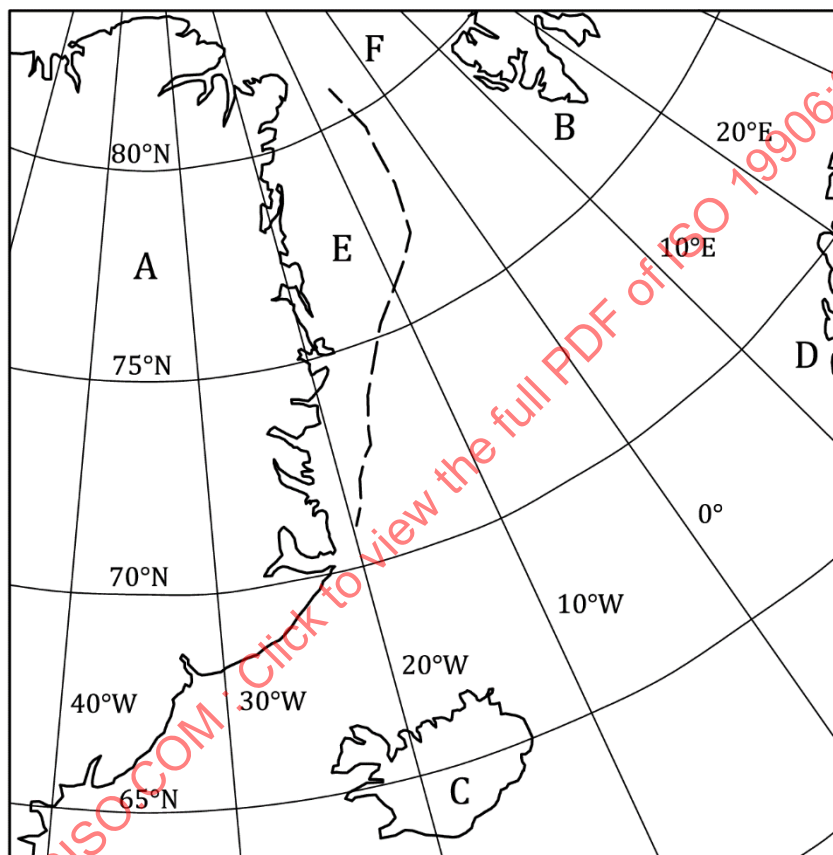
The North East Greenland region is well known for the severity of its physical environment. Some of the key factors of note include limited open-water occurrences (see Figure B.6-2), heavy pack-ice conditions, icebergs, low temperatures and poor visibility.

Recently collected physical environmental data for offshore North East Greenland have been included the Greenland database administrated by the Mineral License and Safety Authority (MSLA) of Greenland.

The main source for information on the physical environment of offshore North East Greenland used in this document is Reference [470].

Table B.6-1 — General information for North East Greenland

Area of coverage	70° N to 80° N, 0° W to 24° W
Length of winter season	October to June
Length of summer season	July to September
Range of water depths, metres	100 to 1 000
NOTE Since there is year-round presence of sea ice in large parts of the region, it can be argued that the winter season lasts all year.	

**Key**

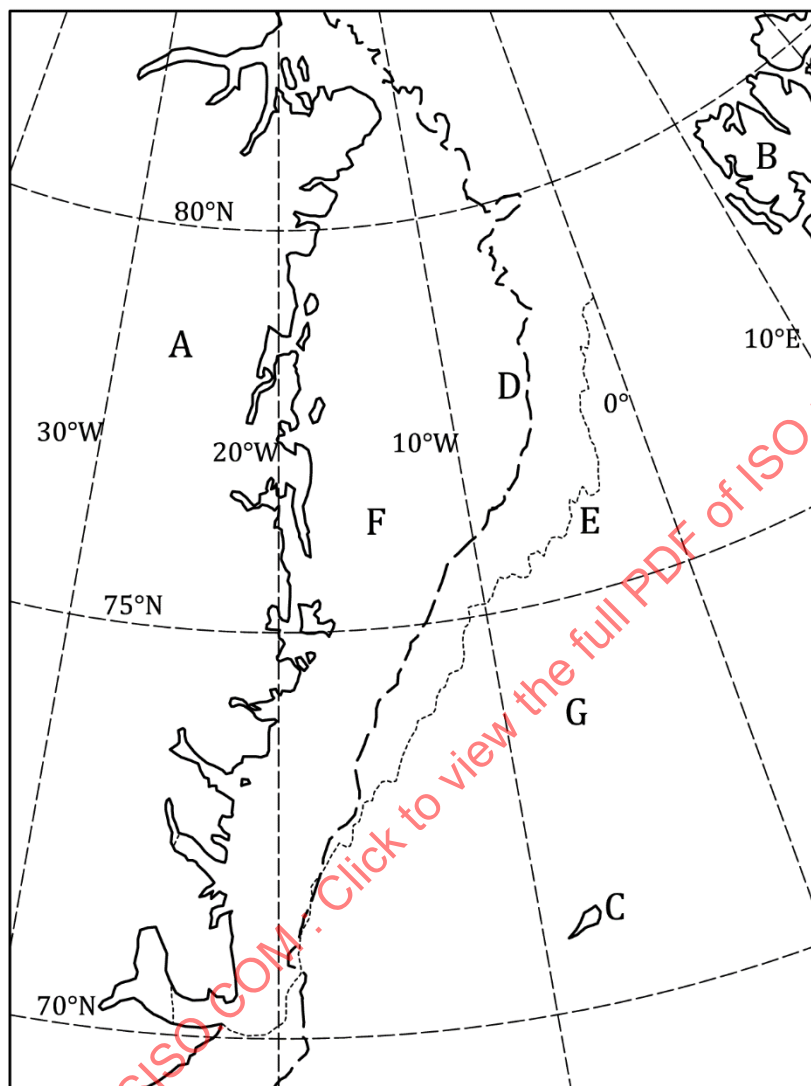
A Greenland
 B Svalbard
 C Iceland

D Norway
 E Greenland Sea
 F Fram Strait

Figure B.6-1 — Map of the North East Greenland region**B.6.2 Greenland technical information****B.6.2.1 Air temperatures**

In the north, with sea ice occurring much of the year, summers are cool and winters are very cold, with an average temperature range between the coldest and warmest months of about 30 °C. In summer, freezing temperatures can occur over sea ice and/or within fog. In winter, very low temperatures occur over snow-covered solid sea ice. Over open water, air temperatures normally are below those of the sea

surface due to the prevailing advection of cold air. In the coastal zone, summer temperatures as high as 15 °C or more can occur, under foehn (a warm, dry wind on the lee side of a mountain range) conditions, even in winter.



Key

- A Greenland
- B Svalbard
- C Jan Mayen
- D Greenland Shelf break
- E 50 % boundary for 1/10 sea ice concentration (no data east of 0° longitude)
- F ice-covered area
- G ice-free area

Figure B.6-2 —ice coverage offshore North East Greenland in September (1972 to 2009)

B.6.2.2 Visibility

Fog (visibility less than 1 km) is primarily a summer phenomenon. Its frequency increases during May, has its peak value in June and July, and reduces in late August. The estimated frequency of fog in July is

20 % to 30 % of the total time over the coldest parts of the sea area. Fog is less frequent in the coastal region.

Temperatures within fog are often 1 °C to 2 °C below that of the sea surface. Freezing temperatures within fog over a cold water surface are not unusual, and icing with rime ice or clear ice can occur. In winter, fog can form occasionally within a warm and moist air mass advected from the south. Sea smoke forms within cold air flowing from drift ice or from cold land out over open water. The occurrence is often very local but in a very cold air mass it can be more widespread.

In winter, snow showers are present much of the time over open water, causing moderate or poor visibility.

B.6.2.3 Precipitation

Snowfall is limited to short spells of cold weather in the northern part of the area. Generally, October and June are the rain-to-snow transition months in the north.

B.6.2.4 Wind

North of latitude 65 °N, the annual mean wind speed is 5 m/s to 6 m/s. The maximum speed in the northernmost part of the area occurs in October to November. Gale-force winds (above 13,8 m/s) are relatively rare in the northern part of the area, less than 5 % in winter and less than 1 % in summer.

B.6.2.5 Oceanography

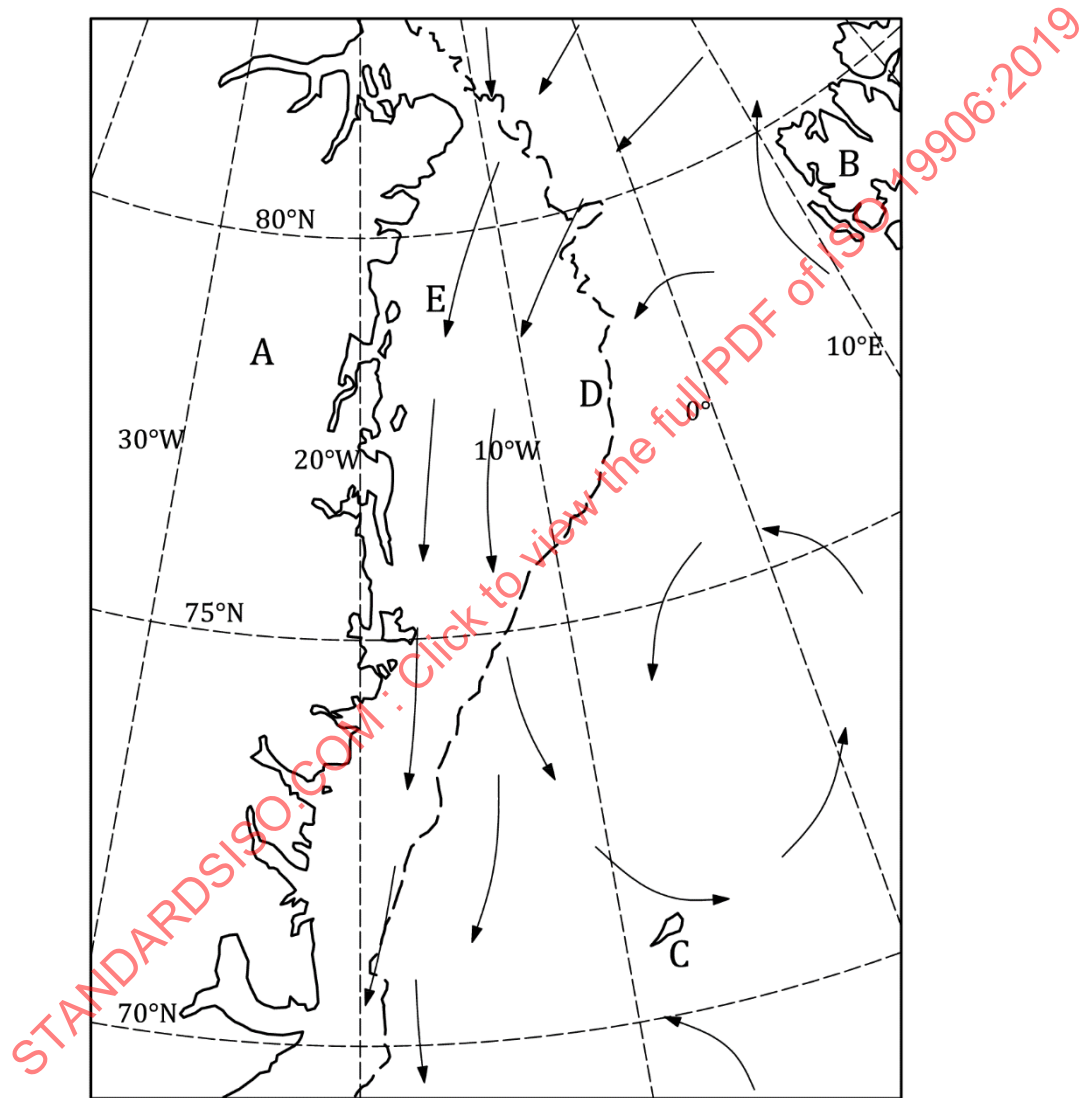
The oceanography of the Nordic Seas including the western Greenland Sea is dominated by two primary water masses, the Atlantic water and Polar water. Warm (6 °C to 8 °C), saline (35,0 psu to 35,2 psu) Atlantic water enters the Nordic Seas in three branches crossing the Greenland Scotland Ridge. The second major water mass is the light, low saline (31,0 psu to 34,8 psu) and cold (−1,8 °C to −1,4 °C) polar water mass deriving from the upper Arctic Ocean and being exported south along with FY and MY mobile pack ice. In the Fram Strait region, part of the Atlantic water recirculates and returns south along the East Greenland shelf break with a high salinity, warm core aligned with the steepest part of the slope near the 2000 m isobaths occupying the depth interval between 100 m to 500 m. The general circulation is illustrated in Figure B.6-3. Geostrophic velocity estimates yield relatively weak circulation (0 cm/s to 10 cm/s) which contrasts to much higher estimates based on ice drift. There is some evidence for a general intensification seasonally near the coast (0 km to 30 km) forming a coastal summer jet. Drifter data from the shelf region have demonstrated highly variable currents related to storm activity, with peak currents reaching 100 cm/s to 200 cm/s. The topography on the shelf is relatively complex, favouring the formation of eddies and closed-circulation loops. These are evident from sea ice drift data and can persist for weeks in the summer period, altering the general southward drift pattern.

B.6.2.6 Waves

Waves offshore North East Greenland are a combination of wind-driven waves as well as swells. Swells coming from low-pressure activity over the north Atlantic affect the area from time to time.

Waves in the Greenland Sea are affected by the distribution of sea ice. In cases where winds blow from the ice, the distance to the ice edge influences wave height, since the ice edge acts as a coastline. Wind-driven waves need a certain distance to the ice edge/coastline, as well as persistent wind direction, to reach the maximum height for a given wind speed. Another way the ice affects the wave height is the damping effect when the sea is partly covered by ice, see 6.4.2.

During summer, the significant wave height (in open water) is relatively low compared with the significant wave height in winter. The significant wave heights are usually higher in southern parts of the region.



Key

- A Greenland
- B Svalbard
- C Jan Mayen
- D Greenland Shelf break
- E East Greenland current

Figure B.6-3 — General ocean surface circulation offshore North East Greenland
 [Source: Oceanographic Atlas of the Polar Seas^[471]]

B.6.2.7 Sea Ice

A wide belt of second-year and MY sea ice originating from the Arctic Ocean is normally present most of the year, covering the entire east coast of Greenland. Under normal conditions, the MY ice reaches the Cape Farewell area in December/January, depending on the intensity of the East Greenland Current and the amount of sea ice in it. Due to long periods with strong northwesterly winds, ice often passes Cape Farewell only for short periods. The amount of MY ice in the South Greenland waters peaks in early summer.

The ice regime offshore North East Greenland is divided into three different zones. Near the coast, there is an area with landfast ice during the spring season. To the east, near the shelf edge, the conditions can be characterized as an “ice river” with an outflow of ice from the Arctic basin. In between these areas, there is a zone of more or less dense drifting pack ice.

The predominant northerly winds create ice pressure, and rafted ice with partly thick ridges in different directions (not only coast-parallel) is frequent. The landfast ice extends approximately 130 km out from the coast in the north and about 55 km in the south. In the summer season, the land fast ice is broken into large floes and drifts away from shore.

Ice thicker than 2 m is normal, and ice ridges with keels deeper than 30 m can occur. Freeze-up usually starts at the end of September in the entire region, but there are large inter-annual variations.

B.6.2.8 Icebergs

Most of the icebergs in Northeast Greenland waters originate from the Fjorden glacier and Zacharie isbræ i Jøkelbugten around 79°N. Icebergs from Storstrømmen isbræ around 76°30'N can also enter the region from the southwest. Calved icebergs normally stay trapped within the landfast ice, where they can survive in the cold water for many years. However, in years of extensive break-up of the landfast ice, the icebergs can be released and start to drift out onto the shelf. Thereafter, they can be caught in the swift East Greenland Current and drift around the southern tip of Greenland, as documented in 2002, 2003 and 2008^[470].

While grounded, the icebergs typically act as anchors for the landfast ice. Keel drafts of icebergs in Northeast-Greenland are frequently in the range of 50 m to 80 m, with waterline lengths of up to several kilometres. Little is known about drift speed, especially in nearshore areas. Within the mobile pack ice in the East Greenland Current, icebergs are expected to drift with the sea ice, which has been monitored with moored instruments. Iceberg drift can occasionally deviate from the sea ice drift, depending on parameters such as sea ice strength, sea ice thickness, current stratification and iceberg draft.

Table B.6-2 — North East Greenland meteorological conditions

Parameter		Average annual value
Air temperature	Maximum, degrees Celsius	6
	Minimum, degrees Celsius	–33
Wind speed at 10 m elevation	10 min average, metres per second	30
Wind direction	Dominant (direction/percentage occurrence)	N/27

Table B.6-3 — North East Greenland oceanographic conditions

Parameter		Average annual value
Waves	Significant wave height, metres	4
	Spectral peak period, seconds	8
	Maximum individual wave height, metres	10
	Average direction of extreme waves (from)	SSE
Current	Near-surface maximum speed, centimetres per second	100
	Mid-layer maximum speed, centimetres per second	45
	Bottom maximum speed, centimetres per second	30
Water temperature	Annual surface maximum, degrees Celsius	2
	Summer surface average, degrees Celsius	-1
	Annual bottom maximum, degrees Celsius	1,2
	Annual bottom average, degrees Celsius	0,5

Table B.6-4 — North East Greenland sea ice and iceberg conditions

Parameter		Average annual value
Sea ice		
Occurrence	First ice	Year round
	Last ice	Year round
Level ice	Ice thickness, metres (first year, second-year and MY)	2,5/3,5
Ice ridge	Keel draft, metres	40
Icebergs		
Size	Mean mass, million tonnes	0,5 to 1
	Maximum mass, million tonnes	12
	Mean draught, metres	60 to 100
	Maximum draught, metres	300 (depending on water depth)
Drift	Mean direction (to)	SSW
Frequency	Months present	All year

B.7 Beaufort Sea

B.7.1 Description of region

During the intense exploration of the Beaufort Sea in the 1970s and 1980s, a considerable amount of environmental information was collected by the oil industry. A large amount of the data was processed and published as part of the Environmental Impact Statement^[472]. Copies of this report are not easily obtained, but they can be viewed at the Arctic Institute of North America at the University of Calgary, Alberta.

More recently, Devon Canada developed an environmental assessment for its operations^[474].

There are three main bathymetric features in the southeastern Beaufort Sea:

- a) the continental shelf, which slopes gently from the coastline to water depths of approximately 100 m;
- b) the continental slope, angling steeply from the edge of this shelf to depths of 1 000 m;
- c) the trench-like Mackenzie (or Herschel) Canyon, which transects a portion of the shelf.

In most Beaufort locations, the seabed consists of 0,5 m to 35 m of recent marine clays or silty clays that have been carried onto the continental shelf from the mouth of the Mackenzie River. These sediments are grey to black, soft to firm and often contain traces of fine sand and organics. Coarse materials such as sands and fine gravels can also be encountered.

Permafrost is widespread beneath the Beaufort Sea. A relict permafrost layer, formed during the Wisconsin era, is typically encountered between 50 m and 150 m below the seafloor, which can be several hundred metres (or more) in thickness. Permafrost can also be found in fairly close proximity to the seafloor, with ice lensing and visible inter-granular ice often being observed in shallow boreholes. In addition, there are a number of large pingo-like features on the floor of the southern Beaufort Sea. The Canadian Hydrographic Service has identified over 200 of these features between the 20 m and the 200 m isobaths and from 128° W to 136° W. Most of these features are between 200 m and 1 000 m in diameter, have sloped sides of less than 5°, and can rise to within 18 m of the sea surface. Pockets of shallow gas and deeper gas hydrate formations are additional factors of note.

The seabed of the Beaufort Sea is heavily scoured by large ice features, both FY and MY ice ridges. The maximum ice gouge depth is 5 m, measured in 30 m water depth on the basis of repetitive mapping surveys in 1978-2008. The spatial frequency of ice gouges varies significantly across the Beaufort shelf. Sonar records indicate that the maximum spatial frequency is almost 20 ice gouges per kilometre per year for water depths of 0 m to 10 m (over a survey route length of 8 km) and is approximately 6 ice gouges per kilometre per year for water depths of 20 m to 30 m (over a survey route length of 5 km). New technology using multi-beam sonar is continually improving the knowledge of the scouring in the Beaufort Sea. The Geological Survey of Canada at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, maintains an up-to-date database on information related to scouring in the Beaufort Sea.

Table B.7-1 — General information for the Beaufort Sea

Area of coverage	69° N to 75 °N, 125° W to 152° W
Length of ice covered season	early October to late July
Length of open water season	August to early October
Range of water depths, metres	2 to 90, to several thousand

A map of the Beaufort Sea is provided in Figure B.7-1.

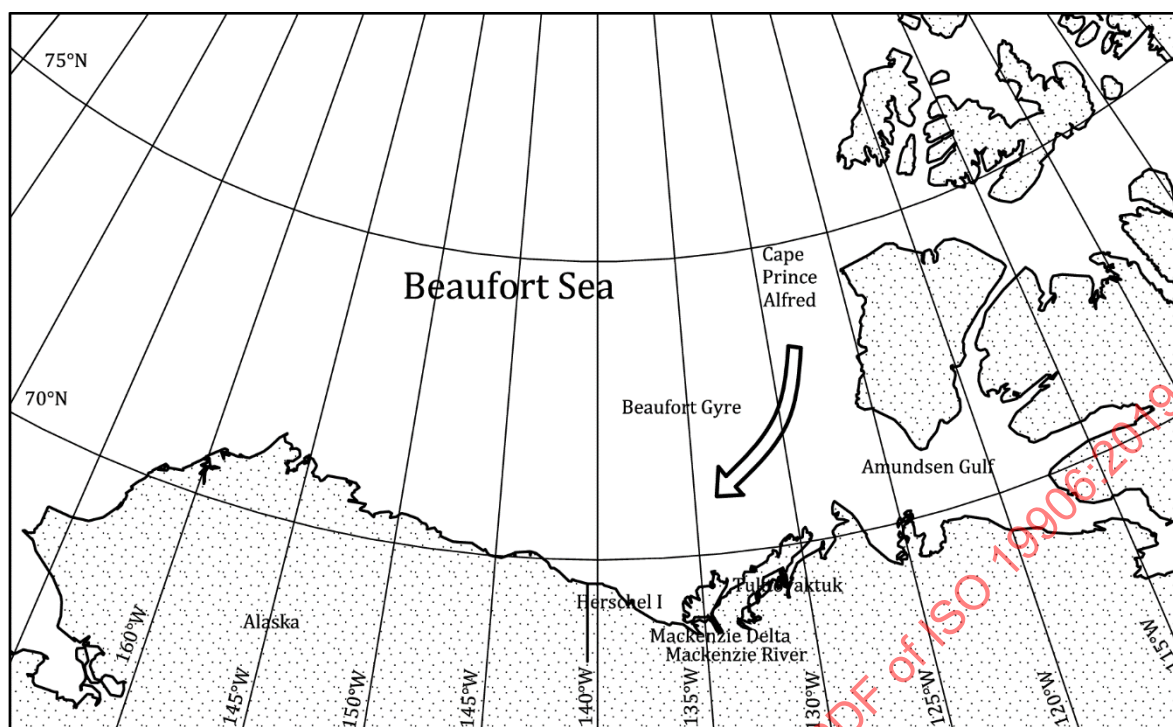


Figure B.7-1 — Map of the Beaufort Sea

B.7.2 Beaufort Sea technical information

B.7.2.1 Climate

Winds in the Beaufort Sea are influenced by the sharp thermal contrast of the land and water to the high coastal lands. Once every 50 years, winds with an hourly average of 29 m/s and a 1 min average of 39 m/s can be expected. The dominant wind direction ranges from the northeast to southeast during any month of the year. Southerly winds are rare during the summer months. From July to September, extended periods of easterly winds are common, although westerly to northwesterly winds in excess of 10 m/s can become persistent. Half of all strong winds with speeds exceeding 14 m/s are from the west or northwest. These winds are responsible for the MY ice intrusions into the coastal waters.

B.7.2.2 Hydrology

In the offshore Beaufort, the ocean surface flow is dominated by the clockwise circulation of the Beaufort Gyre, with typical flow speeds of 5 cm/s to 10 cm/s but which can reach over 100 cm/s during storms, at the southern rim of the Gyre over the western Beaufort Sea.

In the Beaufort Sea, extreme wind, wave, and surge conditions occur during autumn storms prior to freeze-up. Easterly storms are related to a steepening of the surface pressure gradient over the north coast of Alaska, as lows enter the Alaskan Peninsula from the Bering Sea or Gulf of Alaska and are blocked by the polar anticyclone. Easterly storms are characterized by strong winds of long duration (usually several days). Westerly storms are associated with extra-tropical cyclones that track from west to east or northwest to southeast across the Beaufort Sea. The strong winds associated with westerly storms are typically of shorter duration than those for easterly storms. Westerly storms produce positive storm

surges along the coast, while easterly storms produce negative surges. Outside the breaker zone, easterly storms produce somewhat higher waves than westerly storms. Close to shore where wave heights are limited by breaking, westerly storms can produce higher waves.

The data in Table B.7-3 are from the Canadian offshore. Although limited tide, current and surge data are available for the Alaskan offshore (with 15-year record at Prudhoe Bay), these data are not included in the table.

B.7.2.3 Ice conditions

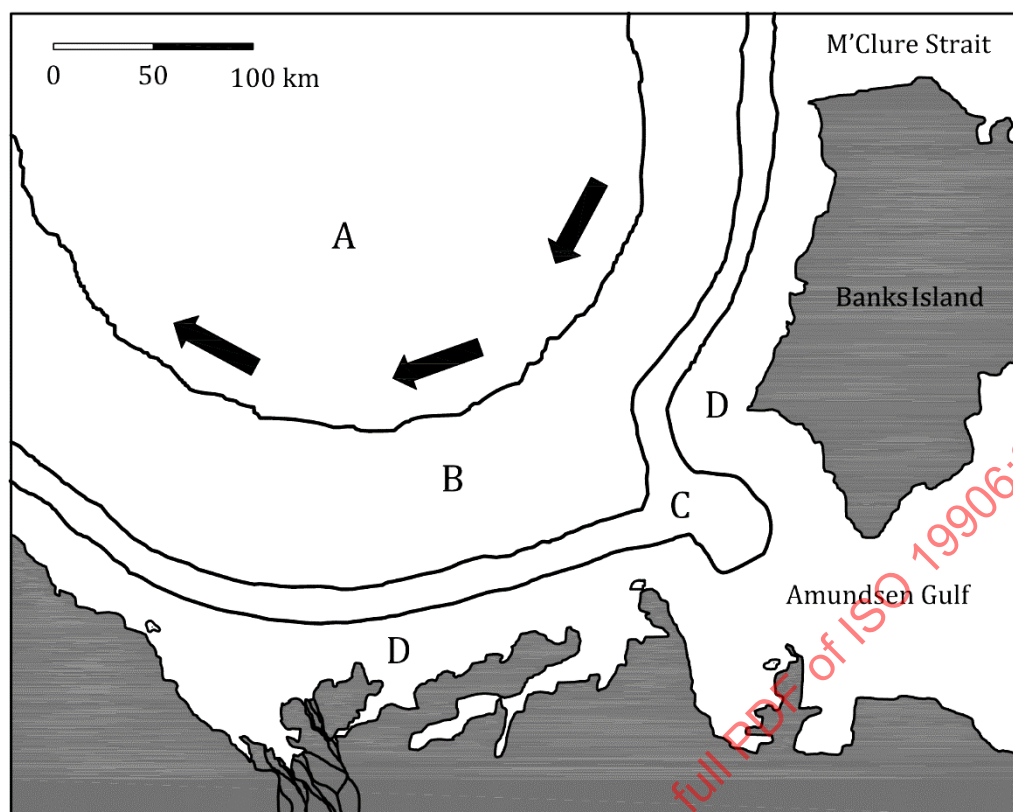
The ice in the Beaufort Sea can be subdivided into three regions (see Figure B.7-2):

- a) arctic polar pack zone;
- b) seasonal or transitional (shear) zone;
- c) landfast ice zone.

The arctic polar pack is composed of old or MY ice with a level-ice thickness up to 4,5 m to 5 m and ridges that can be 25 m thick. The polar pack continuously circulates with the currents and winds in the Arctic Ocean, and is present year round. Its degree of penetration into the Beaufort Sea at any given time is dependent on the wind regime. On average, the boundary of the arctic pack lies from near Cape Prince Alfred off Banks Island southwestward to some 200 km north of Herschel Island and then westward some 200 km off the Alaska north coast.

The seasonal transitional zone extends from the edge of the (stationary) landfast ice to the edge of the moving polar pack ice. The width of this zone can vary from a few kilometres to over 300 km, both within a season and from year to year. Although this region is primarily composed of FY ice, there can be a large number of MY and second-year ice floes. This ice is highly dynamic, and movement can take place throughout the winter with movements of 3 km/day to 13 km/day. The moving ice results in deformations in the ice sheet and the creation of both ridges and leads. The number of ridges increases rapidly in the first part of the winter and remains relatively constant after February. Ridge heights (sails) can range up to 6 m. If the ridge survives the summer season, it largely desalinates and consolidates to form an MY ice ridge.

The landfast ice is extensive and forms out to a water depth of approximately 20 m. This region is composed primarily of FY ice. MY ice, if present during the freeze-up period, is frozen into the sheet. The ice begins to grow over the late September to mid-October period and reaches a maximum thickness of approximately 1,9 m in late April. In spring, the northwest winds die off and the east and southeast winds become predominant, so that a polynya develops along the edge of the landfast ice. In June, melt begins in the Mackenzie delta and an open water area also develops quickly there. Typically, the Amundsen Gulf fractures in late June and the ice drifts out and decays. The fast ice along the Tuktoyaktuk Peninsula fractures in early July. During a cold summer, the landfast ice along the Tuktoyaktuk Peninsula might not completely break until mid-July. These cold summers occur because northwesterly winds keep the arctic pack close to shore.

**Key**

A	polar pack ice zone	C	active shear zone
B	transition zone	D	landfast ice zone

Figure B.7-2 — Schematic showing different sea ice zones in the Canadian Beaufort Sea (after Kovacs and Mellor^[473])

Open drift ice conditions do not develop along the entire coastline from Point Barrow to the Canadian Beaufort Sea until the first week of August, and an open water route does not develop until the first week of September. Freeze-up in the Beaufort depends to a very great extent on the location of the southern limit of the arctic pack. New ice formation starts among the MY floes in late September and spreads both southward and seaward from the coast. By late October much of the ice is at the FY stage (i.e. >30 cm thick) right out to the arctic pack.

Ice islands and MY hummock fields represent the largest ice features in this region. Ice islands are of glacial origin and, although rare, are extremely large. Ice islands with an area of up to 697 km² and a thickness of up to 60 m have been documented. They present a potential threat to offshore structures in waters greater than 20 m deep.

The most comprehensive and up-to-date source of information on ice conditions for the Canadian Arctic (including the Beaufort Sea) can be obtained by contacting the Canadian Ice Service^[475]. Information on ice properties and ice strength can be obtained from the National Research Council of Canada^[476] and the DFO Bedford Institute of Oceanography^[477]. Reference [478] provides updated values for sea ice parameters for this region.

Table B.7-2 — Beaufort Sea meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	20	10 to 30
	Minimum, degrees Celsius	−30	−20 to −40
	Freezing Degree Days	4 500	3 500 to 5 500
Wind speed at 10 m elevation	10 min average, metres per second	24	18 to 32
Wind direction	Dominant winter direction, degrees	95	ND
	Dominant summer direction, degrees	50 (50 % of strong winds are from N and NW)	ND
Precipitation	Annual rainfall, millimetres	150	100 to 200
	Annual snowfall, millimetres	750	600 to 1 100
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	20 % of the time	ND

Table B.7-3 — Beaufort Sea oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, offshore (>100 m water depth)	Significant wave height annual maximum, metres	3,7	1,8 to 8,5
	Range of zero-crossing periods, seconds	6,7	4,5 to 9,8
Current	Near-surface maximum speed, centimetres per second	40	20 to 100
	Bottom maximum speed, centimetres per second	2 to 5	1 to 50
Tidal current	Maximum surface speed, centimetres per second	low	ND
Tide	Tidal range (total), metres	0,3	0,3 to 0,6
Wind-induced surge	Water depth increase range total, metres	1	1 to 4
Water salinity	Average surface salinity, g/kg	2 to 30	0 to 33
Water temperature	Summer surface maximum, degrees Celsius	10	2 to 12
	Summer surface average, degrees Celsius	5 to 7	0 to 10
Seabed geotechnical — Ice-induced gouge	Ice gouge depth, metres	0,6	0,1 to 5
	Water depth range, metres	≈30	≈50
Seismic	Magnitude	3 to 5	5,5 (in 1937) and 6,5 (in 1920)

Table B.7-4 — Beaufort Sea sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	October	Late September to late October
	Last ice	July	Early July to mid-August
Level ice (FY)	Landfast ice thickness, metres	1,8	1,5 to 2,3
	Floe thickness, metres	1,8	1,5 to 2,3
Rafted ice	Rafted ice thickness, metres	3	2,5 to 4,5
Rubble fields	Sail height, metres	5	3 to 6
	Length, metres	100 to 1 000	100 to 1 000
Ridges (FY)	Sail height, metres	5	1 to 7
	Keel depth, metres	25	6 to 30
Stamukhi	Water depth range, metres	20	15 to 30
	Sail height, metres	5 to 10	up to 20
Level ice (second- and MY)	Ice thickness, metres	3 to 6	2 to 11
	Floe thickness, metres	5	2 to 20
Ridges (second- and MY)	Sail height, metres	Significant	Significant
	Keel depth, metres	20	10 to 35
Rubble fields (second- and MY)	Average sail height, metres	2 to 5	3 to 6
	Length annual maximum, metres	750	50 to 2 300
Ice movement	Speed in nearshore, metres per second	0,06	0,04 to 0,2
	Speed in offshore, metres per second	0,08	0 to 1,5
Icebergs/ice islands			
Size	Mass, million tonnes	10	ND
Frequency	Months present	Poorly known	Poorly known
	Number per year	Poorly known	Poorly known
	Maximum number per month	Rare	Rare

B.8 Chukchi Sea

B.8.1 Description of region

The Chukchi Sea is situated between two continents: Asia and America. In the west, the sea adjoins the East Siberian Sea; in the east, it adjoins the Beaufort Sea; and in the south, it is connected with the Bering Sea through the Bering Strait. In the north, the Chukchi Sea has an open border with the Arctic Basin. This northern border is generally defined as the edge of the continental shelf.

Table B.8-1 — General information for the Chukchi Sea

Parameter	Region			
	Southwestern	Northwestern	Southeastern	Northeastern
Area of coverage (See Figure B.8-1)	Key item 1	Key item 2	Key item 3	Key item 4
Length of winter season	10 to 12 months	10 to 12 months	November to mid-June	October to mid-July
Length of summer season	August to September in the southern regions	0 to 2 months	Mid-June to October	Mid-July to September
Water depth range, metres	0 to 50	50 to 100	0 to 50	0 to 50

The sea is divided into four parts for the purpose of this document: southwestern (see Figure B.8-1, key item 1), northwestern (see Figure B.8-1, key item 2), southeastern (see Figure B.8-1, key item 3) and northeastern (see Figure B.8-1, key item 4).

B.8.2 Chukchi Sea technical information

B.8.2.1 Climate

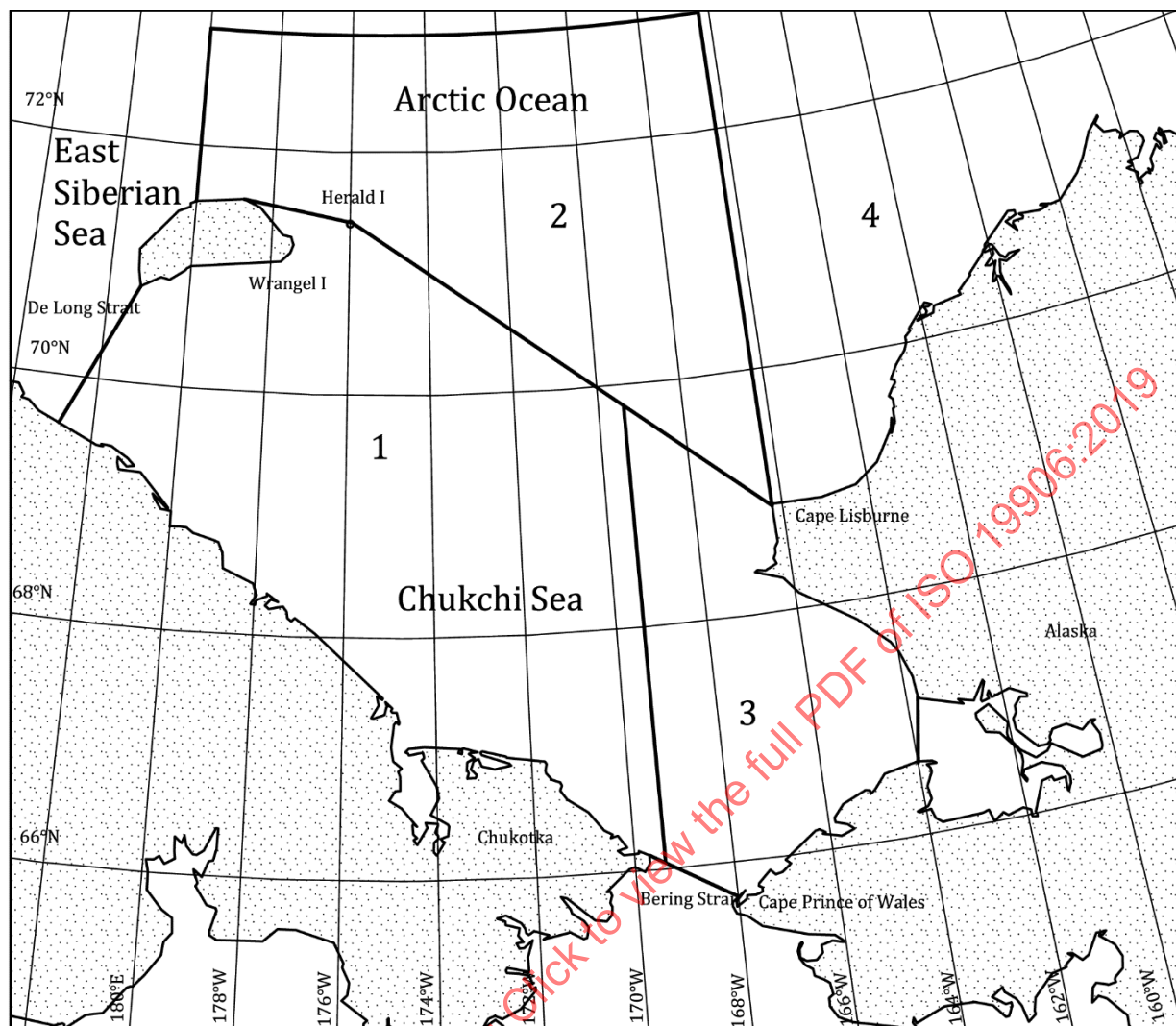
The climate of the Chukchi Sea is influenced by the two oceans — the Arctic and Pacific — and the two continents — Asia and America — that surround it. Due to its latitude and large north-south extent, the period of 24 h of darkness lasts 60 days to 80 days in the northern regions but only a few days near the Bering Strait.

Atmospheric circulation, which plays an important role in forming the Chukchi Sea climate, is controlled by the interaction of three centres of atmospheric action: the Arctic High, the Siberian High (in summer it is a low) and the Aleutian Low.

In winter, three to four storms per month, generally coming from the southwest, pass over the sea. Storm passage is usually accompanied by sharp increases in air temperature, increasing cloudiness, strong winds and fog. In spring and summer when the Aleutian Low weakens, the number of storms decreases to about one or two per month, all of which come from the south.

Easterly winds predominate during the major part of the year. In autumn and winter, easterly winds have a northerly component. In the June-July time frame, southwesterly winds are observed over the northern portion of the sea, while southerly winds are observed near the Bering Strait.

In winter months, the mean wind speed is about 6 m/s to 7 m/s; in spring and summer, it is 5 m/s to 6 m/s; and in autumn it increases to 7 m/s to 8 m/s. In the autumn-winter time period, the maximum wind speed can reach 35 m/s to 40 m/s. From May until August, the maximum wind speed does not exceed 28 m/s to 30 m/s.



Key

1 southwestern part	3 southeastern part
2 northwestern part	4 northeastern part

Figure B.8-1 — Borders and parts of the Chukchi Sea

The number of days with winds ≥ 15 m/s at the coast is about 40 days per year to 70 days per year; the majority occur in October and November, which have such winds for 8 days per month to 10 days per month. Further off the coast in the open sea, winds with these speeds are observed less frequently.

The annual number of days with winds ≤ 5 m/s varies from 40 days in the south to 60 days to 65 days in the north.

For a large portion of the year, freezing air temperatures (< 0 °C) are observed. The duration of air temperature > 0 °C varies from four months near the Bering Strait to one month in the north. The monthly mean air temperature in the winter months varies from -18 °C to -22 °C near the Bering Strait to -26 °C to -28 °C in the north. In April and May, the monthly mean air temperature increases to -8 °C in April and to -2 °C in May. The monthly mean air temperature in July and August is 3 °C to 4 °C in the south and 0 °C to -1 °C in the north. In October, the region cools quickly and the air temperature in the north drops to -10 °C to -12 °C.

The lowest air temperature observed in winter is in the range of $-40\text{ }^{\circ}\text{C}$ to $-45\text{ }^{\circ}\text{C}$. The summer high air temperature in the coastal zone and the region near the Bering Strait reaches $28\text{ }^{\circ}\text{C}$ to $30\text{ }^{\circ}\text{C}$, while in the open sea it does not exceed $15\text{ }^{\circ}\text{C}$ to $20\text{ }^{\circ}\text{C}$.

B.8.2.2 Hydrology

The vertical water structure of the Chukchi Sea is a result of the interaction of northward-flowing Pacific water, surface Arctic water and subsurface Atlantic water. Pacific water flows north through the Bering Strait and propagates in three northerly flowing branches: the Alaska branch in the east, the Herald branch and the De Long branch in the west. The warm water of the Pacific flow is sufficient to fully melt the ice in the southern half of the area. In the western part of the Chukchi Sea, the Chukotka Coastal Current flows southward along the Russian coastline from the East Siberian Sea through the De Long Strait. In winter, this cold water current transports ice southward to the Bering Sea through the western part of the Bering Strait; see Figure B.8-2.

In summer, the warmest water is observed in the southern and eastern regions, where the mean water temperature reaches $5\text{ }^{\circ}\text{C}$ to $6\text{ }^{\circ}\text{C}$. To the north, the water temperature decreases near the marginal ice zone to $0\text{ }^{\circ}\text{C}$. Along the Alaskan coast, the water temperature sometimes reaches $10\text{ }^{\circ}\text{C}$ to $15\text{ }^{\circ}\text{C}$. Northward-flowing Bering Sea water, with 31 g/kg salinity, occupies the southern and central parts of the Chukchi Sea. Salinity decreases to the west and, in the De Long Strait, it is on average 27 g/kg to 28 g/kg .

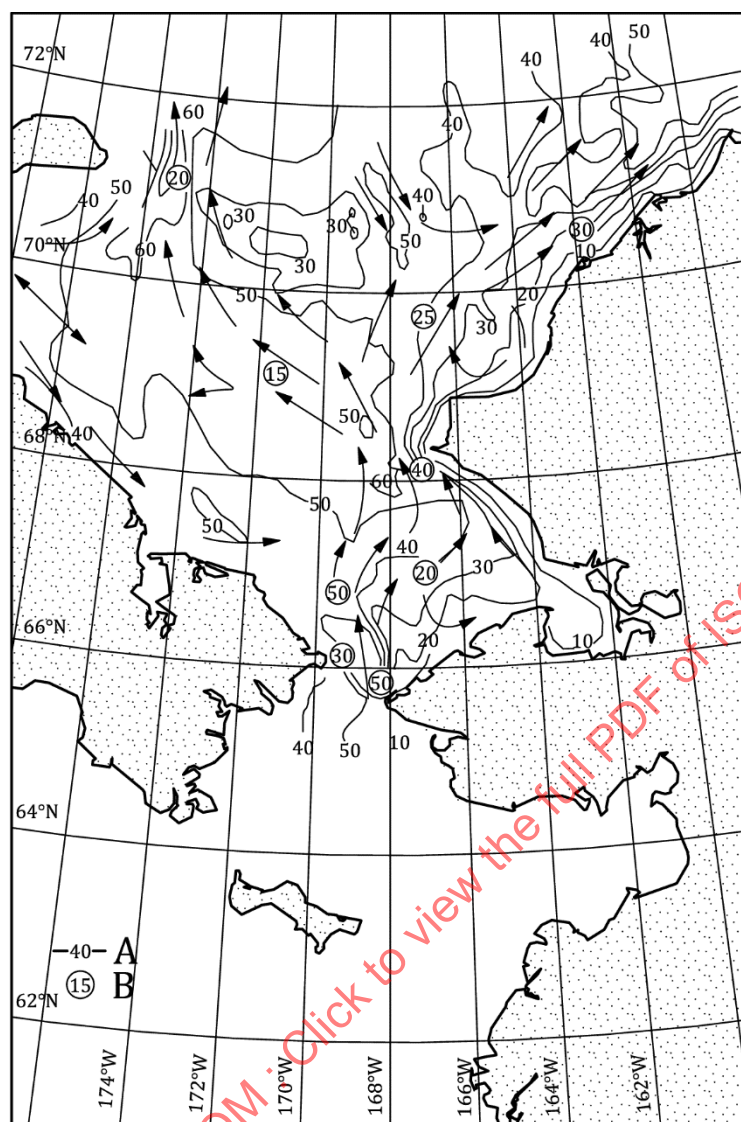
Semi-diurnal tides prevail in the region; tidal currents do not exceed 10 cm/s to 20 cm/s in the open sea and increase slightly in the bays and gulfs. Wind-caused fluctuations of sea level are significant and range from 2 m to 3 m in the coastal zones. The maximum sea level fluctuations due to wind are connected with storm transits.

The open-water period generally starts in the June-July time frame and lasts until October. The highest wave heights are observed in September until the beginning of October.

Additional data can be found in References [480] and [481].

B.8.2.3 Sea ice

The Chukchi Sea is entirely covered by ice from the November-December time frame until the May-June time frame. Prior to water being open, a large part of the Chukchi Sea is covered by thick FY ice with a predominant thickness of 120 cm to 140 cm . Old ice (MY and second-year) can be found in concentrations up to $4/10$ in the northern portions. In the south, in severe ice years, the MY ice concentration is slightly less than $2/10$. Reference [482] provides updated values for sea ice parameters for this region. Further information can also be found in Reference [483].



Key

- A water depths, expressed in metres
- B current speeds, expressed in centimetres per second

Figure B.8-2 — Diagram of the surface currents of the Chukchi Sea^[479]

Landfast ice is not generally found along the Chukotka and Alaska coasts, due to the presence of deep water in the coastal zone. Generally, when present, the landfast ice width along the Chukotka coast varies within a range of 5 km to 20 km. The landfast ice width along the Alaskan coast is greater and can reach 40 km to 60 km, but its variability on a monthly or annual scale is large. Shear ridges form on an annual basis northeast of Cape Lisburne. The outer edge of this shear zone migrates seaward as the season progresses, and the entire region is subject to seabed gouging from ice ridge keels.

Due to the predominance of easterly winds, a polynya (flaw lead) can be formed beyond the Alaska landfast ice. A similar polynya forms beyond the landfast ice of the Russian coastline under westerly winds.

In winter, concentrations of ridged and deformed ice can reach 6/10 in the southern regions. In the Russian coastal zone, the deformed ice concentration can reach 10/10 coverage.

Ice decay begins in mid-May starting in the south at the Bering Strait. The Herald branch of the northward-flowing current divides the ice cover into two ice parts: the Northern Chukchi massif (to the north of 72 °N) consisting mainly of old ice, and the Wrangel ice massif located in the west. By the end of June, all landfast ice is gone.

On average, by the end of September, 8/10 of the sea is ice-free. In unfavourable years, ice occupies about half of the sea and the Wrangel ice massif blocks the De Long Strait. During the summers of 2007 to 2009, the Chukchi Sea was totally ice-free.

On average, stable ice formation begins in late October along the northern Russian coastline and progresses steadily to the south. The mean time for 10/10 ice coverage is 15 November. Around the end of October to the beginning of November, landfast ice starts to form along the Chukotka coast. Due to the large amount of open water during the last three summers, ice freeze-up was delayed and it was not until mid-December that the Chukchi Sea was 100 % ice-covered.

Table B.8-2 — Chukchi Sea meteorological conditions

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	27,5	20 to 30	18,2	15 to 20	20	15 to 25	16	10 to 20
	Minimum, degrees Celsius	-46	-40 to -50	-45	-40 to -48	-40	-35 to -45	-44	-40 to -50
	Freezing Degree Days	ND	ND	ND	ND	3 300	2 500 to 3 600	4 000	3 500 to 4 500
Wind speed at 10 m elevation	10 min average, metres per second	39	ND	43	ND	ND	ND	ND	ND
Wind direction	Dominant winter (direction/percentage occurrence)	NE/33	ND	NE/33	ND	E/25 to 35	ND	SE/25 to 30	ND
	Dominant summer (direction/percentage occurrence)	E/29	ND	E/29	ND	W to NW/25 to 30	ND	E/25 to 40	ND

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Precipitation	Annual rainfall, millimetres	380	ND	265	ND	221	150 to 300	157	100 to 200
	Annual snowfall, millimetres	ND	ND	ND	ND	1 143	900 to 1 400	530	300 to 700
Visibility (fog, snow, etc.)	Annual number days with visibility <1 km	65	ND	75	ND	>30	20 to 40	>30	20 to 40

Table B.8-3 — Chukchi Sea oceanographic conditions

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Waves, nearshore (<100 m water depth)	Significant wave height, metres	6,0 to 8,0	12,0 to 14,0	ND	ND	8	6 to 10	6	5 to 8
	Range of zero-crossing periods, seconds	6 to 7	6 to 10	ND	ND	8 to 12	8 to 14	8 to 10	8 to 12
Current	Near-surface maximum speed, metres per second	15 to 20	ND	ND	ND	>50	~100 (localized regions only)	>50	~100 (localized regions only)
	Bottom maximum speed, metres per second	ND	ND	ND	ND	<10	8 to 10	<10	8 to 10
Tidal current	Maximum surface speed, metres per second	ND	ND	ND	ND	15	10 to 20	15	10 to 20
Tide	Tidal range (total), metres	0,3 to 0,6	ND	ND	ND	ND	ND	0,4	0,3 to 0,5
Wind induced surge	Water depth range, total, metres	3,0 to 3,7	ND	ND	ND	30 to 32	29 to 33	30 to 32	29 to 33

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Water salinity	Average surface salinity, g/kg	28 to 31	ND	ND	ND	8	6 to 10	6	5 to 8
Water temperature	Summer surface maximum, degrees Celsius	6 to 7	ND	ND	ND	16	14 to 18	11	10 to 12
	Summer surface average, degrees Celsius	1 to 5	ND	ND	ND	10	8 to 12	6	5 to 7
Seabed geotechnical — Ice-induced gouge	Ice gouge depth, metres	ND	ND	ND	ND	ND	ND	ND	ND
	Water depth range, metres	ND	ND	ND	ND	ND	ND	ND	ND
Seismic	Magnitude	ND	ND	ND	ND	ND	ND	ND	ND

Table B.8-4 — Chukchi Sea sea ice conditions

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Occurrence	First ice	Mid-Nov.	Early to late Nov.	Early Oct.	All year	Dec.	Late Nov. to late Dec.	Nov.	Late Oct. to early December
	Last ice	Late June	Early June to late July	Early Aug.	All year	May	Late April to late May	July	Mid-June to late August
Level ice (FY)	Landfast ice thickness, metres	1,6 to 1,8	1,5 to 2,0	None	None	1,2	0,9 to 1,2	1,5	1,3 to 1,7
	Floe thickness, metres	0,7 to 1,2	0,1 to 1,8	1,2 to 1,8	0,5 to 2,0	0,5 to 1,2	0,5 to 1,8	0,7 to 1,4	0,7 to 1,8
Rafted ice	Rafted ice thickness, metres	ND	ND	ND	ND	1,0 to 2,0	1,0 to 3,0	1,0 to 2,0	1,0 to 3,0
Rubble fields	Sail height, metres	ND	ND	ND	ND	1 to 2	1 to 3	2	1 to 3
	Length, metres	ND	ND	ND	ND	300 to 1 000	300 to 1 000	300 to 1 000	300 to 1 000

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Ridges (FY)	Sail height, metres	1,7 to 2,0	1,5 to 2,5	2,0 to 2,2	1,0 to 2,5	1 to 2	1 to 3	2	1 to 6
	Keel depth, metres	ND	ND	ND	ND	10	8 to 15	10	6 to 26
Stamukhi	Water depth range, metres	ND	ND	None	None	None	None	None	None
	Sail height, metres	ND	ND	None	None	None	None	None	None
Level ice (second- and MY)	Floe thickness, metres	1,8 to 2,4	ND	3,4 to 3,9	2,0 to 5,0	None	None	2 to 4	2 to 6
Ridges (second- and MY)	Sail height, metres	ND	ND	ND	ND	None	None	1 to 2	1 to 3
	Keel depth, metres	ND	ND	ND	ND	None	None	4 to 8	4 to 10
Ice movement	Speed in nearshore, metres per second	ND	ND	ND	ND	0,2 to 0,3	0,1 to 0,3	0,1 to 0,2	0,1 to 0,3
	Speed in offshore, metres per second	0,10 to 0,15	ND	0,15 to 0,20	ND	0,3 to 0,5	0,3 to 0,5	0,2 to 0,3	0 to 1,1

B.9 Bering Sea

B.9.1 Description of region

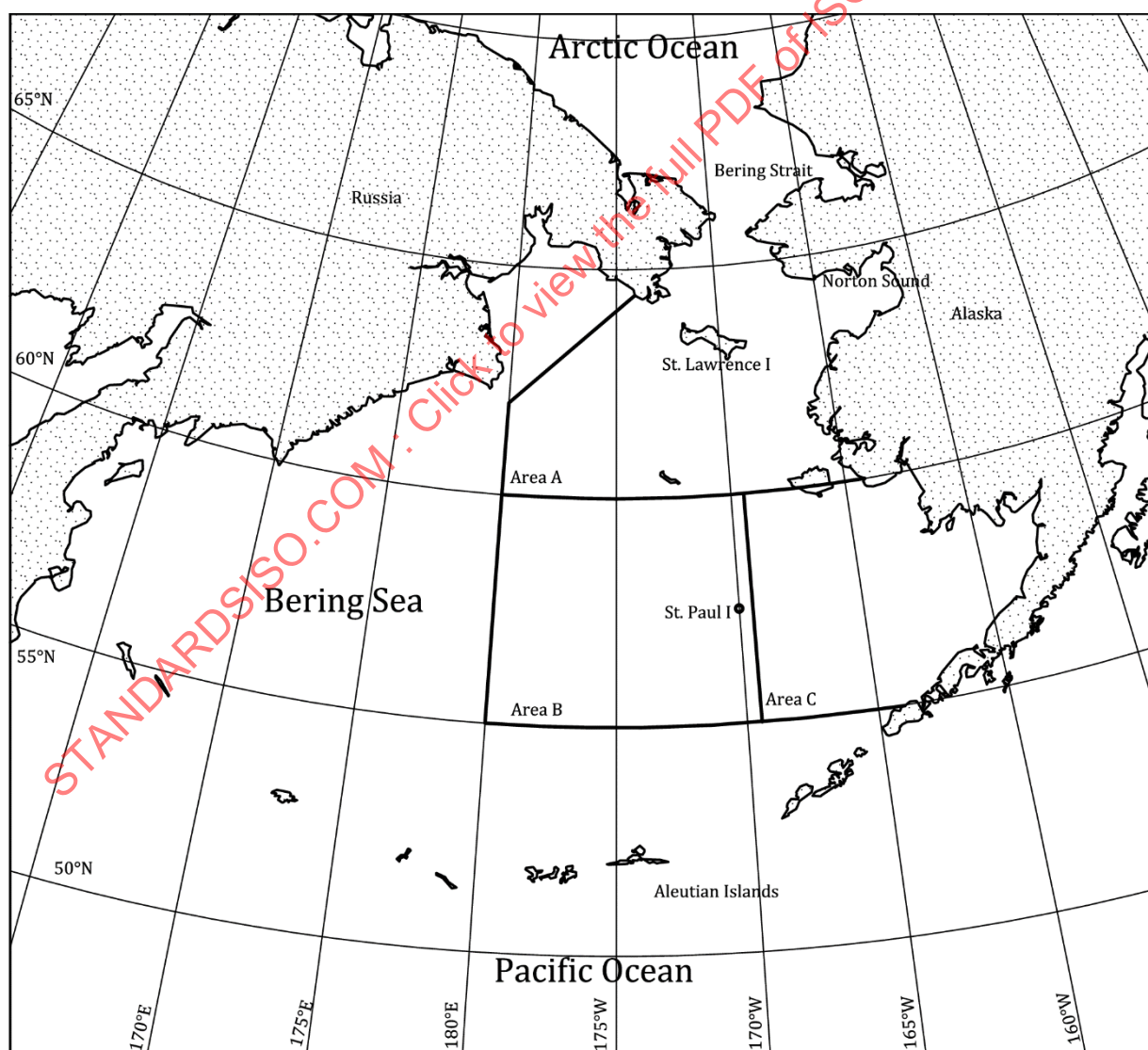
The Bering Sea separates the northern portion of the North American continent, i.e. Alaska, from the Asian continent, specifically the Russian mainland provinces of Chukotka and Kamchatka. The southern boundary of the Bering Sea is the Aleutian Island chain (at approximately 51 °N) and the northern boundary is the Bering Strait at 66 °N.

The Bering Sea is composed of a northeastern shelf with water depths shallower than 200 m and a deep basin in the southwest with water depths greater than 3 000 m. Deep channels in the Aleutian Island chain allow waters from the North Pacific Ocean to mix with Bering Sea water, while the Bering Strait, with a water depth of 50 m and less, provides exchange with the Arctic Ocean.

Table B.9-1 — General information for the Bering Sea

Area of coverage	60 °N to 65 °N, US regions east of 180 °W	55 °N to 60 °N, 169 °W to 180 °W	55 °N to 60 °N, 169 °W to 180 °W	60 °N to 65 °N, Russian regions west of 180 °W
Length of winter season, days	180	135	180	210
Length of summer season, days	185	230	185	155
Water depth range, metres	50 to 200	50 to 3 000	0 to 200	0 to 200

Only the northern portion of the Bering Sea, generally the region north of the 200 m isobath, is ice covered during the winter. Figure B.9-1 shows regions for which environmental information is provided in the table. Information for the Russian coastal region north of the 60° latitude line is also provided.

Figure B.9-1 — Map of the Bering Sea^[484]

B.9.2 Bering Sea technical information

B.9.2.1 Climate

The climate of the Bering Sea is affected by storms coming from the Pacific Ocean that enter the Bering Sea in the southwest and head towards the Bering Strait or the Norton Sound region. A secondary storm track, more common in winter, is for storms to come off the Russian mainland and head southeast. Storms are most severe in autumn and winter.

Due to the presence of open water in the southwest, the winter air temperature is generally warmer in the southwest and colder in the ice-covered regions of the northeast. In December, the minimum temperatures are -4°C to -6°C in the southwest and -38°C to -40°C in the northeast. Minimum air temperatures along the Russian coast are slightly warmer and are in the range of -28°C to -32°C . Maximum air temperatures are highest in July to August, when temperatures of 12°C are found in the central Bering Sea and 16°C to 20°C are found in coastal regions.

Water temperatures range from lows of -2°C (northeast) to 8°C (south central) in winter to highs of 2°C (Bering Strait) to 14°C (off the Aleutian Islands) in summer.

Precipitation is lightest in June and July with less than 10 % of all observations reporting any form of precipitation except for coastal regions, where this value increases to 20 % off the Russian coast and to 30 % off the Alaskan coast. Reports of precipitation increase subsequently until December when 40 % of all observations in the central Bering Sea report some form of precipitation. A decrease in precipitation of 15 % to 20 % is reported along the coastal regions. These values remain fairly constant through the winter then start to decrease in April and May.

The presence of fog increases from the ice covered periods when it is rarely found (less than 5 % of all observations reported fog) to July and August, when 10 % to 15 % of all observations report visibility of less than 1 km. In September, the presence of fog decreases significantly with 5 % of all observations reporting visibility of less than 1 km. These values hold through autumn until the period of ice formation, when 5 % to 10 % of all observations report visibility of less than 1 km. After ice formation, the presence of fog again decreases.

Wind speeds are lowest in June and July with average speeds around 6 m/s found in the northern and central parts of the sea and slightly higher speeds along the Aleutian Islands. Wind speeds increase through autumn and by November average greater than 10 m/s, except along the Russian coast where they are slightly lower, 8 m/s to 9 m/s. Average wind speeds stay at speeds greater than 10 m/s through winter, except for the northern ice covered regions where they decrease to 8 m/s to 9 m/s. In March and April, speeds again start to decrease towards the low values of June and July, except for the Aleutian Islands where average speeds remain in the greater than 10 m/s range.

Winter winds in the northern Bering Sea are generally from the north and northwest, while the southern regions have a fairly evenly distributed direction. Summer winds in all regions have an even wind direction distribution.

B.9.2.2 Hydrology

Currents in the Bering Sea are variable, with significant exchange of water with the North Pacific Ocean through channels in the Aleutian Islands. There have been reports that, during the summer, there is a closed anti-clockwise eddy-type feature in the southwest deep basin with speeds of less than 0,5 m/s, northward flowing waters in the central Bering Sea with speeds of greater than 0,5 m/s, a second anti-clockwise eddy feature south of St Paul Island with speeds less than 0,2 m/s and a weaker anti-clockwise flow in area C of Figure B.9-1. In the northern Bering Strait, current flow is mainly northwards, sometimes at speeds greater than 1,0 m/s, but reversals of flow through the strait have been reported^{[485][486]}. In winter, these features are less pronounced and the entire open water region in the southwest appears to have an anti-clockwise flow. Flow in the north is still mainly towards the Bering Strait, but at a reduced speed of less than 0,2 m/s with reversals due to the passage of storms.

The tracking of ice floes has shown that in winter, the Bering Sea surface currents are generally north to south due mainly to northerly winds. Ice is continually grown in the north, drifts south under the influence of these winds and melts at the southern ice edge near the 200 m isobath^[487].

Most of the Bering Sea is of the mixed tide type, but Norton Sound has a diurnal tide and some of the central Alaskan coast and northern Russian coast have a semi-diurnal tide. The tidal range in most of the Bering Sea is less than 0,6 m. A slightly higher tidal range of 0,6 m to 1,2 m is found in Norton Sound, but in the inner regions of area C of Figure B.9-1 the tidal range can reach 5 m.

The mean wave height from May to August is less than 1,0 m, but starts to increase in September. By November, it is greater than 2,0 m and it stays at this value in the open water regions until March, when it starts to decrease back to a value less than 1,0 m.

Ice starts to form in northern coastal regions in October and, by November, sea ice starts to grow in the northern offshore region. It reaches its maximum extent by late March and by June is found only in the northern and Bering Strait regions. The Bering Sea is entirely ice-free by the middle to the end of July. The extent of sea ice is greatly influenced by wind, as a prolonged northerly wind pushes ice further southward at reduced concentrations while a prolonged southerly wind compresses the ice northwards and creates high ice concentrations. The wind also creates polynyas behind the large islands of the Bering Sea, some of which can be up to tens of kilometres in extent.

Most of the ice found in the Bering Sea is locally grown and, since it is ice-free in summer, the ice is of the FY type. Reports of MY ice passing through the Bering Strait during a reversal can be found in the literature, but this ice generally stays north of St Lawrence Island. Stamukha type features can be found in Norton Sound, especially in the eastern and southern regions where a higher tidal range is present. All FY ice features are present in the Bering Sea. As there are no glaciers found in the Bering Sea coastal regions, icebergs are not a concern.

Table B.9-2 — Bering Sea meteorological conditions

Parameter		Offshore Alaska area A		Offshore Alaska area B		Offshore Alaska area C		Offshore coastal Russia	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	16	14 to 20	14	12 to 16	18	14 to 20	16	14 to 20
	Minimum, degrees Celsius	−36	−32 to −40	−20	−18 to −24	−28	−24 to −32	−30	−24 to −36
	Freezing Degree Days	2 300	ND	200	ND	1 500	ND	ND	ND
Wind speed at 10 m elevation	10 min average, metres per second	25	23 to 28	28	27 to 30	29	27 to 30	32	29 to 35
Wind direction	Dominant winter (direction/ percentage occurrence)	NE/40	ND	NE/25	ND	N to NE/40	ND	N to NE/45	ND
	Dominant summer (direction/ percentage occurrence)	SW/20	ND	SE to W/60	ND	SW to W/45	ND	None	ND
Precipitation	Annual rainfall, millimetres	600	ND	590	ND	500	ND	ND	ND
	Annual snowfall, millimetres	1 400	ND	1400	ND	1 200	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility <1 km	115	ND	130	ND	110	ND	120	ND