
**Underwater acoustics — Measurement
of radiated underwater sound from
percussive pile driving**

*Acoustique sous-marine — Mesurage du son sous-marin émis lors de
l'enfoncement de pieux marins*

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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 on 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 the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 3, *Underwater acoustics*.

Introduction

This document was written to provide a standardized measurement method for the measurement of the radiated underwater sound during percussive pile driving.

Sound is often an unintended by-product of man-made activities, and the increasing number of sound-producing human activities in oceans, seas, lakes, rivers and harbours have led to concern over noise pollution from unwanted sound and its potential effect on aquatic life. In some countries, there is already incipient regulation with regard to the impact of the radiated underwater sound, requiring acoustic monitoring for environmental impact assessment during construction projects.

Percussive pile driving can be a significant source of low-frequency impulsive underwater sound. During the process, a pile is driven into the seabed (or river-bed, etc.) using a hammer, which is typically driven hydraulically. Such a technique is commonly used to position piles in shallow water construction applications. Examples of such applications include the following:

- construction of offshore wind farms;
- construction and mooring of platforms for the offshore oil and gas industry;
- construction of bridge supports and foundations in rivers, estuaries, harbours and quays (and close proximity to them);
- mooring and positioning of aquatic renewable energy devices.

In the scientific literature, a number of attempts to measure the water-borne noise levels have been reported^{[1]-[13]}. Often, these are difficult to compare because different acoustic metrics are used, and this has led to guidance being provided to address the need within individual countries^{[14]-[16]}. The measurement of piling noise is made difficult by a number of factors.

- The source extends from the water surface to the seabed (or river-bed, etc.), generating sound waves in water, air and seabed, and vibrating the seabed surface.
- The environment is often shallow water which gives rise to substantial reverberation, and bathymetric features and seabed (or river-bed, etc.) interaction can strongly influence the propagation of the sound.

Often, simple assumptions about equivalent point sources have been used in measurements and for propagation modelling without sufficient validation. Progress with modelling the source has been reported in the scientific literature, but a complete understanding has not yet been achieved^{[17]-[22]}.

The aim of this document is to provide procedures and methodologies for measurement of sound radiation into the water, and recommend acoustic metrics to describe the sound field. The assessment of impact of the radiated sound on marine life is not part of the scope of this document.

Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving

1 Scope

This document describes the methodologies, procedures, and measurement systems to be used for the measurement of the radiated underwater acoustic sound generated during pile driving using percussive blows with a hammer.

A major motivation for undertaking measurements of the sound radiated during percussive pile driving is as part of an assessment of impact on aquatic fauna required by regulatory frameworks. This document describes a generic approach to measurements that can be applied to different regulatory requirements.

This document is suitable for measurement of percussive pile driving undertaken for offshore installation of foundations (monopiles, jackets, tripods, etc.) used in construction of offshore wind farms, oil and gas platforms, and other inshore structures such as bridge foundations and aquatic renewable energy devices. This document does not cover measurement of the sound radiated by vibro-piling or sheet piling. This document does not cover piling in water of depth less than 4 m or greater than 100 m.

The procedures described herein provide guidance on making measurements to satisfy the following objectives:

- to monitor source output during piling, for example, for regulatory purposes;
- to provide consistency in comparison of piling noise from different construction projects;
- for validation of modelling or predictions.

This document covers only the measurement of the sound field radiated during percussive pile driving. The scope of this document does not include the assessment of exposure metrics, or the use of exposure criteria. No attempt is made to prescribe a methodology for generating maps of the acoustic field in the vicinity of the source.

In the normative part of this document, requirements and procedures are described for measurement of the sound field at specific ranges from the pile being driven. In this part of the document, no procedure is provided for determination of an acoustic output metric that is independent of the propagation path between source and receiver (such as a source level). Ideally, such a metric would have some predictive utility (for example, in calculating noise impact zones and noise maps). However, some information on the determination of a possible acoustic output metric is provided in [Annex A](#).

This document covers only the measurement of *sound pressure* in the water column. The scope does not include measurement of sound particle velocity in the water column due to the propagating sound wave, or seabed vibration caused by waves propagating across the sea-floor. This exclusion does not imply that such measures are unimportant; indeed, their importance in assessing the impact on aquatic life is recognized. However, at the time of drafting, measurement of these quantities is not yet mature enough for standardization.

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.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 18405 (especially: sound pressure, sound pressure level, mean-square sound pressure level, sound exposure, sound exposure level, peak sound pressure, peak sound pressure level) and the following apply.

NOTE Although the definitions of sound exposure and sound exposure level are taken from ISO 18405, specific nomenclature is used in this document for sound exposure level calculated over the duration of one acoustic pulse, and over the duration of multiple acoustic pulses; this nomenclature is described in 3.2.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

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

3.1

pulse duration

percentage energy signal duration over the acoustic pulse

Note 1 to entry: The percentage energy signal duration is defined in ISO 18405.

Note 2 to entry: The energy percentage over which the pulse duration has been calculated should be stated with the result. For the purposes of this document, the energy percentage for the pulse duration is 90 %.

Note 3 to entry: In general, in shallow water, the acoustic pulse includes multiple arrivals of the outgoing acoustic waves, including multi-path signal arrivals from surface and seabed. In reverberant environments such as harbours, where sound waves may be reflected by boundaries such as harbour walls, it may be difficult to identify individual outgoing acoustic pulses.

3.2

sound exposure level

SEL

level of the sound exposure, for a specified reference value

Note 1 to entry: The sound exposure level is as defined in ISO 18405.

Note 2 to entry: The sound exposure level for an individual acoustic pulse (corresponding to a single hammer strike) is calculated over the pulse duration on the basis of 100 % of the pulse energy. For the purposes of this document, this is termed the *single strike sound exposure level* (abbreviated as SEL_{SS}). It is recognized that in the scientific literature, this parameter is sometimes called the single pulse sound exposure level.

Note 3 to entry: The sound exposure level over a defined period of time, which includes multiple acoustic pulses, is, for the purposes of this document, termed the *cumulative sound exposure level* (abbreviated as SEL_{CUM}). When reporting the cumulative sound exposure level, the number of pulses and the time duration over which the cumulative sound exposure level has been calculated are stated.

Note 4 to entry: In the acoustic near field, sound exposure is not related to the sound intensity or energy in the straightforward manner that applies for the acoustic far field. Therefore, care should be taken when interpreting measurements of SEL made in the acoustic near field.

3.3

pulse repetition frequency

pulse repetition rate

number of hammer strikes per unit time

Note 1 to entry: Typically stated as the number of strikes (or acoustic pulses) per second.

Note 2 to entry: It is common for the pulse repetition frequency to be less than 1 per second.

3.4**background noise**

all sound recorded by the hydrophone in the absence of the pile driving signal for a specified pile driving acoustic signal being measured

3.5**measurement system**

data acquisition system consisting of, but not limited to, one or more hydrophone(s), conditioning preamplifier(s), analogue-to-digital converter(s), computer and ancillary peripherals

3.6**frequency range**

span from the lowest frequency to the highest frequency over which the measurement system is able to measure, for a given uncertainty

Note 1 to entry: The frequency range is expressed as the lowest frequency to the highest frequency.

3.7**dynamic range**

amplitude range over which a measurement system is able to measure, for a given tolerance of distortion, expressed as a range from the lowest to the highest amplitude

Note 1 to entry: Dynamic range can also be expressed in decibels representing the difference between the level of the noise floor created by the system self-noise and the maximum level which can be measured with a specified maximum allowable distortion. It can be expressed for a single frequency or at a range of frequencies.

3.8**field calibration**

method of using known inputs, possibly using physical stimuli (such as a known and calibrated/traceable acoustic or vibration source) or electrical input (charge or voltage signal injection) at the input (or other stage) of a measurement system in order to ascertain that the system is, in fact, responding properly (i.e. within the system's stated uncertainty) to the known stimulus

[SOURCE: ISO 17208-1:2016, 3.9]^[23]

3.9**measurement uncertainty**

estimate of the range (or dispersion) of values within which the true value is considered to lie to a specified degree of confidence (for example, for a confidence level of 95 %)

[SOURCE: ISO/IEC Guide 98-3:2008]

3.10**hydrophone**

underwater sound transducer that provides an electrical signal in response to fluctuations in pressure, and is designed to respond to the pressure of a sound wave

Note 1 to entry: If the electrical signal is proportional to the incident sound pressure, the hydrophone is said to have a linear response.

3.11**hammer energy**

kinetic energy of the hammer used for the pile driving for a specific blow

Note 1 to entry: This is equal to the kinetic energy with which the hammer mass strikes the pile.

Note 2 to entry: The hammer energy is expressed in kJ.

3.12**pile dimensions**

dimensions of the pile in terms of the overall length, diameter and wall thickness (if hollow)

3.13

offshore

marine area, including coastal areas, regional seas and continental shelf, but excluding harbours, coastal inlets, inland waterways, river estuaries, and rivers

3.14

inshore

marine or aquatic region, including harbours, coastal inlets, inland waterways, river estuaries, and rivers, but excluding regional seas, continental shelf and coastal areas

3.15

equivalent bandwidth noise pressure

p_w
ratio of the root-mean-square noise voltage at a specified central frequency in the relevant frequency band present at the electrical terminals of the hydrophone, in the absence of pressure fluctuations at the hydrophone input, to its free-field open-circuit hydrophone voltage sensitivity at a specified frequency

Note 1 to entry: Equivalent bandwidth noise pressure is expressed in pascals, Pa.

[SOURCE: IEC 60500:—][24]

3.16

equivalent bandwidth noise pressure level

ten times the logarithm to the base 10 of the ratio of the square of the value of equivalent bandwidth noise pressure, p_w , of a hydrophone to the square of a reference pressure, p_0 , in decibels

Note 1 to entry: Equivalent bandwidth noise pressure level is expressed in decibels, dB.

Note 2 to entry: The value of the reference pressure, p_0 , is 1 μ Pa.

[SOURCE: IEC 60500:—][24]

3.17

signal-to-noise ratio

ratio of the mean-square broadband signal voltage after all processing to the mean-square broadband noise voltage after all processing

Note 1 to entry: The noise voltage is the voltage caused by non-acoustic noise and background noise.

Note 2 to entry: The time duration for the mean-square operation on the signal voltage and the background noise voltage shall be the same. This averaging time is specified with the value of signal-to-noise ratio.

Note 3 to entry: As a broadband quantity, the signal-to-noise ratio is evaluated over a specified frequency band. This may be the entire range of interest, which for this document is a minimum of 20 Hz to 20 kHz, or a specific frequency band such as a third-octave band. The applicable frequency band is stated with the value of the signal-to-noise ratio.

Note 4 to entry: The signal-to-noise may be expressed as a level difference in decibels.

3.18

system sensitivity

quotient of the root-mean-square open-circuit voltage at a specified point in the measurement system (usually the electrical output terminals) to the incident root-mean-square sound pressure that would be present at the position of the reference centre of the hydrophone in the undisturbed free field if the hydrophone was removed for specified frequency and specified direction of plane wave sound

Note 1 to entry: The system sensitivity is defined here for an acoustic measurement system designed to measure sound pressure signals in water. The measurement system will typically consist of hydrophone(s) connected to amplifier(s) and filter(s), and will feed an output voltage into a digital acquisition and storage system. Note that the response of the hydrophone(s), amplifier(s) and filter(s) will in general vary with acoustic frequency.

Note 2 to entry: The system sensitivity is defined here as an acoustic free-field sensitivity using the free-field sensitivity of the hydrophone. If the hydrophone is physically attached to the body of an acoustic recorder (rather than deployed on an extension cable), diffraction and scattering of sound by the recorder body may affect the free-field sensitivity at kilohertz frequencies, causing enhanced directivity compared to the response of the free hydrophone.

Note 3 to entry: The system sensitivity is described in terms of the electrical voltage developed per pascal of acoustic pressure, and is stated in units of V/Pa. The sensitivity *level* is sometimes expressed in decibels as dB re 1 V/ μ Pa. The system sensitivity accounts for the response of the hydrophone(s), gain of amplifiers, and insertion loss of filters within the system.

Note 4 to entry: For *digital* systems, where the system records the sound as a digital waveform (rather than providing an analogue voltage output), the calibration of the digitiser (analogue to digital converter) may be incorporated into the overall sensitivity of the whole system including the digitizer. This may be termed the *digital system sensitivity*, which is the number of digital counts per unit change in sound pressure (unit Pa⁻¹).

Note 5 to entry: In general, the measuring system may introduce a phase delay into the measured signal. This may be accounted for by representing the system sensitivity as a complex valued quantity, the modulus of which represents the magnitude-only response (and is described by the definition above), and the phase of which describes the phase response of the system. Note that the complex-valued system sensitivity will in general vary with acoustic frequency.

[SOURCE: IEC 60500:—]^[24]

4 Instrumentation

4.1 General

This clause deals with the choice of measuring instrumentation and the key performance specifications, system calibration, and data quality assurance.

The measuring system generally consists of the following instruments:

- hydrophone(s);
- amplifier(s) and signal conditioning equipment;
- digitization and storage equipment.

The amplifier can be a separate element in the system with an adjustable gain, or may be an integral part of the hydrophone with no possibility for gain adjustment. Digitization is provided by an analogue to digital converter (ADC) and the electronic storage is typically provided by a computer hard drive or flash drive memory.

The measuring system may consist of individual components, as listed above, or an integrated system forming part of an autonomous recorder that provides a self-contained recording system.

4.2 Performance of the measuring system

4.2.1 Sensitivity

The sensitivity of the measuring system should be chosen to be an appropriate value for the amplitude of the sound being measured. The aim in the choice of the system sensitivity is to

- avoid poor signal-to-noise ratio for low amplitude signals, and
- avoid nonlinearity, clipping and system saturation for high amplitude signals.

NOTE 1 It is the latter of these two criteria that is most important for measurement of percussive pile driving because it is a high amplitude source, and distortion of the measured signal will render the results of no value. To build in some flexibility, it is preferable to have some selectable gain in the amplification stages, or in the settings of the ADC. These can then be set to appropriate values once the sound levels are known after some initial measurements. However, note that for autonomous recorders and hydrophones which have integral preamplifiers, the gain cannot usually be modified after deployment.

NOTE 2 If measurements of background noise are necessary then it might not be appropriate to use the same hydrophone or gain setting for the background noise measurements as those used for the measurement of the noise radiated from the pile-driving. For measurement of background noise, a hydrophone with low-noise performance and high sensitivity is generally preferred.

NOTE 3 The sensitivity is described in terms of the electrical voltage developed per pascal of acoustic pressure, and is stated in units of V/Pa. The sensitivity *level* is often expressed in decibels as dB re 1 V/ μ Pa. Where the system records the sound as a digital waveform (rather than providing an analogue voltage), the sensitivity is expressed in digital counts per pascal. Note that the range of numerical values produced by an ADC relate to the number of bits used in the conversion, the full voltage range allowed for the analogue signal being represented by values covering a range equal to 2^N where N is the number of bits of the ADC. For example, a 16 bit ADC represents the full scale voltage range with 2^{16} values (e.g. -32 768 to +32 767), which is equivalent to a dynamic range of approximately 96 dB.

NOTE 4 Note also that if extra cable is added to a hydrophone which does not have an integral preamplifier, this will reduce the overall sensitivity for the hydrophone due to the extra electrical loading caused by the capacitance of the extension cable. Either the hydrophone is calibrated with the extension cable connected, or the effect of the electrical loading is calculated. See [Annex B](#) for details. For hydrophones that have an integral preamplifier within the hydrophone body, adding extension cable will not affect the sensitivity.

4.2.2 Frequency range and sampling rate

The frequency response of the measuring system shall extend to a high enough frequency to faithfully record all frequency components of interest within the measured signals. This requires that the hydrophone, and any amplifier and filter, be sufficiently broadband.

For the measurement of percussive pile driving, at minimum the system frequency range shall extend from no more than 20 Hz to no less than 20 kHz.

NOTE 1 In general, when selecting a suitable minimum frequency range for the measurements, consideration of the hearing abilities of the relevant receptors is given on a case by case basis. However, note that measurements at acoustic frequencies of less than 20 Hz are difficult in very shallow water where low frequency waves do not propagate. In addition, at such low acoustic frequencies, contaminating signals due to artefacts such as flow noise and cable strum become more prevalent (see [5.3](#)).

NOTE 2 The requirement for unambiguous representation of the signals within the desired frequency range requires the sampling rate, f_s , of the ADC within the recording system to be greater than the Nyquist rate of the signal which is input to the ADC. Where the measured data are to be represented in one-third octave bands, the maximum frequency of interest will be the upper limit of the maximum one-third octave frequency band of interest.

NOTE 3 It is desirable that the system sensitivity be invariant with frequency over the frequency range of interest (i.e. that it possess a “flat response”), to within a tolerance of 2 dB. Note that it is possible to correct for the variation in the sensitivity with frequency with better accuracy than the above tolerance if the hydrophone and measuring system is calibrated over the full frequency range of interest.

NOTE 4 The one-third octave bands are calculated using either base-10 or base-2, and the choice is stated when presenting the results. The two calculation methods will give slightly different results, and base-10 is the preferred method (IEC 61260-1). (Note that the base-10 representation of a one-third octave band is referred to as a “decidecade” in ISO 18405).

4.2.3 Directivity

The hydrophone used shall have an omnidirectional response such that its sensitivity is invariant with the direction of the incoming sound wave to within a tolerance of 2 dB over the frequency range of interest.

NOTE 1 This requirement is not difficult to satisfy at frequencies up to 20 kHz. However, one issue that can cause enhanced directionality is where the hydrophone is deployed close to another structure that is capable of reflecting the sound waves. The combination of the direct and reflected waves causes interference, the nature of which will change depending on the arrival angle for the sound wave. This effect can be evident at kilohertz frequencies if the hydrophone is deployed close to a support structure such as a heavy mooring or support, or a recorder case that houses electronics and batteries but is mostly air-filled. Similarly, if the hydrophone has a guard deployed around it (a protective cage to prevent damage of the element by impacts), this can influence the directivity at kilohertz frequencies. If necessary, the above effects can be quantified by directional response measurements of the hydrophone together with the mounting, in a free-field environment.

4.2.4 Signal-to-noise ratio requirements

A signal-to-noise ratio of at least 10 dB (expressed as a level difference) shall be required for measurements.

NOTE 1 When considering signal-to-noise ratio, all contributions to noise are relevant. These include system self-noise (4.2.5) and platform-related deployment noise (5.3.1) as well as background noise (3.4).

NOTE 2 For measurements of percussive pile driving where high amplitude signals are commonplace, this criterion is only likely to be challenging at significant range from the source (tens of kilometres).

4.2.5 System self-noise

To achieve acceptable signal-to-noise ratio when measuring acoustic signals, the system self-noise (expressed as the equivalent bandwidth noise pressure level) shall be at least 10 dB below the lowest signal level (expressed as the mean-square signal voltage after all processing) to be measured in the frequency band of interest.

NOTE 1 In the context considered here, the system self-noise is considered to be the noise originating from the hydrophone and recording system (for considerations of deployment and platform noise, see 5.3). The system self-noise is the noise generated by the system *in the absence of any signal due to an external acoustic stimulus*. This noise is electrical in nature and is generated by the hydrophone itself and any electronic components such as amplifiers and ADCs. This is normally expressed as an equivalent bandwidth noise pressure level. With a typical recording system, it is possible for the spectral density of the equivalent bandwidth noise pressure to approach the Knudsen sea-state zero levels (which include distant shipping noise) at 63 Hz and 125 Hz, the values for which are approximately 64 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ and 59 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ respectively^[25].

NOTE 2 For good quality measurements of background noise, a measuring system with sufficiently low self-noise is used. It might not be appropriate to use the same hydrophone for the background noise measurements as that used for the measurement of the sound radiated from the pile-driving. For measurement of background noise, a hydrophone with low-noise performance and high sensitivity is generally required. For a system designed to measure very low sound levels, a maximum system self-noise of 47 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ at 63 Hz and 43 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ at 125 Hz is preferred^[25].

4.2.6 Dynamic range

The system dynamic range shall be chosen to be sufficient to enable the highest expected sound pressure, at the measurement position, to be recorded faithfully without distortion or saturation caused by the hydrophone, amplifier, and ADC.

NOTE 1 The dynamic range of the measuring system is the amplitude range over which the system can faithfully measure the sound pressure. This ranges from the noise floor of the system (which defines the lowest measurable signal) to the highest amplitude of signal that can be measured without significant distortion.

NOTE 2 High amplitude sounds which are beyond the maximum capability of the measuring system will cause distortions in the measured data. For example, clipping can occur where the peaks of the signal are missing from the data (the peaks being truncated at the full-scale value of the system ADC). The measuring system is required to be linear over the full dynamic range, requiring that the system sensitivity is constant over the full range of measurable sound pressure. Systems with dynamic ranges of in excess of 60 dB are preferred for measurement of pile driving noise. For some systems, when approaching the high amplitude limit, the response might no longer be linear due to limits in the performance of components such as amplifiers. Therefore, it is advisable that a measurement system is not used close to the limit of its dynamic range unless the linearity has been checked.

NOTE 3 A method to mitigate problems with dynamic range is to have some flexibility in the sensitivity, often achieved by use of adjustable gains for amplifier stages and scale settings on ADCs. However, where a system has been deployed remotely (for example, an autonomous recording system), control over the system settings after deployment might not be possible. In this case, some knowledge of the likely range of sound pressure levels is required to optimize the available dynamic range (this knowledge can be obtained from reported levels in the scientific literature or from approximate theoretical calculations).

4.3 Calibration

4.3.1 Full system calibration

The full measuring system shall be calibrated over the full frequency range of interest indicated in [4.2.2](#).

The components that require calibration are as follows:

- hydrophone;
- amplifiers;
- filters;
- analogue to digital converter (ADC) – the range setting (full-scale) and the calibration factor of the ADC shall be known.

The calibration of the hydrophones shall be traceable to national or international standards. The hydrophone calibration should conform to IEC 60565.

NOTE 1 It is possible to calibrate a hydrophone and recording system with an overall uncertainty of better than 1 dB (expressed at a 95 % confidence level). It is preferred that the time duration between full laboratory calibrations is not more than two years, and that a field calibration check (see [4.3.2](#)) be carried out before and after every major deployment or sea-trial^[26].

NOTE 2 Hydrophone calibration data are typically expressed at a succession of discrete frequencies, or in the form of a calibration curve. If the recorded data are already processed into one-third octave bands before the correction for hydrophone sensitivity is applied, the required calibration values are the mean sensitivities for each of the frequency bands. Where the hydrophone sensitivity is not flat, a constant value across the band cannot be assumed.

NOTE 3 Amplifier performance is typically expressed as a gain factor, either in terms of a linear gain (e.g. x10) or in decibels (e.g. 20 dB). Note that the amplifier gain might vary with frequency, particularly at the extremes of the operating frequency range.

NOTE 4 The filter performance is typically expressed as an insertion loss factor, a positive number expressed either as a linear factor or in decibels. By definition, a filter response varies with frequency, and is fully characterised over the full operating frequency range of the system.

NOTE 5 The range setting (full-scale) and the calibration factor of the ADC will depend on the digital amplitude output values (counts) of the ADC for a stated input voltage, and is typically expressed as counts per volt.

4.3.2 Field calibration checks

In-situ field checks on the system calibration should be undertaken just before and after deployment and in between any repeated deployments.

NOTE 1 To do this, it is advisable to make use of a commercially available hydrophone-calibrator, which provides the hydrophone with a signal of known amplitude at a single-frequency (commonly 250 Hz). The calibrator typically consists of an air-pistonphone that generates a known sound pressure level inside a small coupler into which the hydrophone is inserted. The sound pressure depends on the free-volume inside the coupler when the hydrophone is inserted, and so the coupler is calibrated for each type of hydrophone that is used with it. Although the hydrophone calibrator provides a check at only one frequency, it does allow the entire system to be checked using an acoustic stimulus.

NOTE 2 It is also possible to undertake an electrical check calibration of the system components. If the hydrophone in use has an insert voltage capability (many commercial hydrophones with integral preamplifiers have this facility), this can be used to check the electrical integrity and perform a calibration by electrical signal injection. This is a useful technique when deploying long cabled systems from vessels, and can be performed without retrieving the hydrophones. However, the method does not perform an acoustical check on the hydrophone element.

4.4 Data storage

4.4.1 Data quality

If data compression formats are used in order to increase the storage capacity (and thereby the recording duration), the data compression techniques used shall be lossless, or the effect on the data quality shall be demonstrated. All analysis shall be carried out on uncompressed data.

4.4.2 Auxiliary calibration data

Any crucial auxiliary data or metadata that are needed for interpretation of the results should be recorded (for example, the scale factor or setting of the ADC, or the gains of any amplifiers, the sampling rate and the resolution).

NOTE It is desirable that such calibration data information be included in a file header or log file so that the information is kept with the data. Though a number of suitable data formats exist (for example, WAV file format), there is no standardised format for storing ocean noise data.

4.4.3 Longevity

If data storage is required to be long-term (many years), consideration should be given to the likely future compatibility of the storage media and data format. Note that some formats and storage media become obsolete over time.

5 Deployment for measurement

5.1 Deployment methodology

5.1.1 General

One of the following generic deployment methods shall be adopted depending on available resource and conditions.

5.1.2 Vessel based deployments

This involves deployment of hydrophones (either individually, or in arrays) from a vessel, with the analysis and recording equipment remaining on the vessel, which can be either anchored or drifting. The method has the advantage that deployments can be quick and mobile, and a relatively large area can

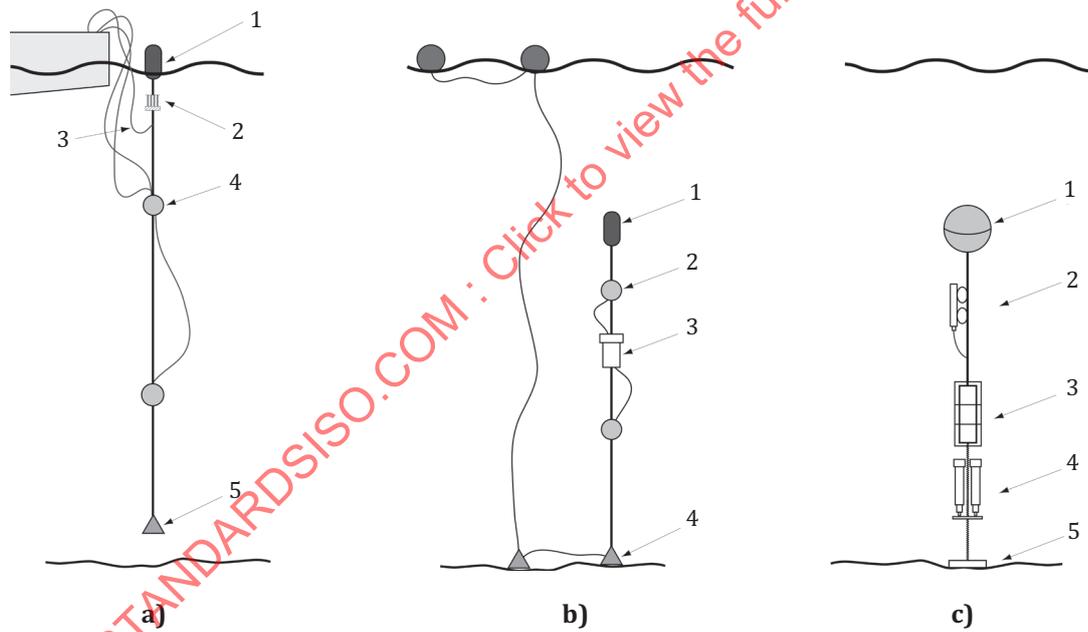
be covered fairly cost-effectively. The risk of losing instrumentation is low, the data can be monitored as they are acquired, and instrument settings can be adjusted in real time to provide the optimum settings for high quality data (for example to avoid saturation and distortion). This deployment method is suitable for measuring piling noise, especially if there is a need to measure the acoustic field as a function of range from the source. [Figure 1](#) shows an example of a vessel-based deployment configuration. Vessel-based deployments can suffer from certain types of platform-related noise (see [5.3](#) for further details).

5.1.3 Static deployments (moored systems)

Static systems are a good alternative to vessel-deployed systems. Each system provides a measurement at a fixed range for the duration of the piling sequence. This is very important when the source output varies with time (as commonly occurs with percussive pile driving). [Figure 1](#) shows an example of a fixed deployment configuration. Multiple units may be used to obtain measurements as a function of range.

A bottom-mounted deployment is preferable to a surface deployment to minimise parasitic signals from the influence of surface wave action, to keep the hydrophone away from the pressure-release water-air surface, and to minimise disturbance by surface vessels. Cost effective solutions for most deployments are autonomous recorders, which are archival and store data on memory cards or local drives with the data only available after recovery. Recovery requires either an acoustic release system or a surface buoy deployed from a seabed anchor, which enables the recorder to be hauled to the surface.

NOTE A number of typical deployment configurations are possible, many of which are presented in the scientific literature [\[27\]-\[30\]](#).



Key

- | | | |
|---------------------|-------------------|--------------------|
| a) | b) | c) |
| 1 surface buoy | 1 subsurface buoy | 1 subsurface buoy |
| 2 suspension device | 2 hydrophones | 2 hydrophones |
| 3 retrieval rope | 3 recording pod | 3 recording pod |
| 4 hydrophones | 4 bottom anchor | 4 acoustic release |
| 5 weight | | 5 weight |

Figure 1 — Examples of deployment configurations deployed from a) surface vessel, b) bottom-mounted with surface float, and c) bottom-mounted with acoustic release¹⁾

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5.1.4 Drifting systems

Drifting systems typically consist of a hydrophone and recorder attached to a drogue or sea-anchor which causes the whole system to drift with the prevailing current. These have the advantage that the effects of flow noise are minimised in high tidal flow areas. A GPS receiver is used to provide a log of positional data. Note that a synchronized time stamp on the audio-track is needed to accurately link to the GPS time.

A drifting system does not make a measurement in one location and there is limited control with regard to the direction of travel. The range from the source is a crucial parameter and this will be constantly changing as the system drifts past the source. This problem can be mitigated if the drifting system has a GPS receiver to provide positional data from which the range can be calculated, but the azimuth angle from the recorder to the source will also tend to change as the system drifts past the source. It is possible to use several drifting systems at once to partially get around the problem with directivity. Also, use of several systems at once allows the separation of time-dependence from spatial-dependence for time-varying sounds.

5.2 Hydrophone deployment

5.2.1 Hydrophone deployment depth in offshore waters

The measuring hydrophone shall be positioned in the lower half of the water column, between a height 2 m above the sea floor and one-half the total water depth (measured from the sea surface)^{[15][16]}.

The spatial distribution of underwater sound pressure is depth dependent. A stronger dependence on depth is present in the upper quarter of an acoustic wavelength in the water column. For this reason, the hydrophone shall not be placed close to the water surface. For measurements in inshore waters, see 5.2.2.

NOTE 1 In some cases, there is a need to select other hydrophone depths, for example, if the depths stated above are impractical or if there is a specific interest in the impact of noise on species that reside closer to the sea bottom or near the sea surface. Percussive pile driving can generate surface waves on the seabed around the pile. The sound pressure and sound particle velocity associated with these waves decrease quickly when moving away from the seabed. Therefore, if there is a desire to investigate the levels of sound that might impact on bottom-dwelling species, it is preferable to undertake measurements close to the seabed.

NOTE 2 If hydrophones are deployed from the surface in the presence of strong currents, note that the actual hydrophone position can be influenced by displacement of the cable under the influence of the current. Attaching a weight to the end of the cable will mitigate the effect, but to be sure of the hydrophone depths, it is possible to attach a depth sensor to the cables adjacent to the hydrophone.

5.2.2 Hydrophone deployment depth in inshore waters

For hydrophone measurements in inshore waters such as harbours and river estuaries, the hydrophone measurement depth shall be half of the water depth at the measurement location.

5.2.3 Number of hydrophones

Generally, the use of more than one hydrophone per measurement location has several advantages.

- *Redundancy*: If one hydrophone or measurement channel fails, there is a back-up.
- *Dynamic range*: Two hydrophones with different sensitivities may be chosen to mitigate the requirement for a larger dynamic range than can be covered by a single measurement hydrophone or channel.
- *Spatial averaging*: Use of more than one hydrophone allows averaging of the measured data.

If using two hydrophones, it is recommended that these be placed at two depths in the lower half of the water column, ideally between $\frac{1}{2}$ and $\frac{3}{4}$ of the total depth (measured from the sea surface) with the separation between hydrophones maximized (as far as reasonably possible)^{[15][16]}.

5.3 Minimization of platform-related deployment self-noise

5.3.1 General

In addition to the self-noise of the measuring system itself (see 4.2.5), the measured data can also be contaminated by signals originating from the platform or method of deployment. This is sometimes called “platform noise” or “deployment noise”. These parasitic signals are due to the deployment method for the hydrophone and recording system and its interaction with the surrounding environment (e.g. current, wave action, etc.). Care shall be taken in the design of the deployment systems to avoid contamination from these sources. Often, the presence of the contaminating signals is not easy to predict or to detect (even though it is present in the data). The platform-related deployment noise will in general add to the system self-noise (see 4.2.5) and to the background noise.

The following illustrates some of the more common sources of unwanted parasitic signals that contribute to the platform self-noise of the deployed system, and provides advice with regard to mitigation.

5.3.2 Flow noise

Care shall be taken to avoid contamination from flow noise. Any flow of the medium relative to the hydrophone or cable can induce turbulent pressure fluctuations at low frequency that will be sensed by a pressure sensitive hydrophone. This noise is produced in a turbulent layer around the hydrophone, and gives rise to low frequency signals (typically <100 Hz), with the frequency dependent upon the hydrophone diameter and the speed of the current. It can be the major source of deployment noise in high flow environments. For autonomous recorders where the hydrophone is protruding from the recorder body, the problem can be exacerbated by turbulent flow around the end of the recorder casing. Strong fluid flow can also cause vibration of moorings and excite resonances in the recorder body.

Mitigation: An acoustically-transparent shield (similar in effect to a “sonar-dome”) can be used. This moves the turbulent layer away from the hydrophone’s sensing element. However, this might not always be a practical solution. Alternatively, locate the hydrophone closer to the seabed where the current flow is reduced, or measuring at slack tide where the tidal current is minimised (not always practicable). The other main mitigation is to employ *drifting systems* where the system moves with the current and the relative motion of the hydrophone and medium is substantially reduced.

NOTE It is not always easy to check for the presence of flow-induced noise, but for long-term deployments, the recorded signals at low frequencies (<100 Hz) are likely to correlate with tidal information. The flow noise signal will show the same cyclic variations as the tides. If measurements have been made at both slack tide and at full tidal flow, it might be possible to quantify the effect of flow noise by comparison of the data.

5.3.3 Cable strum

Care shall be taken to avoid contamination from cable strum. This occurs when cables are pulled taut by the action of currents, and the cable is then caused to vibrate by the action of the water flow around it, producing parasitic low frequency signals.

Mitigation: The effect can be mitigated by use of bottom-mounted deployments, and by the use of mechanical fairings, often in spiral or helical form around cables and housings[27][28]. However, bottom deployed hydrophones on long riser cables can be subject to significant displacement and strum due to tidal flow. If surface deployments are used, decoupling of the hydrophone from suspension cables using compliant couplings (for example, using elastic rope or a flexible loop) will reduce the problem.

5.3.4 Surface heave

Care shall be taken to avoid contamination from surface heave effects. Any system deployed from the surface, for example, a system attached to a surface buoy or vessel, will have the potential to be affected by the action of waves or swell. Although the buoy or vessel will follow the surface movements, the hydrophone suspended in the water column is unlikely to be able to follow the movements of the water surface exactly, which will cause changes in the hydrophone depth of immersion creating very low

frequency hydrostatic pressure fluctuations detected by the hydrophone. These hydrostatic pressure fluctuations are sensed by the hydrophone and, although they are low frequency, they can have a relatively high amplitude and require a high system dynamic range to avoid distortion and saturation of the ADC in the recorder (see 4.2.6). For example, a 10 cm change in height of the water column above the hydrophone will cause a 1 kPa pressure change, equivalent to 180 dB re 1 μ Pa (a 100 cm change causing a pressure change of 10 kPa, equivalent to 200 dB re 1 μ Pa).

Mitigation: Mounting the hydrophone/recorder from the seabed rather than the sea surface, using a bottom-mounted frame or sub-surface buoy arrangement, will reduce the problem so long as the water is not so shallow that the hydrophone is close to the surface (the influence of surface water waves should be negligible). If surface deployments are used, decoupling of the hydrophone from the surface motion using compliant couplings (for example, using elastic rope and/or motion dampers) will reduce the problem (such a design is sometimes called an anti-heave suspension). Additionally, since the frequency of the signals is very low (<10 Hz), the use of a high pass electronic filter can eliminate the signals. However, this shall be placed before the ADC to avoid saturation. A number of commercial hydrophones that have integral preamplifiers have built-in high pass filters with a cut-off of between 5 Hz and 10 Hz as mitigation for low frequency parasitic signals.

5.3.5 Vessel noise

Care shall be taken to avoid contamination from vessel noise. Deployments undertaken from a vessel shall be made under conditions as quiet as possible within vessel operational constraints and safe working practices. Ideally, this means that the engines should be switched off, and as little noise as possible made on the vessel itself by machinery and crew (the engine condition during measurements shall be stated with the results). Preferably, the generator should be switched off to avoid noise. This requires that the measurement instrumentation be powered from batteries. If the vessel is anchored, the anchor chain can be a source of noise. If the echo-sounder on the vessel produces frequencies within the frequency range of interest, this shall also be switched off during the measurements. If the engine or auxiliary systems on the vessel are operational during measurements, the operator shall demonstrate that the requirements for signal-to-noise ratio are met (4.2.4).

Another source of noise from vessel deployments is the noise of wave action on the vessel hull (sometimes called “wave slap”). This can be reduced by orienting the vessel into the waves, and by deploying the hydrophones on long cables using floats or buoys to increase the distance from the vessel to the hydrophones; however, in practice this is difficult to eliminate completely.

5.3.6 Mechanical noise

Care shall be taken to avoid contamination from mechanical noise. This includes (i) debris and/or sediment impacting the hydrophone; (ii) biological abrasion noise; (iii) hydrophone and cables rubbing against each other; (iv) mooring cables rubbing together. Any opportunity for parts of the mooring system to impact against each other will cause noise, which can be picked up by the hydrophone. This is especially true if the mooring involves metal parts which can come into contact (for example, chains).

Mitigation: To minimize the problems: avoid using metal moorings if possible; avoid metal coming into contact with metal (such as with shackles); avoid the use of chains in the moorings and supports; avoid placing hydrophone so close to the seabed that sediment can impact on the hydrophone; avoid hydrophones touching the support cables by attaching them with vibration isolators (compliant couplings). It should also be noted that long-term deployments require servicing at intervals to remove biological fouling.

5.3.7 Electrical noise

Care shall be taken to avoid contamination from electrical noise. This can be a significant source of parasitic signals. For vessel-based deployments, preferably the generator and the inverter should be switched off (as well as the engine) to avoid electrical interference (electrical supplies on vessels can suffer from electrical noise). This requires that the measurement instrumentation be powered directly from batteries.

6 Acoustic measurement configuration

6.1 Spatial sampling (choosing measurement locations)

6.1.1 Criteria for measurement locations

The measurement locations shall be chosen to satisfy at least one of the following requirements:

- a) measurement at a fixed location to monitor the source output for comparison with other percussive pile driving events;
- b) measurement to assess the accuracy of predictions made in environmental impact assessments, environmental impact statements, or environment statements;
- c) measurement at ranges that allow comparison with a normative threshold level, for example, where specific impact criteria are expected to be exceeded;
- d) measurement at specific sites which are regarded as sensitive because of the presence of specific species of aquatic fauna;
- e) measurement in order to derive a source output metric, which can be compared with other sources and used in noise mapping and prediction of “impact zones”.

6.1.2 Recommended locations for offshore measurements

6.1.2.1 Minimum requirement for offshore measurements

As a minimum requirement, for offshore measurements of underwater noise from pile-driving, measurement shall be made in at least one location. Where measurements are made at only one location, this shall be as close as possible to 750 m range from the pile. This measurement should be of the entire piling sequence. The actual range from the pile to the measurement locations shall be reported with the results.

NOTE 1 The range of 750 m is chosen because there have been a large number of measurements already made at this range by researchers, allowing for a degree of comparison in results. The minimum requirement does not reflect the needs of any specific regulator, which may differ.

NOTE 2 It is recognized that, although a measurement at one fixed range is *one possible* measure of the acoustic output of the pile driving source, it is not independent of propagation path, and it has no predictive utility for other locations for the pile under study, nor for other piling scenarios.

NOTE 3 It is quite likely that measurement at a range of exactly 750 m will not be feasible. The actual range from the pile to the measurement locations is stated with the results.

NOTE 4 Currently, there is no wide consensus on the most appropriate source output metric for percussive pile driving, but the above measurement will provide data that may be useful in future calculations if such consensus is developed, providing the measurement transect does not have severe bathymetric features (large sand banks or trenches). They can also be valuable in validation of models of source radiation mechanisms.

NOTE 5 For measurements which are not considered “offshore”, for example, in harbours, inland waterways, etc., where a measurement at 750 m is not feasible, refer to [6.1.3](#) for measurement in inshore environments.

6.1.2.2 Measurements at additional locations

If the requirement is to satisfy criteria [6.1.1](#) b), c) and d), measurements are required at additional ranges from the pile location. These may be at a variety of different azimuthal bearings from the pile, depending on the requirement (see [6.1.5](#)). To monitor the levels at the boundary of impact zones for exposure of marine fauna can require measurement at significant distance from the source, where the acoustic signal has been significantly attenuated by propagation losses.

The minimum range for additional measurement locations shall be three times the local water depth at the pile location.

NOTE The purpose of the minimum range criterion is to reduce the influence of variation with measurement depth. The significance of which is greatest for distances of less than three times the local water depth (see also [6.1.3.2](#)).

6.1.2.3 Measurements along a transect

Measurements may also be made as a function of range along a transect radiating away from the source on a constant bearing. This allows an empirical estimate to be made of the decay of the acoustic metrics with distance.

In this case, the measurements shall be along a bearing that does not have severe bathymetric features (large sand banks or trenches). The transect measurements shall be combined with at least one measurement of the entire piling sequence at a fixed location. This bearing shall not be oriented parallel to a severely sloping shoreline to avoid bathymetric refraction effects^[31].

NOTE 1 Currently, there is no wide consensus on the most appropriate source output metric for percussive pile driving, but the above measurements will provide data which may be useful in future calculations when such consensus is developed. They can also be valuable in validation of models of source radiation mechanisms.

NOTE 2 The procedure can be expedited in one of two ways.

- a) A mobile measurement platform such as small vessel is used for the measurements, and while the source is operational, the vessel moves along a linear transect away from the source, stopping to measure at a number of ranges from the source; at the same time, a fixed monitoring station measures the entire piling sequence.
- b) A series of recorders are stationed along a linear transect from the source and these recorders measure the radiated noise along the transect simultaneously.

6.1.3 Recommended locations for inshore measurements

6.1.3.1 General

For inshore waters, for example, rivers, estuaries, and harbours, the requirements for the measurement are different from those for offshore, and measurement at 750 m may not be appropriate or even possible. In these environments, measurements closer to the pile are necessary and shall follow the measurement location criteria outlined in [6.1.3.2](#) and hydrophone depth criteria in [5.2.2](#). All other aspects of this document remain applicable when performing measurements of radiated noise from percussive pile driving in inshore waters.

6.1.3.2 Choice of measurement locations

For inshore waters, it is recommended that the measurement be performed at a distance from the pile of three times the local water depth at the pile location.

If this is not feasible, the measurement should be made at the shortest distance which is no less than three times the local water depth at the pile location.

NOTE 1 There is observational and theoretical evidence that the broadband underwater acoustic field associated with percussive pile driving is highly depth-dependent for measurement distances less than three times the water depth^{[20][21]}. The above criteria reduce the influence of variation with measurement depth. The significance of which is greatest for distances of less than three times the local water depth and applies to both the peak sound pressure level and sound exposure level.

NOTE 2 For situations where water depth varies as a function of range from the pile, the water depth at the pile is used for establishing the minimum measurement range in the above criteria.

6.1.4 Measurements of background noise for the purposes of SNR determination

Measurements of background noise, calculated from the mean-square broadband noise voltage after all processing, shall be undertaken when sound from pile-driving is not present. This can be either before or after the pile-driving or during any significant gaps in the pile-driving sequence. It is recommended that any such measurements are performed at one of the locations used for measurement of the pile-driving noise, or at a location which is considered representative.

From the background noise measurements, the signal-to-noise ratio (SNR) shall be determined (see 3.17).

NOTE 1 The averaging time used for determining the background noise is the same as that used for the measurement of the time-averaged signal in 6.4.2.2.2.

NOTE 2 Background noise is evaluated over the frequency range of interest, which for this document is a minimum of 20 Hz to 20 kHz. The background noise is often expressed in third-octave bands.

NOTE 3 The signal to noise ratio is typically expressed as a level difference in decibels.

6.1.5 Measurements of piles driven at a slant angle to the seabed

The sound radiated from piles driven at a slant angle to the seabed should be measured over a variety of different azimuthal bearings from the pile for full characterization of the acoustic output. This assumes that measurements are possible at a number of different locations (see 6.1.2.2).

For these measurements, the minimum range from the pile shall be three times the local water depth at the pile location. For the measurements, the azimuthal bearing from the pile shall be recorded.

Ideally, the underwater sound from an individual slanting pile should be measured in three directions: in the pitch direction, in the opposite direction and in the perpendicular direction.

Piles driven at "rake" are often used in Jacket-type structures. With a Jacket-type structure, the multiple legs define multiple pitch directions. For full characterization, some azimuthal spatial sampling of the field is required. Ideally, a minimum of four orthogonal bearings is recommended.

NOTE When driven, slanting piles, often referred to as "rakers", emit differently at different azimuth angles because the wave front emitted in different directions by a driven slanting pile has different elevation angles relative to the seafloor.

6.2 Temporal sampling — Measurement duration

To characterize the radiated sound from the pile driving as a function of time, measurements need to be undertaken for a period which covers any output variation of the pile driving. This shall be undertaken with a monitoring station at a fixed range from the source for the duration of the piling sequence.

NOTE 1 The monitoring station is either a static autonomous recorder or a vessel-based deployment which is moored or anchored at one location.

NOTE 2 The variation in source output during piling is well recognized. It can occur because of tidal changes causing significant water depth changes, increased seabed penetration, or hammer energy increase during the soft start period.

6.3 Distance measurement

The distance from the pile to the measurement location shall be determined with an accuracy of 5 % or better.

NOTE 1 The range can be determined using laser range finding equipment at relatively short ranges. For greater ranges, a more practical solution is to use the GPS coordinates of the pile and measurement position to derive the range.

NOTE 2 When using a laser range finder, it may be necessary to correct for the radius of the pile to obtain the distance to the centre of the pile.

6.4 Data processing and calculation of acoustic metrics

6.4.1 Data processing steps

The output of the acquisition system is assumed to be a signal waveform consisting of a digitized time series expressed in digital counts and representing the signal detected by the hydrophone and recorded by the acquisition system. The data processing and analysis procedure shall be conducted according to the following steps.

- a) Inspect the digitized time signals of the hydrophone recordings obtained over a discrete time series, t , where t_i corresponds to the i^{th} point in the time series. Confirm that these data exhibit the expected pulsed (transient) sounds, with suitable signal-to-noise ratio. If there are unexpected disturbances, or if the signals show signs of “clipping” (overloading the maximum allowed amplitude of the measurement chain), then these parts of signal are not suitable for analysis and should be discarded.
- b) If required, apply digital low, high, or band-pass filtering to the data, to limit the frequency content of the signal to the overall band of interest.
- c) Select periods of the signals for further analysis. If acoustic pulses are to be characterized, these can be found either by visual inspection of the waveform, or in an automated manner using a routine that checks where the recorded signal exceeds a given threshold. Identify and isolate the specific periods of the waveform to be analysed containing the data of interest (these may be periods containing individual acoustic pulses or sequences of multiple pulses).
- d) Convert the signal waveform to a representation of electrical voltage in volts, $V(t_i)$, by dividing by the sensitivity of the digitiser ADC (analogue to digital converter), where the digitizer sensitivity is the number of digital counts per volt (V^{-1}). See 4.2.1.
- e) Convert the signal voltage waveform in volts, $V(t_i)$, to a sound pressure waveform $p(t_i)$ in pascals by dividing by the system sensitivity, M_s in V/Pa (assuming the system does not introduce a phase delay):

$$p(t_i) = V(t_i) / M_s \quad (1)$$

If the response characteristics of the measurement chain are not uniform in the frequency range of interest, then an appropriate frequency-dependent correction shall be applied under step f) If a phase delay is introduced by the system, see 6.4.2.1.3 for further guidance.

- f) Convert the time waveform in the selected periods to a frequency spectrum expressed as frequency bands, either using Fourier analysis or via digital filtering. The frequency bands shall be calculated as one-third octave bands. If frequency-dependent calibration corrections are required, apply them here to the voltage spectra $V(f_i)$ [obtained by taking the Fourier transform of $V(t_i)$] to obtain the acoustic frequency spectra $P(f_i)$, using a frequency spectral representation of the modulus (magnitude only) of the system sensitivity, $M(f_i)$ (see 3.18 and 4.2.1):

$$P(f_i) = V(f_i) / M(f_i) \quad (2)$$

- g) Determine the acoustic metrics to be calculated (e.g. sound pressure level, sound exposure level and peak sound pressure level) according to the procedures outlined in 6.4.2 from the selected periods of the sound pressure waveform.
- h) Perform a statistical analysis of the calculated acoustic metrics for the selected periods for reporting of results.

NOTE 1 The phase information in the signal can be distorted by a non-uniform frequency response in a measuring system or by filtering of the signal. For calculation of acoustic metrics which depend on the energy or power in the signal (eg SPL and SEL), this is not usually a problem. However, a non-uniform phase response may have a significant effect on time-domain metrics such as peak sound pressure. See 6.4.2.1.3.

NOTE 2 The system sensitivity in Step e) accounts for the sensitivity of the hydrophone(s), gain of amplifiers, and insertion loss of filters. For digital systems, the calibration of the digitizer (analogue to digital converter) in Step d) may be incorporated into the system sensitivity, in which case Steps d) and e) are combined into one step and the digital system sensitivity is the number of digital counts per pascal (Pa⁻¹). See 3.18 and 4.2.1.

NOTE 3 Either base-10 or base-2 may be used for calculation of one-third octave bands, the two calculation methods giving slightly different results, and the choice being stated when presenting the results. Base-10 is the preferred method (IEC 61260-1). (Note that the base-10 representation of a one-third octave band is referred to as a “decidecade” in ISO 18405).

NOTE 4 The combination of time sampling increment, t_i , and number of points acquired, N_p , determines the frequency increment, f_i , of the spectrum of the measured signal according to the equation: $f_i = 1/(t_i N_p)$. Frequently, it is found that this frequency increment of the spectrum of the measured data differs from that supplied between consecutive points in the hydrophone calibration data. To ensure that calibration data are available at the appropriate frequency points, it may be necessary to interpolate values at the required spacing from the calibration data[32].

6.4.2 Acoustic metrics to be calculated

6.4.2.1 Analysis of individual acoustic pulses

6.4.2.1.1 General

Analysis of the transient sound from an individual acoustic pulse requires either manual or automated identification of the specific acoustic pulses in the recorded time series of the sound pressure. A portion of the recording is then selected which contains the specific acoustic pulse to be analysed (with the pulse corresponding to a single hammer strike).

6.4.2.1.2 Single strike sound exposure level (SEL_{SS})

The single strike sound exposure level (abbreviation: SEL_{SS}) shall be calculated for a specific acoustic pulse as a broadband value (single number for a stated bandwidth) and in one-third octave frequency band levels covering at least the frequency range from 20 Hz to 20 kHz (a wider bandwidth may be used if necessary (see 4.2.2)).

To calculate the SEL_{SS} corresponding to a specific acoustic pulse requires the SEL be calculated over the pulse duration as the percentage energy signal duration. The 0 % sound exposure point (t_0) is selected at the “start” of the acoustic pulse, just before the $E(t_i)$ curve begins to rise, and the 100 % sound exposure point (t_{100}) just after the “end” of the pulse, where it levels off. This can be difficult to determine due to the variation in background noise preceding (and overlapping) the acoustic event, as well as the background noise following the event. Consequently, it may be necessary to identify these points subjectively.

The single strike sound exposure is then calculated in $\mu\text{Pa}^2\text{s}$ for the entire duration of the pulse from the digitized time series (t_i) of the sound pressure waveform $p(t_i)$, using a numerical computer implementation of Formula (3), where f_s is the sampling rate, and t_0 and t_{100} are the 0 % and 100 % sound exposure points described above:

$$E_{100} = \frac{1}{f_s} \sum_{i=t_0 f_s}^{t_{100} f_s} \{p^2(t_i)\} \quad (3)$$

The total broadband single strike sound exposure level (symbol: L_{E100}) in dB re 1 $\mu\text{Pa}^2\text{s}$ is given in Formula (4):

$$L_{E100} = 10 \log_{10} \frac{E_{100}}{E_{\text{ref}}} \text{ dB} \quad (4)$$

where $E_{100} = E(t_{100})$ which is 100 % of the sound exposure and E_{ref} is 1 $\mu\text{Pa}^2\text{s}$.

If the pulse duration is greater than the period between hammer strikes, then successive pulses will overlap and the period between hammer strikes will limit the time over which the SEL_{SS} is integrated. In this case, the integration time for SEL_{SS} shall be chosen to be the period between hammer strikes. For such cases, the mean SEL_{SS} for a pulse sequence may be obtained by integrating over the entire pulse sequence and dividing by the number of pulses.

NOTE 1 A one-third octave band analysis of the sound exposure level can be obtained by applying [Formulae \(3\)](#) and [\(4\)](#) to the time series after digital filtering with one-third octave band filters.

NOTE 2 Where successive acoustic pulses overlap in time at the receiver, the ability to measure individual pulses may be compromised by more than one pulse appearing in the time window. This may perhaps be because the hammer strike repetition period is shorter than the reverberation time of the channel, or because measurements are being made in a highly reverberant environment like a harbour, or because measurements are made at large ranges from the pile such that the pulse duration is increased by dispersion during propagation. This effect may “even out” between successive pulses in a pulse train, but there is scope for error (most obviously at the start and end of the pulse sequence). In this case, the mean SEL_{SS} may be calculated over a pulse sequence.

6.4.2.1.3 Peak sound pressure, peak sound pressure level

The peak sound pressure and peak sound pressure level shall be calculated for each acoustic pulse from the sound pressure waveform (time domain signal) with the portion of the waveform corresponding to the pulse identified as described in [6.4.1](#) and [6.4.2.1.1](#).

The peak sound pressure, p_{pk} , is expressed in pascals (Pa) and calculated as the greatest magnitude of the sound pressure, $p(t_i)$, for the time duration of the acoustic pulse. This may be given by [Formula \(5\)](#):

$$p_{pk} = \max_{t_0 \leq t_i \leq t_{100}} |p(t_i)| \quad (5)$$

where t_0 is the time at the start of the acoustic pulse, and t_{100} is the time at the end of the pulse (as described in [6.4.2.1.2](#)).

The peak sound pressure level, $L_{p,pk}$, is expressed in decibels and is given by [Formula \(6\)](#):

$$L_{p,pk} = 20 \log_{10} \left(\frac{p_{pk}}{p_0} \right) \text{ dB} \quad (6)$$

where the reference value, p_0 , is 1 μPa .

NOTE 1 A peak sound pressure can arise from a compressional (positive) or rarefactional (negative) sound pressure. The peak sound pressure is sometimes referred to as the zero-to-peak sound pressure.

NOTE 2 The accuracy of the estimation of the peak sound pressure and peak sound pressure level can be affected by the bandwidth and frequency response of the measuring system. The frequency response magnitude is ideally invariant with frequency to within a tolerance of 2 dB in the range 20 Hz to 20 kHz (see [4.2.2](#)). For best accuracy, influences that cause fluctuations in the frequency response are ideally avoided, examples being resonances in the hydrophone response or application of digital filtering within the overall frequency range.

NOTE 3 The phase information in the signal can be distorted by a non-uniform frequency response in a measuring system or by filtering of the signal. For calculation of peak sound pressure and peak sound pressure level, a non-uniform phase response may have a significant effect on the accuracy of the estimation of the peak value of the acoustic pulse. For best accuracy, influences that cause fluctuations in the phase response are ideally avoided, examples being resonances in the hydrophone response or application of digital filtering within the overall frequency range.

NOTE 4 The system sensitivity, $M_s(f)$, is actually a complex valued quantity describing the magnitude and the phase response of the system (see 3.18 and 4.2.1). Historically, the hydrophone sensitivity has typically been available as a magnitude-only quantity, but calibration methods do exist for determination of phase response[24]. If the system sensitivity has a magnitude and non-zero phase response which varies appreciably with frequency in the range of interest (minimum of 20 Hz to 20 kHz), the sound pressure waveform may be derived from the measured voltage waveform, $V(f)$, by a process of deconvolution using the relation $p(t_i) = \mathcal{I}^{-1} [V(f) / M_s(f)]$ [32].

6.4.2.2 Time-integrated analysis of sound

6.4.2.2.1 General

The time-integrated analysis of sound includes time signals captured either for measuring background noise or measurements obtained of the entire piling sequence or sections of the piling sequence.

6.4.2.2.2 Sound pressure level (SPL)

The broadband sound pressure level, SPL, averaged over time T (in seconds), can be obtained in dB re 1 μPa from the digitized time series (t_i) of the sound pressure $p(t_i)$, recorded at a sampling rate f_s (in Hertz), where the reference sound pressure p_0 is 1 μPa , using a numerical computer implementation of Formula (7):

$$L_p = 10 \log_{10} \frac{1}{T f_s} \sum_{i=1}^{T f_s} \frac{p(t_i)^2}{p_0^2} \text{ dB} \quad (7)$$

Representation of the sound pressure level, L_p , in a specified frequency band, averaged over time, T , (in seconds), can be obtained by applying the same formula to the time series after digital filtering into frequency bands. The broadband SPL should be equal to the power sum of the levels in the individual frequency bands (the power sum being calculated by summing the mean squared sound pressures in each band). The frequency band spectrum can also be obtained via power summation of the narrowband levels within each frequency band.

The background noise level may be calculated as the SPL during a period of time when no piling pulses are present, the period being deemed to be representative of background noise.

It is recommended that the SPL be calculated over a specified time (T). The time is always stated with the results.

NOTE In the context of reporting of radiated sound from marine pile driving, in some publications the SPL has been referred to as the *unweighted equivalent continuous sound level* (L_{eq}), calculated using a reference value for sound pressure of 1 μPa . The definition used is identical to that for SPL and it is intended as the same quantity[16].

6.4.2.2.3 Cumulative sound exposure level (SEL_{cum})

To calculate the cumulative sound exposure level (abbreviation: SEL_{cum}), the single strike sound exposure associated with each hammer strike shall be summed up over a specified duration (a duration which includes multiple pulses). This shall be calculated from ten times the logarithm to the base 10 of the ratio of the cumulative sound exposure (symbol: E_{cum}) to the reference sound exposure (symbol:

E_0), the cumulative sound exposure being the sum of the time integrals of the time-varying square of the instantaneous sound pressure over multiple acoustic pulses, as given in [Formula \(8\)](#):

$$L_{E_{cum}} = 10 \log_{10} \frac{E_{cum}}{E_0} \text{ dB} \quad (8)$$

with cumulative sound exposure E_{cum} for N acoustic pulses, each with single strike sound exposure (symbol: E_n) given by [Formula \(9\)](#):

$$E_{cum} = \sum_{n=1}^N E_n \quad (9)$$

where E_0 is the reference sound exposure of 1 $\mu\text{Pa}^2\text{s}$.

6.4.2.3 Analysis of temporal metrics

6.4.2.3.1 Pulse duration

The pulse duration shall be calculated as the percentage energy signal duration based on 90 % energy percentage.

6.4.2.3.2 Pulse repetition frequency

This should be obtained from the hammer piling sequence information, usually supplied by the hammer or construction contractor. If this information is not available then it can be calculated from the time gap between each acoustic pulse and reported as an average for a defined piling period.

NOTE 1 Where the hammer strike repetition period is shorter than the pulse duration, the ability to measure the time between individual pulses may be compromised.

7 Measurement uncertainty

7.1 General

The value of a measurement is extremely limited without some estimation of the uncertainty. The uncertainty is an estimate of the range of values within which the true value is considered to lie to a specified degree of confidence (for example, for a confidence level of 95 %). Any uncertainty analysis shall be made in accordance with the international Guide to Expression of Uncertainty in Measurement (ISO/IEC Guide 98-3:2008)[\[33\]](#).

Note that uncertainty estimation should be distinguished from the natural variation in the measured quantity that might occur due to the fact that the quantity itself is changing over time. For example, the noise radiated during a piling operation will vary during a soft-start where the hammer energy is increasing gradually, or in rough weather due to the sea-state influencing the propagation loss.

There are two general classes of uncertainty. Type A uncertainty is sometimes described as the “random uncertainty” or repeatability, and may be assessed by making repeated measurements of a quantity and examining the statistical spread in the results. For piling, it might not be possible to make repeated measurements if the event being measured is unique. The Type A uncertainty is a measure of the precision in the measurement – high precision is obtained if the measurements are repeatable with little dispersion in results.

The second category is the Type B uncertainty, which is sometimes referred to as the “systematic uncertainty”, and represents the potential for systematic bias in a measurement (for example caused by incorrect instrument calibration). This category of uncertainty cannot be assessed using repeated measurements, and shall be evaluated by consideration of the potential influencing factors on the measurement accuracy.

7.2 Sources of uncertainty

7.2.1 Uncertainty in the calibration of instrumentation

Uncertainty in the calibration of instrumentation will contribute to the overall uncertainty. It is possible to calibrate a hydrophone in laboratory conditions with an uncertainty of 0,5 dB, and the overall uncertainty of the recording system can be of the order of 1 dB. Uncertainties introduced by instrumentation can be significant; for example, an uncalibrated preamplifier with a 10 dB offset will cause every measurement to be in error by this factor (an example of systematic bias or Type B uncertainty).

7.2.2 Uncertainty in the position of source and receiver

For measurements in the ocean, it is not a trivial matter to achieve high positional accuracy. In measurement of radiated noise from a source, use of GPS or laser range finding equipment can provide extra confidence, but residual uncertainty is inevitable. The relative uncertainty is likely to be greater if the source-receiver ranges are short: a fixed 10 m error equates to a 10 % error in a range of 100 m, but a 0,1 % error in a range of 10 km. For short ranges, laser range finding equipment is an appropriate choice for determination of distance, but for larger ranges (hundreds of metres) GPS fixing is acceptable.

7.2.3 Spurious signals introduced by the deployment

Although every attempt should be made to eliminate sources of spurious signals such as those identified in 5.3, this is not always possible. Estimates should be made of any residual effects for inclusion in the uncertainty analysis.

7.3 Evaluating uncertainty

When evaluating uncertainty, there are a number of steps recommended.

- Check for any spurious artefacts and eliminate spurious signals (try to estimate any residual effects).
- Assess the uncertainty in the instrument calibration (check that this is valid across the entire frequency range).
- Check for consistency in the results (for example, between hydrophones deployed at similar ranges; do the measurements vary with position or range as expected or are there anomalous results in the data set?).
- Check any assumptions made (is it possible to assign uncertainties to these assumptions?).
- Consider conducting a sensitivity analysis [this involves varying the input parameters (for example to a model or calculation) and determining the sensitivity of the results to these changes].
- List uncertainty contributions and assign values.
- Combine the uncertainties according to the ISO/IEC Guide 98-3.

8 Reporting of results

8.1 Auxiliary data and metadata

8.1.1 General

The report of results should include as much of the following information as possible where they are pertinent to the measurement survey. It is beneficial to record any auxiliary data that are relevant, since these can be correlated with the measured noise levels during analysis.

8.1.2 Mandatory

Auxiliary data to record shall include the following:

- date and times of recordings;
- hydrophone depth in the water column;
- GPS locations of sources, hydrophones and recording systems;
- seabed/river-bed type at the measurement location (Folk sediment classification or similar is sufficient; the classification used shall be stated)^[34];
- water depth at measurement locations and tidal variations in water depth during piling;
- description of significant sources of measurement uncertainty;
- operating conditions of measuring vessel.

NOTE In very shallow water, the tidal variation can have a significant effect on the sound propagation and greater precision is required in the reporting.

8.1.3 Optional

It is recommended that the following auxiliary data be recorded where available:

- wind speed (and associated measurement height);
- significant wave height;
- rate of rainfall and other precipitation, including snow;
- water temperature and air temperature and associated measurement position;
- the presence of vessels in the area where measurements are being made, up to a 10 km radius around the measurement location;
- the presence of any aquatic mammals in the area which are audible from the acoustic data;
- the presence of any distant sound generating activity such as geophysical surveying which are audible from the acoustic data;
- sound speed profile of the water column.

NOTE 1 The sound speed profile can be obtained from measurements of conductivity, temperature and hydrostatic pressure as a function of depth in the water column using a Conductivity, Temperature and Depth (CTD) probe. From this information the salinity, density and sound speed profiles can be calculated from standard equations. Alternatively, the sound speed profile can be measured directly, using a velocimeter.

NOTE 2 The presence of vessels in the area may be monitored by keeping a log of the visible vessels; a receiver of ship traffic Automatic Identification System (AIS) is useful for logging larger vessels which have an AIS transponder.

8.2 Pile characteristics

The following information about the pile being driven shall be recorded (where available):

- identifier and location for pile;
- pile dimensions;
- seabed/river-bed type at the pile (Folk sediment classification or similar is sufficient; the classification used shall be stated)^[34];

- water depth at the pile;
- hammer model and system (e.g. S-1800 hydraulic hammer using a cushion);
- hammer energy history with energy per blow including soft start period;
- description of any noise mitigation system used including any additional information which might have an influence on noise reduction (e.g. air flow in the case of a bubble curtain);
- foundation type, e.g. monopile or jacket (for jacket or tripod-type foundations, whether the jacket/tripod is in place during piling should be stated);
- pile material type (e.g. steel, concrete, etc.);
- seabed or river-bed penetration depth (either as a depth history per blow or as a final depth, reported as metres below the bottom);
- pile material properties;
- any sub-bottom layers into which the pile is driven;
- dynamic (force and velocity) response of the pile, e.g. as measured according to the ASTM D4945-08.

8.3 Deployment configuration

8.3.1 Mandatory

The following information about the deployment configuration shall be recorded:

- measurement system description (including acquisition system type, bandwidth, system self-noise, dynamic range, sampling rate, filtering used, etc.);
- data compression routine, if one was used;
- suspension system description/diagram and platform description (vessel, surface buoy, bottom mounting, etc.);
- hydrophone depths;
- hydrophone type/model/directionality/nominal sensitivity;
- calibration details (performed by laboratory traceable to national standards, including dates and certificates);
- field calibration methods and results.

8.3.2 Optional

Other useful data to record includes

- system component description and diagram.

8.4 Reporting of measurement results

8.4.1 Mandatory

The following measurement results shall be reported for each hydrophone at each measurement location.

- The single strike sound exposure level (as a broadband value). This can be expressed for every pulse in the sequence or as an average value over a defined time period with some indication of the statistical variation.
- The single strike sound exposure level for each frequency band in tabulated and graphical form. This can be expressed for every acoustic pulse (corresponding to a hammer strike) in the sequence or as an average value over a stated number of pulses within a defined time period with some indication of the statistical variation.
- The peak sound pressure and peak sound pressure level. This can be expressed for every pulse in the sequence or as an average value over a defined time period with some indication of the statistical variation.
- The signal-to-noise ratio calculated from background noise level (see 3.17 and 6.1.4) for the duration that is selected to determine E100 (see 6.4.2.1.2).

NOTE 1 To indicate the statistical variation, a report of the minimum and maximum values which occurred with the associated hammer energy stated at the start, middle and end of the piling sequence can be provided. This can also be provided over other specified time periods during the piling sequence (for example, for the main sequence after any soft start has ended). Greater detail can be provided on the dispersion of measured values, for example by inclusion of percentiles.

NOTE 2 The bandwidth over which the acoustic metrics are calculated is stated where appropriate.

NOTE 3 The measurement uncertainties are stated with reported values where appropriate, including any specific sources of uncertainty, where known (examples include uncertainty of instrument calibration).

8.4.2 Optional

It is recommended that the following measurement results be reported.

- The SPL over the specified averaging times, including a single pulse or longer duration, as required (see 6.4.2.2). The averaging time shall be stated.
- Cumulative sound exposure level as a single number for the entire piling sequence.
- The pulse repetition frequency as an average value during a stated period of the piling.
- The pulse duration for the associated broadband pulse SEL values reported.
- The SPL for each one-third octave band in either tabulated or graphical form. The averaging time shall be stated.
- The peak compressional sound pressure level, and peak rarefactional sound pressure level.

NOTE 1 To indicate the statistical variation, a report of the minimum and maximum values which occurred with the associated hammer energy stated at the start, middle and end of the piling sequence can be provided. This can also be provided over other specified time periods during the piling sequence (for example, for the main sequence after any soft start has ended). Greater detail can be provided on the dispersion of measured values, for example by inclusion of percentiles.

NOTE 2 The bandwidth over which the acoustic metrics are calculated is stated where appropriate.

NOTE 3 The measurement uncertainties are stated with reported values where appropriate, including any specific sources of uncertainty, where known (examples include uncertainty of instrument calibration).

NOTE 4 The cumulative sound exposure level can also be presented as a cumulative plot with time.

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