INTERNATIONAL STANDARD

ISO 22476-4

Second edition
2021-09

Geotechnical investigation and testing — Field testing —

Part 4:
Prebored pressuremeter test by Ménard procedure

Reconnaissance et essais géotechniques — Essais en place —

Partie 4: Essai pressiométrique dans un forage préalable selon la procédure Ménard

Reference number
ISO 22476-4:2021(E)

Contents

Page

Foreword v

Introduction vi

1 Scope 1

2 Normative references 1

3 Terms, definitions and symbols 1
- 3.1 Terms and definitions 1
- 3.2 Symbols 3

4 Equipment 6
- 4.1 General description 6
- 4.2 Pressuremeter probe 6
  - 4.2.1 General 6
  - 4.2.2 Probe with flexible cover 8
  - 4.2.3 Probe with flexible cover and an additional more rigid protection 8
  - 4.2.4 Probe with flexible cover and slotted tube 9
- 4.3 Connecting lines and injected fluid 10
- 4.4 Pressure and volume control unit 11
  - 4.4.1 General 11
  - 4.4.2 Measurement and control 11
  - 4.4.3 Data logger 12

5 Test procedure 12
- 5.1 Assembling the parts 12
- 5.2 Calibration and corrections 13
- 5.3 Pressuremeter test pocket and probe placing 13
- 5.4 Preparation for testing 13
- 5.5 Establishing the loading programme 14
- 5.6 Establishing the pressure of the guard cells for tri-cell probes 15
- 5.7 Expansion 15
  - 5.7.1 General 15
  - 5.7.2 Readings and recordings 15
  - 5.7.3 End of test 16
- 5.8 Back-filling of the pockets 16
- 5.9 Safety requirements 16

6 Test results 16
- 6.1 Data sheet and field print-out or display 16
  - 6.1.1 Data sheet for type A control unit 16
  - 6.1.2 Site print-out for type B and C control units 17
  - 6.1.3 Raw pressuremeter curve 17
- 6.2 Corrected pressuremeter curve 17
- 6.3 Calculated results 18

7 Reporting 19
- 7.1 General 19
- 7.2 Field report 19
- 7.3 Test report 19
  - 7.3.1 General 19
  - 7.3.2 Ménard pressuremeter test report 19
  - 7.3.3 Pressuremeter tests log 20

Annex A (normative) **Geometrical features of pressuremeter probes** 22

Annex B (normative) **Calibration and corrections** 24

Annex C (normative) **Placing the pressuremeter probe in the ground** 33

Annex D (normative) **Obtaining pressuremeter parameters** 41

Annex E (normative) **Uncertainties** 51
Annex F (informative) **Pressuremeter test records** 53
Bibliography 60

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 182, *Geotechnics*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 341, *Geotechnical Investigation and Testing*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This second edition cancels and replaces the first edition (ISO 22476-4:2012), which has been technically revised.

The main changes compared to the previous edition are as follows:

— types of probes;

— correction procedures;

— probe placing techniques in Annex C;

— clarification of D;

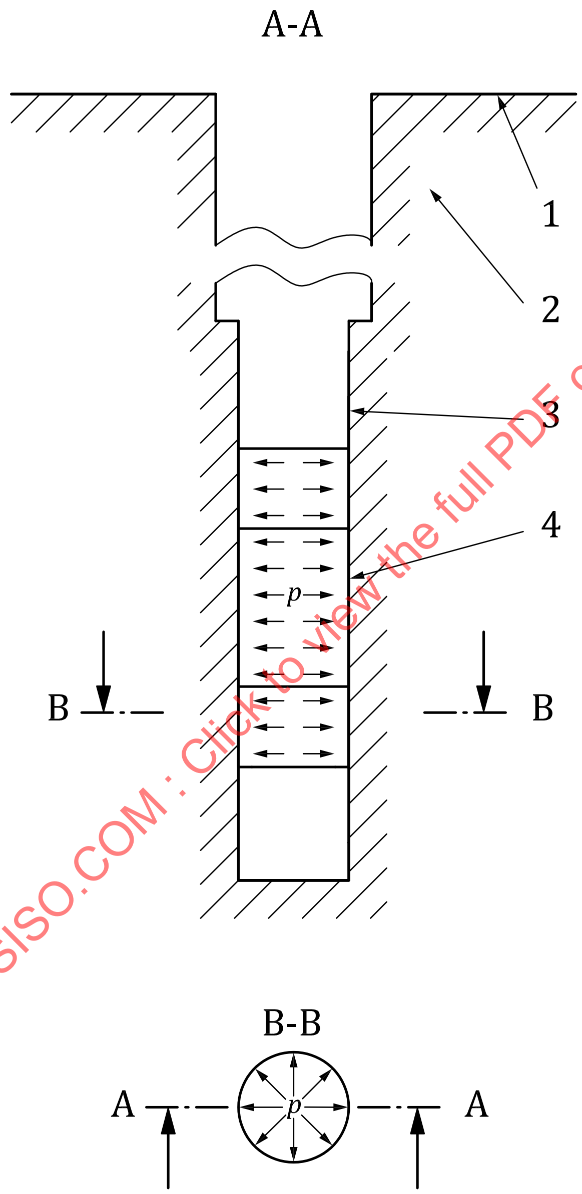
— harmonization of terms and symbols.

A list of all parts in the ISO 22476 series can be found on the ISO website.

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

The Ménard pressuremeter test is performed by the radial expansion of a cylindrical probe of a minimum slenderness of 6, placed in the ground (see Figure 1). During the injection of the fluid volume in the probe, the inflation of the measuring cell first brings the outer cover of the probe into contact with the pocket wall and then producing ground displacement. Pressure applied to and the associated radial expansion of the probe are measured either by volume or radial transducers and recorded so as to obtain the stress-strain relationship of ground as tested.



Key

1	ground surface	*p*	applied pressure
2	ground	A-A	axial section
3	pressuremeter test pocket	B-B	cross section
4	expanding pressuremeter probe		

Figure 1 — Principle of a Ménard pressuremeter test

Together with results of investigations with ISO 22475-1 being available or at least with identification and description of the ground according to ISO 14688-1 and ISO 14689 obtained during the pressuremeter test operations, the tests are performed in order to obtain the quantitative determination of a ground profile, including

— the Ménard pressuremeter modulus E_M,

— the Ménard pressuremeter limit pressure p_{lM}, and

— the Ménard creep pressure p_f.

NOTE 1 This document fulfils the requirement for the Ménard pressuremeter test, as part of geotechnical investigation and testing according to EN 1997-1 and EN 1997-2.

NOTE 2 This document refers to a probe historically described as the "60 mm (also called BX) G type probe", that corresponds to a 58 mm diameter probe with a drilling diameter between 60 mm and 66 mm with a pressure limitation of 5 MPa. If specified by the relevant authority or agreed for a specific project by the relevant parties, a different pressure, not higher than 8 MPa, can be set.

NOTE 3 G type probe refers to probes with an external cover creating guard cells (see 4.2).

NOTE 4 Ménard pressuremeter tests can be carried out with other diameter probes such as 32 mm, 44 mm and 76 mm probes.

NOTE 5 Examples of other probe and pocket drilling dimensions are indicated in Table 1.

Table 1 — Probe and pocket drilling dimensions

Probe Designation	Probe Diameter mm	Drilling diameter (mm) Min	Drilling diameter (mm) Max
AX	44	46	52
NX	70/74	74	80

NOTE 6 Tests with maximum pressures higher than 8 MPa are dealt by ISO 22476-5.

NOTE 7 For the scope of this document (and the associated measuring device and maximum uncertainties given in Table E.1), E_M values up to 500 MPa (that can be determined by calculation) can be commonly obtained. Enhancement of equipment to reduce uncertainties can be implemented to increase the range of measurements. For example, use of GA type equipment and of a shunt for volume measurement can allow measuring E_M values up to 10 000 MPa. Uncertainty calculation can be used to confirm the relevance of these pressuremeter moduli.

Geotechnical investigation and testing — Field testing —

Part 4:
Prebored pressuremeter test by Ménard procedure

1 Scope

This document specifies equipment requirements, the execution of and reporting on the Ménard pressuremeter test.

This document describes the procedure for conducting a Ménard pressuremeter test in natural grounds, treated or untreated fills, either on land or off-shore.

The pressuremeter tests results of this document are suited to a quantitative determination of ground strength and deformation parameters. They can yield lithological information in conjunction with measuring while drilling performed when creating the borehole (according to ISO 22476-15). They can also be combined with direct investigation (e.g. sampling according to ISO 22475-1) or compared with other in situ tests (see EN 1997-2).

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 14688-1, *Geotechnical investigation and testing — Identification and classification of soil — Part 1: Identification and description*

ISO 14689, *Geotechnical investigation and testing — Identification, description and classification of rock*

ISO 22475-1, *Geotechnical investigation and testing – Sampling by drilling and excavation and ground water measurements – Part 1: Technical principles for execution*

ISO 22476-15, *Geotechnical investigation and testing — Field testing — Part 15: Measuring while drilling*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply:

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1.1
pressuremeter probe
cylindrical flexible probe which can be expanded by the application of hydraulic pressure and/or pressurised gas

3.1.2
pressuremeter control unit
set of suitable devices capable of supplying fluid and/or gas pressure to the probe, to adjust pressure steps and take readings of the probe's pressure and the volume or radius of the measuring cell

3.1.3
connecting line
cable that connects the control unit to the probe, delivers fluid and/or gas pressure in the measuring and guard cells

3.1.4
pressuremeter test pocket
circular cylindrical cavity formed in the ground to receive a *pressuremeter probe* (3.1.1)

Note 1 to entry: See Annex C.

3.1.5
pressuremeter borehole
borehole in which *pressuremeter test pockets* (3.1.4) with circular cross sections are made in the ground, and into which the *pressuremeter probe* (3.1.1) is to be placed

Note 1 to entry: See Figure 1.

3.1.6
Ménard pressuremeter test
process during which *a pressuremeter probe* (3.1.1) is inflated in the *pressuremeter test pocket* (3.1.4) and the resulting pocket expansion is measured as a function of time and pressure increments according to a defined programme

Note 1 to entry: See Figure 4.

3.1.7
pressuremeter sounding
sequence of *Ménard pressuremeter tests* (3.1.6) executed from the same station in the *pressuremeter borehole* (3.1.5)

3.1.8
pressure reading
pressure as read at the control unit (CU) elevation in the fluid and/or gas circuit supplying the measuring cell

3.1.9
pressure loss
difference between the pressure inside the probe and the pressure applied to the *pressuremeter test pocket* (3.1.4) wall

3.1.10
volume loss
volume readings on the control unit while probe is kept at constant external diameter

Note 1 to entry: They are due to system compressibility (including membrane, probe, tubing, fluid and control unit).

3.1.11
raw pressuremeter curve
graphical plot of the injected volumes recorded at time 60 s, noted V_{60}, versus the applied pressure at each pressure step, p_r

3.1.12
corrected pressuremeter curve
graphical plot of the corrected volumes V_i or radial displacements versus the corrected pressure p

Note 1 to entry: See Figure 5.

3.1.13
pressuremeter creep
difference in volumes recorded at 60 s and at 30 s at each pressure step: $V_{60} - V_{30} = V_{60/30}$

3.1.14
corrected pressuremeter creep curve
graphical plot of the corrected pressuremeter creep, versus the corrected applied pressure at each pressure step

Note 1 to entry: See Figure 5.

3.1.15
pressuremeter log
graphical report of the results of the *pressuremeter sounding* (3.1.7), together with all the information gathered during the drilling

Note 1 to entry: See F.3.

3.1.16
Ménard pressuremeter modulus
modulus obtained from the section between (p_1, V_1) and (p_2, V_2) of the pressuremeter curve

Note 1 to entry: See Figure D.6.

3.1.17
Ménard pressuremeter limit pressure
pressure at which the volume of the *pressuremeter test pocket* (3.1.4) at the depth of the measuring cell has doubled its original volume

Note 1 to entry: See Figure D.5.

3.1.18
pressuremeter creep pressure
pressure defined as the intersection of two straight lines fitted on the creep curve

Note 1 to entry: See Figure D.4.

3.1.19
operator
person who carries out the test

3.1.20
casing
lengths of tubing inserted into a borehole to prevent the hole caving in or to prevent the loss of flushing medium to the surrounding formation, above pocket location

3.2 Symbols

For the purposes of this document, the symbols in Table 2 apply:

Table 2 — Symbols

Symbol	Description	Unit
A, *B*	Parameters for reciprocal curve fitting method	cm^3, cm^3/MPa

Table 2 *(continued)*

Symbol	Description	Unit
A_1 *to* A_6	Parameters for hyperbolic curve fitting methods	variable
a	Apparatus volume loss coefficient	cm^3/MPa
b, c	Parameters of power law type interpolation for the probe pressure loss correction	variable
d, e	Parameters of linear type interpolation for the probe volume loss correction	variable
d_c	Outside diameter of the central measuring cell, including any additional protection such as a slotted tube	mm
d_{ci}	Outside diameter of the inner part of the probe with slotted tube	mm
d_g	Outside diameter of the guard cells	mm
d_i	Inside diameter of the calibration cylinder used for the volume loss calibration	mm
d_r	Outside diameter of the central measuring cell during expansion as read on the CU, before data correction	cm^3
d_t	Drilling tool diameter	mm
E_M	Ménard pressuremeter modulus	MPa
K	Factor to determine the differential pressure for tri-cell probes	-
l_c	Length of the central measuring cell of the probe, when the cell membrane is fixed on the probe steel core	mm
l_g	Length of each guard cell	mm
l_m	Length along the tube axis of the slotted section of the slotted tube	mm
l_p	Length of the calibration cylinder used for the volume loss calibration	mm
l_t	Length of the cover	mm
m	Parameter of power law type interpolation for the probe pressure loss correction	-
m_E	Minimum value, strictly positive, of the m_i slopes	cm^3/MPa
m_i	Slope of the corrected pressuremeter curve between the two points with coordinates (p_{i-1}, V_{i-1}) and (p_i, V_i)	cm^3/MPa
p	Pressure applied to the ground after correction	MPa
p_c	Fluid or gas pressure in the measuring cell of the pressuremeter probe.	MPa
p_e	Correction for probe pressure loss	MPa
p_E	Pressure at the origin of the segment exhibiting the slope m_E	MPa
p'_E	Pressure at the end of the segment exhibiting the slope m_E	MPa
p_{el}	Ultimate pressure loss of the probe	MPa
p_f	Pressuremeter creep pressure	MPa
p_g	Pressure in the guard cells, read at the CU transducer elevation	-
p_h	Hydrostatic pressure between the control unit indicator and the central measuring cell of the pressuremeter probe	MPa
p_i	Pressuremeter corrected pressure	MPa
p_{lM}	Ménard pressuremeter limit pressure of the ground	MPa
p_{lMDH}	Ménard pressuremeter limit pressure as extrapolated by the double hyperbolic method	MPa
p_{lMH}	Ménard pressuremeter limit pressure as extrapolated by the hyperbolic method	MPa
p_{lMR}	Ménard pressuremeter limit pressure as extrapolated by the reciprocal curve method	MPa
p_m	Pressure loss of the central measuring cell membrane for a specific expansion	MPa
p_r	Pressure in the measuring cell fluid or gas circuit, read at the CU transducer elevation	MPa
p_t	Target pressure for each pressure step according to loading program	MPa

Table 2 *(continued)*

Symbol	Description	Unit
p_0	Pressuremeter horizontal at rest pressure	MPa
p_1	Corrected pressure at the origin of the pressuremeter modulus pressure range	MPa
p_2	Corrected pressure at the end of the pressuremeter modulus pressure range	MPa
t	Time	s
t_h	Time the loading pressure level is held	s
u_s	Pore water pressure in the ground at the depth of the test	MPa
V	Value, after zeroing and data correction, of the volume injected in the central measuring cell and measured 60 s after starting a pressure step	cm^3
V_c	Original volume of the central measuring cell, including the slotted tube, if applicable	cm^3
V_E	Value, after data correction, of the volume injected in the central measuring cell for pressure p_E	cm^3
V'_E	Value, after data correction, of the volume injected in the central measuring cell for pressure p'_E	cm^3
V_e	Correction for volume loss of the whole equipment	
V_i	Corrected volume	cm^3
V_L	Value, after data correction, of the volume injected in the central measuring cell when the original volume of the pressuremeter cavity has doubled	cm^3
V_m	The average corrected volume between V_1 and V_2	cm^3
V_p	Volume corresponding is the intercept on the volume axis of the straight line best fitting the data points on the *p*-*V* curve obtained in the volume loss calibration test (see Figure B.2)	cm^3
V_r	Volume injected in the probe as read on the CU, before data correction	cm^3
V_t	Volume of the central measuring cell including the slotted tube	cm^3
V_1	Corrected volume at the origin of the pressuremeter modulus pressure range	cm^3
V_2	Corrected volume at the end of the pressuremeter modulus pressure range	cm^3
V_{30}	Volume injected in the central measuring cell as read 30 s after the beginning of the pressure step	cm^3
V_{60}	Volume injected in the central measuring cell as read 60 s after the beginning of the pressure step	cm^3
$\mathrm{V}_{60/30}$	Injected volume change from 30 s to 60 s after reaching the pressure step, also called pressuremeter creep	cm^3
$\mathrm{V}_{60/60}$	60 s injected volume change between two successive pressure steps	cm^3
z	Elevation, positively counted above datum	m
z_{CU}	Elevation of the pressure measuring device for the fluid and/or gas injected in the probe	m
z_N	Elevation of the ground surface at the location of the pressuremeter sounding	m
z_p	Elevation of the measuring cell centre during testing	m
z_w	Elevation of the ground water table (or free water surface in a marine or river environment)	m
β	Coefficient used to determine the pressuremeter modulus pressure range	---
γ	Unit weight of ground at the time of testing	kN/m^3
γ_i	Unit weight of the liquid injected in the central measuring cell	kN/m^3
γ_w	Unit weight of water	kN/m^3
Δp	Loading pressure increment	MPa
Δp_1	Initial pressure increment	MPa
r_i	Radius of the measuring cell for transducer *i*	m

Table 2 *(continued)*

Symbol	Description	Unit
Δt_i	Duration to achieve pressure step *i*	s
δV	Tolerance for volume measurement	cm^3
λ_g	Rate of change of pressure head of gas at p_k per metre depth	m^{-1}
ν	Poisson’s ratio	-
σ_{hs}	Total horizontal stress in the ground at test elevation	kPa
σ_{vs}	Total vertical stress in the ground at test depth	kPa

4 Equipment

4.1 General description

The pressuremeter shown schematically in Figure 2 shall include:

— the pressuremeter probe;

— the string of rods to handle the probe;

— the control unit (CU);

— the connecting lines between the control unit and the probe.

Some means of measuring the depth of the test with appropriate measurement error shall be provided (see also Annex E).

4.2 Pressuremeter probe

4.2.1 General

The probe shall be made up of cylindrical cells of circular cross-section along the same axis (see Figure 2). The probe shall consist of a hollow steel core with passages to inject the proper fluids to inflate the cells. The steel core, on its outside curved surface, shall usually bear a network of grooves which uniformly distribute the liquid (if relevant) in the measuring cell under the membrane, applying a uniform pressure on the pressuremeter test pocket wall. The top of the core shall be threaded and coupled to the string of rods handling the probe from ground level.

If the measuring cell has slenderness at least equal to 6, the probe may be mono-cell. Conversely the probe may be tri-cell to respect this criterion. A central measuring cell membrane shall isolate the fluid in the central measuring cell from the gas of the guard cells.

NOTE 1 Compliance with this criterion ensures that the stress field is two-dimensional.

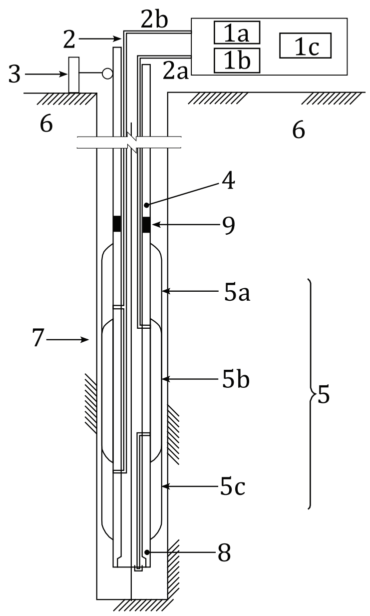
The central measuring cell may be:

— covered by the cover creating guard cell (tri-cell G type probe);

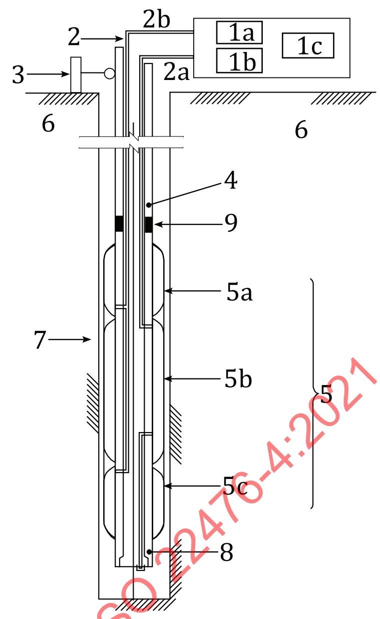
— covered by the cover with specific membranes for guard cells (tri-cell E type probe);

— covered by the cover without guard cells (mono-cell type).

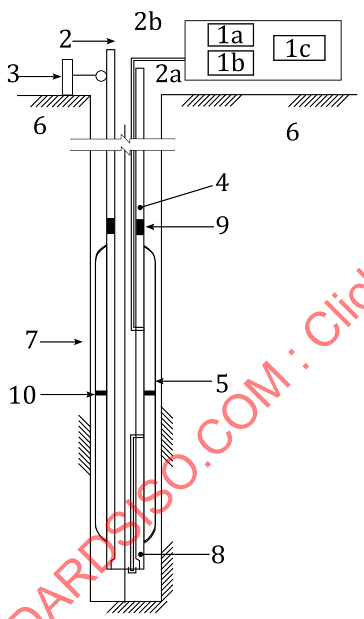
All probes can be equipped for volumetric measurement or by radial transducer or any device providing a reliable measure of either probe volume or radius. Pressure can be measured at control unit level or at probe level.



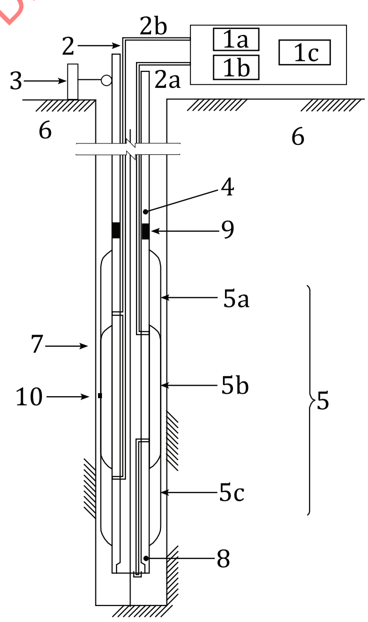
a) Tri-cell probe, G type, with measurement of volume of the measuring cell



b) Tri-cell probe, E type, with measurement of volume of the measuring cell



c) Mono-cell probe, with measurement of radial displacement (optional)



d) Tri-cell probe, with measurement of radial displacement

Key

1a pressurization, differential pressurization and injection devices
1b pressure and volume measuring devices
1c acquisition, storage and printing out of the data (required for CU type B and C)
2 connecting lines: 2a line for liquid injection
2b line for gas injection
3 depth measurement system
4 rods
5 pressuremeter probe
6 ground
7 pressuremeter test pocket
8 hollow probe body

5a upper guard cell

5b central measuring cell

5c lower guard cell

9 probe rod coupling

10 transducers

Figure 2 — Diagram of a Ménard pressuremeter

If expansion is followed by the volume of the measuring cell, the measuring cell shall be inflated by injecting a liquid of low compressibility.

NOTE 2 Alternatively air can be used to inflate the measuring cell and the expansion followed by displacement transducers.

Three types of pressuremeter probes shall be used depending of ground type and conditions according to Annex C:

— hollow probe body with a flexible cover;

— hollow probe body with a flexible cover and an additional more rigid protection;

— hollow probe body with a flexible cover and a slotted steel tube.

These probes are respectively described in Figure 3 a) and Figure 3 b) and their geometrical features are given in Table A.1.

The pressuremeter probe shall be capable of a volumetric expansion such as to enable assessing the Ménard pressuremeter limit pressure within its pressure capabilities.

NOTE 3 For 60 mm probes and probes in 60 mm slotted tubes, 200 + V_c can be used, where 200 and V_c are in cm^3.

NOTE 4 For other dimensions of tri-cell probes and for mono-cell probes, a specific assessment can be made.

4.2.2 Probe with flexible cover

The probe includes:

— one measuring cell, with an outside diameter d_c and a minimum length l_c, which shall expand radially in a pocket and shall apply a uniform pressure to the pocket wall;

— two guard cells if applicable with an outside diameter d_g and a length l_g located above and below the central measuring cell. These cells shall be designed to apply to the pocket wall a pressure close to, but not greater than, the pressure induced by the central measuring cell. These cells should be inflated by gas pressure.

The tri-cell probe should be fitted with a central measuring cell membrane and a flexible cover sleeve. The membrane and the flexible cover shall be fixed to the steel core with sealing system in order to avoid any leakage or pressure loss.

The flexible cover can be reinforced by textile or metallic canvas.

4.2.3 Probe with flexible cover and an additional more rigid protection

A flexible protection made of thin plastic or steel strips, either overlapping (up to half-way) or isolated, running between fixing rings may be added over the cover.

NOTE The flexible protection can be added to reduce damage to the cover from sharp fragments protruding from the pocket wall.

4.2.4 Probe with flexible cover and slotted tube

This probe shall consist of two parts:

— an inner part corresponding to previously described probes, and

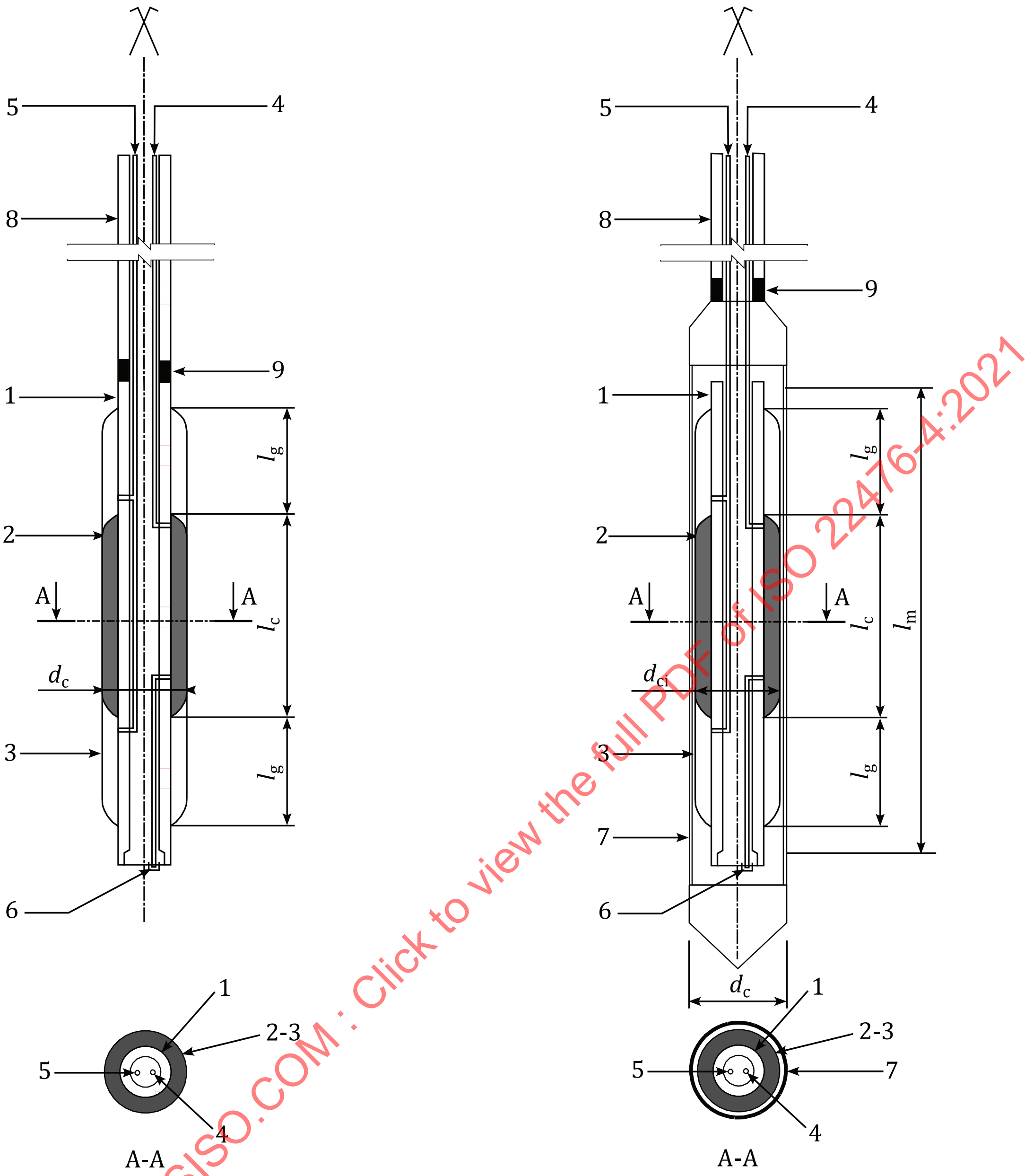
— an outer part which shall be made of a slotted steel tube (see Figure 3). When this slotted tube is pushed or driven into the soil it shall be fitted with an extension pipe ending with a point or a cutting shoe.

The outside steel tube shall carry at least 6 axial slots, evenly distributed round the circumference [Figure 3 b)].

The diameter of the slotted tube shall be verified at intervals appropriate to the use the probe has received, so that it remains compliant with tool diameter (see C.2.2).

The slotted tube should be kept clean, so that it is able to recover its original shape and size.

The assembly within the slotted tube shall be located so as to allow the probe to expand radially with a minimum of resistance. The mid plane of the measuring cell shall correspond to the mid plane of the slots.



a) pressuremeter probe with flexible cover **b) pressuremeter probe with slotted tube**

Key

1 hollow probe body
2 measuring cell membrane
3 external sleeve or flexible cover
4 liquid inlet to the measuring cell
5 gas inlet to the guard cell
6 measuring cell drain outlet
7 slotted tube
8 rods
9 probe-rod coupling

Figure 3 — Description of the pressuremeter probe

4.3 Connecting lines and injected fluid

The flexible lines shall connect the pressure and volume control unit to the probe. They shall convey the liquid to the measuring cell and the gas to the guard cells. They may be parallel or coaxial. When the lines are coaxial the central line shall convey the liquid and the outer line the gas.

The liquid injected into the measuring cell is either water or a liquid of similar viscosity and shall not freeze under the conditions of use.

The injected fluid and inner diameter of the connecting lines shall be selected in order to transmit the fluid from the CU to the probe in a time acceptable for pressure step to apply to the ground. The increment of volume $V_{60/30}$ should be lower than 30 cm^3 at the ultimate pressure loss of the probe p_{el} during central membrane pressure loss test.

NOTE Additives such as ethylene glycol increase notably the viscosity of the fluid and therefore the time to transmit the fluid from the CU to the probe is increased. Alternative fluid like oil can also be chosen.

4.4 Pressure and volume control unit

4.4.1 General

The control unit shall include:

— equipment to pressurize, and so to inflate the probe, and to maintain constant pressures as required during the test;

— equipment to maintain an appropriate pressure difference between the central measuring cell and the guard cells, if relevant;

— device which permits, according to the type defined in Table 1, the reading and recording of the parameters to be measured: time, pressure and volume.

Table 3 — Types of pressuremeter control unit

Type of control unit	Type of test regulation	Type of reading and recording
A	manual	manual
B	manual	automatic
C	automatic	automatic

The control unit shall control the probe cell expansion and permit the simultaneous reading of liquid and/or gas pressures and injected liquid volume or radius of the measuring cell as a function of time.

The pressurizing device shall allow:

— reaching the pressuremeter limit pressure or a pressure p_r at least equal to the maximum pressure defined for the test;

— holding constant each loading pressure level in the measuring cell and in the guard cells during the set time;

— implementing a pressure increment of 0,5 MPa in less than 20 s as measured on the control unit;

— controlling the pressure difference between the measuring cell and the guard cells;

— injecting a volume of liquid in the measuring cell larger than at least its volume at rest V_c, i.e. 700 cm^3 for a 60 mm pressuremeter probe.

If volumetric measurement is used, a valve between the volumeter and the pressure measuring device shall allow stopping the injection.

4.4.2 Measurement and control

4.4.2.1 Time

The accuracy of the device used to measure time shall be in accordance with Annex E.

4.4.2.2 Pressure and volume

The pressure measuring devices for the fluid in the central measuring cell and for the gas in the guard cells shall be located:

— either in the control unit;

— or inside the probe, less than 1 m above the centre of the central measuring cell.

The resolution of measurement of the devices measuring pressure and volume shall be in accordance with Annex E.

4.4.2.3 Display of readings

At the site the pressure and volume control unit shall give a simultaneous and instantaneous display of the following readings: time, pressure of the liquid injected into the measuring cell, volume of the liquid injected or radius of the measuring cell and pressure of the gas in the guard cell circuit when relevant.

4.4.2.4 Volume loss calibration cylinder

The main features of this steel cylinder (Figure B.1) shall be as follows:

— measured inside diameter d_i not more than 10 % of over the probe diameter d_c;

— wall thickness not less than 8 mm;

— length l_p more than 1 m or the slot length l_m, whichever is greater.

4.4.3 Data logger

The data logger, the device to acquire and record the data with type B or C control units, shall be designed to record time, the raw data from the transducers, the zeros, calibration coefficients and identification of each probe and the resulting calibrated data of pressure and volume.

The data logger B or C records p_r and V_r, and in case of radius measurements by transducers, p_r and r_i.

The data logger shall permit the display or the printing of the raw data of pressure and volume (p_r, V_r) at the time interval defined by loading program, and the raw pressuremeter curve.

The data logger shall not interfere with the conduct of a test as specified in 5.7 and it shall not obscure any other measuring devices. It shall be designed so as to automatically:

— record its own identification parameters: control unit number, data logger number;

— require the input of the information necessary to the test, as described in 5.4;

— prevent the input of pressure and volume data or other information not obtained during the testing process.

5 Test procedure

5.1 Assembling the parts

The cover, the membrane and possibly the rigid protection or the slotted tube if required shall be selected according to the expected stress-strain parameters and type of the ground in which the probe is to be used. They shall each fulfil the specifications given in Annex A. Then the probe shall be linked to the control unit through the connecting lines.

The whole system shall be filled with liquid and purged to remove air bubbles.

The whole probe shall be inflated three times to the maximum volume defined in 4.2.

5.2 Calibration and corrections

Calibration and correction shall be performed according to Annex B. Copies or display of the calibration results shall be available at the testing location and later provided with raw data.

5.3 Pressuremeter test pocket and probe placing

In pressuremeter testing, it shall be paramount to achieve a high-quality pocket wall. The procedures and requirements in Annex C shall be followed.

The position of the test should be defined prior to the test and may exceptionally be modified to avoid placing the probe on clear geological localized mechanical transitions (very soft soil on stiff ground).

The preparation of satisfactory pockets shall be the most important step in obtaining acceptable pressuremeter test results.

Three conditions shall be fulfilled to obtain a satisfactory pressuremeter test pocket:

— the equipment and method used to prepare the pressuremeter test pocket shall cause the least possible disturbance to the soil at the cavity wall (see C.1);

— the diameter of the cutting tool shall meet the specified tolerances (see C.2.2);

— the pressuremeter test shall be performed immediately after the pocket is formed (see Table C.1 and C.1.3 and C.1.4)

NOTE An indication of the quality of the pressuremeter test pocket is given by the shape of the pressuremeter curve and the magnitude of scatter of the resulting parameters in one geotechnical unit (see D.2).

5.4 Preparation for testing

The pressure and volume control unit and the data logger shall be protected from direct sunlight.

The position of the pressuremeter sounding shall be marked on a drawing and identified by its location details.

If the sounding is inclined, its slope and direction shall be recorded (see Annex F).

As a next step, for each sounding:

— the acquisition and recording device, i.e. the data logger, shall be initialised (type B and C);

— the initial reading of each transducer shall be checked and, if appropriate, recorded (type A, type B and type C).

The identification parameters of the test are recorded, either in the memory device or on the data sheet with a carbon copy (see Annex F):

— date (year, month, daye, hour and minute) of the test;

— test operator identification;

— report number;

— sounding number;

— type of probe;

— technique of pocket drilling (see Annex C);

— ground identification and description according to ISO 14688-1 and ISO 14689;

— method of probe setting;

— calibration test references (see Annex B);

— elevation z_c of the pressure transducer or value of $z_c - z_N$ for this transducer (see Figure D.1);

— elevation z_s of the test location or depth $(z_N - z_s)$ of the probe (see Figure D.1);

— differential pressure setting (see B.4.4).

5.5 Establishing the loading programme

The loading programme of a pressuremeter test shall be the relationship between time and pressure as applied by the probe to the ground (Figure 4).

At each pressure step the pressure shall be held constant in the measuring cell and in the guard cells, if applicable, for a time t_h. The step duration t_h is chosen in order to catch the soil behaviour and not the hydraulic characteristics of the CU circuit and connecting lines. A value of 60 s is commonly used.

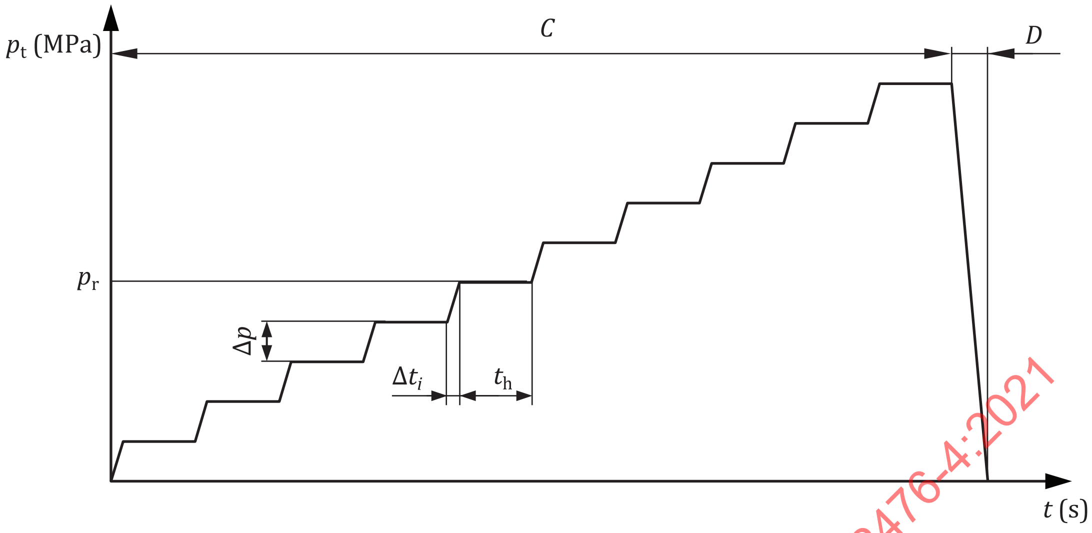
In case of a long connecting line and low external temperature needing the use of additive in fluid with viscosity higher than water, implying slow response of the system, appropriate adjustment to t_h shall be made; or a specific assessment (experimental or theoretical) of pressure loss may be taken into account.

The difference between the target pressure and obtained pressure should not exceed 25 kPa or 1,0 % for type A and type B and 15 kPa or 0,5 % for type C. In case the obtained pressures exceed theses values then the average value of pressure over the whole pressure step shall be recorded.

The initial pressure increment Δp_1 to be used shall be decided by the operator after observation of the drilling parameters, examination of the core or the drill cuttings and by instruction. In case of similar ground conditions, the pressuremeter limit pressure of the previous test may be used and divided by 10. Once the initial readings have been recorded, the operator shall observe the creep parameter $V_{60/30}$ and the differences $V_{60/60}$ between successive 60 s volume readings and as a result may change the pressure increment so as to:

— obtain approximately 10 points during the test, and a minimum of 8 points;

— reach the end of the test (see 5.7.3).



Key

p_t	target pressures	t	time
Δp	pressure increment	Δt_i	pressure increment duration
p_r	pressure step during t_h	t_h	duration of a pressure step
C	loading phase	D	unloading phase

Figure 4 — Loading programme for a Ménard pressuremeter test

A constant pressure increment Δp should be used. If needed, its value may be adjusted up to two times during the test, during the pseudo-elastic phase. The value of the pressure steps should not be modified after exceeding the creep pressure.

The duration Δt_i to apply the pressure increment Δp shall be less than 20 s. Appropriate adjustment to Δt_i shall be made for the case of long connecting line length (when in coil) and viscous injected liquid. The time Δt_i shall be kept constant during the test. Once the test is completed as described in 5.7.3, unloading shall be performed.

5.6 Establishing the pressure of the guard cells for tri-cell probes

The pressure of the gas in the guard cells depends on the type of tri-cell probes and shall be calculated according to B.4.5.

5.7 Expansion

5.7.1 General

The expansion process shall include:

— applying a uniform pressure to the pocket wall through the pressuremeter probe according to the loading programme (see 5.5);

— recording the measuring cell volume changes with time as a function of the loading pressure applied to the measuring cell.

5.7.2 Readings and recordings

At each pressure step the following readings shall be taken.

— In type A, the fluid or gas pressure in the measuring cell required by the loading programme shall be recorded once and the injected volume in the probe at the following times once target pressure is reached: 15 s, 30 s and 60 s. For tri-cell probes, the liquid and gas pressures, the differential pressure and their variations shall be checked. Excessive variation shall be noted (see also 5.5).

— In type B and C, the applied fluid or gas pressure in the measuring cell and the injected volumes in the probe should be recorded each second and shall be displayed at least at the following times: 1 s, 15 s, 30 s and 60 s. Readings of gas pressures at the same times may be used for checking.

The origin of the time for each pressure step is taken at the end of the corresponding pressure increment period t_i. The origin of the time t_0 for each pressure step is taken at the beginning of the load step (see Figure 4) and shall be recorded.

5.7.3 End of test

Unless otherwise specified, the test is terminated when sufficient data have been accumulated for the intended purpose, within the full capabilities of the equipment. These normally are:

— when the pressure p_r reaches at least the pressuremeter limit pressure or a pressure at least equal to 5 MPa (or up to 8 MPa if required);

— when the volume of liquid injected into the measuring cell exceeds the value given in 4.2;

— when at least three pressure steps beyond p_f are obtained;

— when the probe bursts.

NOTE For a 60 mm tri-cell probe, the volume of the probe V_c given in 4.2 corresponds approximately to 600 cm^3.

5.8 Back-filling of the pockets

Method of back-filling of the pockets resulting from the pressuremeter sounding shall be agreed and carried out in accordance with ISO 22475-1, taking into consideration national regulations, technical or authority requirements, the strata, contamination of the ground and its bearing capacity.

If required, backfilling of the hole in the ground resulting from the pressuremeter sounding shall be completed and documented in the test report.

5.9 Safety requirements

It is presupposed that national safety regulations are followed; e.g. for:

— personal protection equipment;

— clean air if working in confined spaces;

— ensuring the safety of personnel and equipment;

Drill rigs shall be in accordance with ISO 22476-15 when applicable.

6 Test results

6.1 Data sheet and field print-out or display

6.1.1 Data sheet for type A control unit

All the data as shown in F.2 shall be fully and carefully recorded.

The operator shall authenticate the data sheet by signing and giving his full name in capital letters.

6.1.2 Site print-out for type B and C control units

At least the following information shall be printed or display at site for any test:

a) before the start of the test:

— the operator's identification;

— a statement that the test will comply with this document;

— the data logger parameters;

— pressurizing and read-out unit number (and data logger number if separate from the unit);

— information input for test identification: as listed in 5.4;

b) at the start of the test:

— date (year, month, day, hour and minute) at the start of the test;

c) at the end of each pressure step:

— loading pressure step number in the series;

— one liquid pressure reading in the time interval between the start of the pressure hold and 15 s later, correct to at least three significant digits;

— readings at 30 s and 60 s after the start of the pressure step of injected volume rounded to the nearest cm^3, or of radius of each displacement transducer;

— the difference between these two readings i.e. $V_{60/30}$;

— the difference between the 60 s injected volume readings of the current and preceding pressure step $V_{60/60}$;

d) at test completion:

— date and time at completion of test;

— computer plot of volume readings V_r against pressure readings p_r at 60 s giving the raw pressuremeter curve;

— the operator shall authenticate the full print-out by signing and giving his full name in capital letters.

6.1.3 Raw pressuremeter curve

The raw pressuremeter curve shall be obtained by plotting control unit readings V_r versus p_r, each at 60 s.

For types B and C control units, the raw pressuremeter curve shall be provided by the data logger printer or screen.

6.2 Corrected pressuremeter curve

The corrected pressuremeter curve (Figure 5) shall give the probe central measuring cell volume V as a function of the pressure p applied to the pocket wall:

$$V = f(p)$$

where

p is the pressure applied by the outer cover of the probe on the pocket wall, after correction for hydraulic head and pressure loss (see D.1.2 and D.1.3);

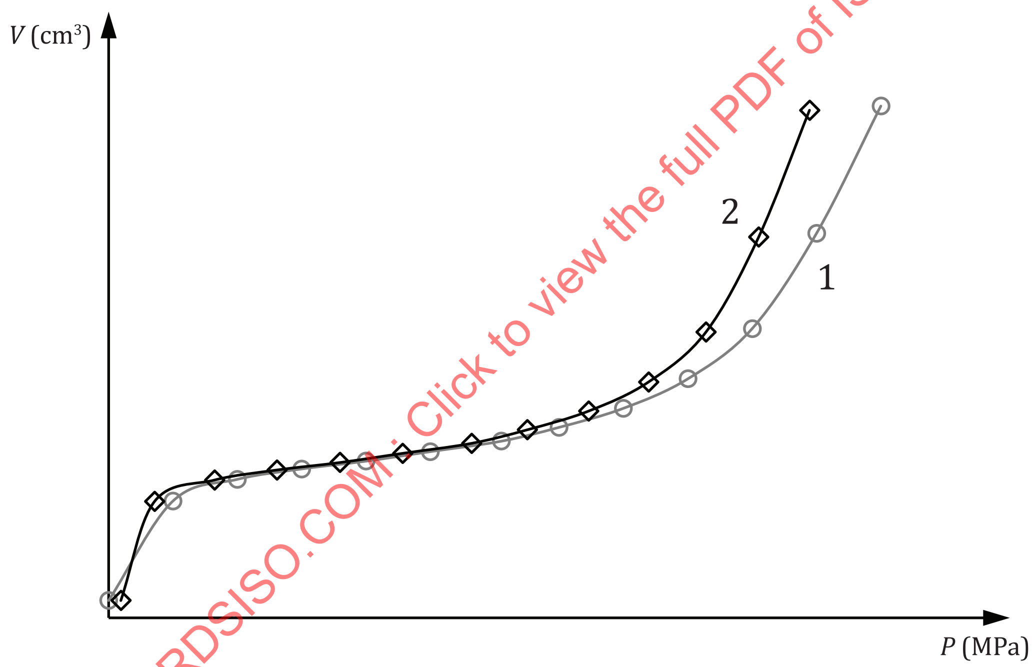
V is the corresponding volume at 60 s after zeroing (see B.4.2), of liquid injected into the probe, and after correction for volume loss (see D.1.4), or the volume calculated by averaging the radial transducers.

The method used to model the pressure loss experimental curve and the parameters shall be reported (see D.1.3).

The corrected pressuremeter curve shall be defined by the succession of coordinates (*p*, *V*) shown in Figure 5.

At the start of the pressuremeter test, the pocket wall shall be loaded by the probe until it returns approximately to its original condition.

From this point the slope of the pressuremeter curve should generally remain sensibly constant for several successive steps. When the test reaches approximately half of its course the radial expansion rate of the probe should increase more rapidly with increasing pressure until reaching ending conditions for the test as defined in 5.7.3.



Key

1 raw pressuremeter curve

2 corrected pressuremeter curve

Figure 5 — Plot of a corrected pressuremeter test

6.3 Calculated results

The pressuremeter test parameters shall be obtained from the information recorded on the data sheet (type A) or either in a numerical format (type B and C).

First, the data shall be examined as recorded to see if and how much of the curve can be analysed (see Annex D).

Next, the methods described in Annex D shall be used:

— to determine the pressuremeter creep pressure p_f (D.3);

— to determine the Ménard pressuremeter limit pressure p_{LM} (D.4);

— to calculate the Ménard pressuremeter modulus E_M (D.5).

7 Reporting

7.1 General

The test results shall be reported in such a fashion that third parties are able to check and fully understand the results.

7.2 Field report

The field report shall contain all data collected in the field (see 5.4 and 6.1).

The field report shall enable to identify the operator in charge (6.1.1 and 6.1.2).

An example of field report for a single pressuremeter test is provided in Annex F.

7.3 Test report

7.3.1 General

The test report shall include the field report (7.2) and the Ménard pressuremeter test report including the obtained pressuremeter parameters and the indication of the process of interpretation. The test report shall be signed by the field manager responsible for the project.

7.3.2 Ménard pressuremeter test report

The report for a single pressuremeter test shall include the corrected data, the pressuremeter curve and the pressuremeter test parameters. An example is provided in Annex F.

It shall also contain the field reports including in the case of type B and C the corresponding readable electronic data recorded on an electronic support as described in 5.7.

The report shall include the following data as a minimum:

a) reference to this document (ISO 22476-4:2021);

b) type of control unit used for the test: A, B or C;

c) identification number of the sounding where the pressuremeter test was performed;

d) elevation of the test or its depth from the top of the sounding or casing;

e) type of drilling technique and drilling tool used to create the pocket and the top and bottom elevations of the drilling stage;

f) time of completion of the pressuremeter test pocket, to the nearest minute;

g) type, make, and serial number of the control unit and of the data logger if separate from the control unit;

h) information on the recent checks of all control and measuring devices used (see B.1);

i) time at the start of the test, correct to the minute;

j) type of probe used (see 4.2) and its details (cover type, rigid protection, slotted tube, etc.), the volume loss and the pressure loss calibration test results as defined in Annex B;

k) differential pressure ($p_r - p_g$) at control unit elevation;

l) table of the liquid pressure and volume readings at 1 s (type B and C only), 15 s, 30 s and 60 s at each pressure loading level;

m) p,V coordinates of each point used to plot the corrected pressuremeter curve;

n) all mishaps during the test (such as a probe bursting);

o) elevations of the pressuremeter sounding top z_N and the pressure transducers z_c as shown in F.2 and Figure D.1;

p) elevation of the drilling fluid level when applicable and the ground water table when known: z_c;

q) name of the company performing the pressuremeter sounding i.e. drilling and testing;

r) corrected pressuremeter curve and the methods used for pressure and volume loss corrections;

s) Ménard pressuremeter modulus E_M and the method used to obtain it;

t) Ménard pressuremeter limit pressure p_{LM} and the method used to obtain it;

u) creep pressure p_f and the method used to obtain it;

v) ground identification and description according to ISO 14688-1 and ISO 14689 for the pressuremeter test pocket.

7.3.3 Pressuremeter tests log

A pressuremeter tests log, as shown in F.3, shall include as a minimum:

a) reference to this document (ISO 22476-4:2021);

b) type of control unit used: A or B or C;

c) pressuremeter soundings layout drawing and, if appropriate, the grid references of the soundings;

d) ground surface elevation z_N at the pressuremeter borehole measured from a stated datum;

e) level of the fluid in the borehole resulting from the pressuremeter sounding at specified times, and the elevation of the ground water table, if known;

f) pocket formation technique with reference to Table C.1 and the dates at which the various pockets were formed;

g) pressuremeter sounding inclination and direction;

h) information on the ground strata;

i) drilling parameters according to ISO 22476-15;

j) graphical representation of the pressuremeter parameters as a function of depth, with a depth scale and the following values:

— Ménard pressuremeter modulus E_M ;

— Ménard pressuremeter limit pressure p_{LM} ;

— pressuremeter creep pressure p_f.

Pressures and pressuremeter moduli shall be quoted to at least two significant digits.

For the same site, it is recommended to have a common scale for all pressuremeter logs.

k) comments on the test procedure, mishaps and any other information which may affect the test results.

Annex A
(normative)

Geometrical features of pressuremeter probes

A.1 Geometrical specifications for probes

Table A.1 shall be read in conjunction with 4.2 and Figure 3 a) and Figure 3 b).

Table A.1 — Geometrical specifications for 60 mm tri-cell pressuremeter probes

			Symbols	Unit	Value	Tolerance
Hollow probe body with flexible cover		Central measuring cell length	l_c	mm	210	$^{+5}_{0}$
		Guard cell length	l_g	mm	120	±15
		Outside diameter	D_c	mm	60	±5
Probe with slotted tube [see Figure 3 b)]	Inner part: central measuring cell	Central measuring cell length	l_c	mm	370	±5
		Guard cell length	l_g	mm	110	±5
		Central measuring cell outside diameter	d_{ci}	mm	44	±2
	Slotted tube	Outside diameter	d_c	mm	60	±5
		Slot length (along tube axis)	l_m	mm	≥ 800	-

The tube slotted length l_m is measured along the tube axis. This length shall be the greater of:

$1{,}3\ (l_c + 2\ l_g)$ or 800 mm

NOTE 1 Other length of the measuring cell can be used. For the 60 mm slotted tube, a 210 mm central measuring cell has been historically used.

NOTE 2 A 60 mm flexible cover probe be used as inner part of a slotted tube of 76 mm of outside diameter. Alternatively, a 76 mm flexible cover probe can be used.

The inner diameter of the probe shall be such as to evacuate the water or mud through the stem so as to avoid any detrimental variations of pressure (preloading or suction) in the borehole wall when placing the probe.

The drain tap of the measuring cell shall protrude from the bottom of the steel core. A probe shoe or cutting shoe may be used to protect the drain tap when inserting the probe in the test cavity. Such shoes shall have openings for the same reasons.

NOTE 3 These variations of pressure induce an effect on the quality of the borehole wall.

NOTE 4 If no slotted tube is involved, the hollow probe body is designed to withstand pushing.

A.2 Selecting pressuremeter probe and components

The pressuremeter probe pressure loss, including the slotted tube when applicable, shall be as small as possible when compared with the expected value of the limit pressure at test depth.

The choice of probe major components shall be guided by the following conditions:

a) for the central cell membrane, if applicable

$p_m \leq 80$ kPa

b) for the whole probe

when $p_{lM} \leq 900$ kPa, then: $p_{el} \leq p_{lM}/3 + 25$ kPa

when $p_{lM} > 900$ kPa, then: $p_{el} \leq \min \{ [p_{lM}/18 + 275 \text{ kPa}] ; 350 \text{ kPa} \}$

Annex B
(normative)

Calibration and corrections

B.1 Measuring devices

All control and measuring devices shall be periodically checked and calibrated against reference standards to show that they provide reliable and accurate measurements. The calibration interval shall be such that the resolution required can be verified, and should be less than one year

NOTE 1 Verification of the required resolution can be based on the record of previous calibrations.

The uncertainties of measurements summarized in Annex E shall be considered.

If one part of the system is repaired or exchanged the calibration shall be verified.

A copy of the latest calibration test report shall be available at the job site.

In addition to the calibration of the measuring devices, corrections shall be applied to the field readings for the pressure loss and the volume loss of the whole equipment. If the stiffness of the central measuring cell membrane of a tri-cell probe is not given by the supplier, then it shall be independently measured as given in B.2.

NOTE 2 Pressure loss is due to the added stiffness of the central measuring cell membrane (tri-cell probe case), the flexible cover and the slotted tube (if any). It varies with the probe inflated volume.

NOTE 3 Volume loss is due to the expansion of the pressure connecting line, the pressure measuring device and the compression of any gas contained in the liquid injected into the central measuring cell. It varies with the probe pressure.

B.2 Pressure loss of central measuring cell membrane alone

B.2.1 General

The pressure loss value p_m, which is a constant value for each batch of central measuring cell membranes, shall be obtained from the membrane supplier. If this information is not available, it shall be determined by using an inflation test on each membrane as described in B.2.2 and B.2.3.

B.2.2 Preparation of pressuremeter probe for central cell membrane pressure loss test

The probe shall be fitted with the central measuring cell membrane only, connected by a short connecting line (less than 2 m) and held vertically. The central measuring cell and the line shall be purged to remove air bubbles. Then the membrane shall be inflated at least three times by injecting a volume of liquid given in 4.2.

For this operation the pressurizing and read-out unit shall be fitted with a pressure measuring device accurate to better than 10 kPa.

The device measuring the injected volume shall be zeroed by bringing the centre of the measuring cell to the level of the pressure measuring device.

B.2.3 Measurement of central cell membrane pressure loss

The membrane shall be inflated in pressure increments Δp equal to 10 kPa. The volume of liquid V_{60} measured at 60 s shall be used to plot the curve:

$$V_{60} = f(p)$$

The membrane pressure loss p_m shall be given by the pressure for which the volume of liquid injected in the cell is the maximum volumetric expansion given in 4.2.1.

B.3 Checking measuring devices at site

Readings of the analog and digital indicating instruments of the control unit shall be compared with any other available measuring device (for example against display of the data logger, additional pressure gauges, etc.) at least at the beginning of each new contract. Any difference shall be investigated.

Further, the control unit shall be checked for correct operation of pressure and volume measuring devices as specified in a written procedure, for instance, by comparing the readings obtained on the various pressure transducers and in case of types B and C control units, by comparing the readings of the volumeter and the data logger display.

The equipment shall be corrected, replaced or repaired when the difference between readings is larger than the following values:

a) for pressure readings, the largest of:

— 5 % of the mean value of the two readings; or

— 1 % of the full-scale measurement;

b) for volumes: 3 cm^3.

B.4 Reading corrections

B.4.1 General

The stiffness of the membrane and cover assembly decreases during their first expansions and this decrease shall be minimised by some preliminary exercising as described in B.4.2.

The operations described in B.4.3 and B.4.4 shall then be carried out as follows:

— at each change of pressuremeter probe configuration;

— at each change of connecting lines between the probe and control unit;

— at intervals appropriate to the use the probe has received, e.g. weekly for daily operation.

These operations shall be performed when the probe is ready to be inserted in the pressuremeter test pocket; that is when the connecting lines are fitted and gas bubbles have been purged from the central measuring cell and the liquid circuit.

B.4.2 Probe pre-inflation and zeroing of the volume measuring device

Before use, any probe shall first be inflated at least 3 times in the open air by injecting a volume of liquid exceeding 1,2 times the volume of the probe V_c or the expansion during the current step is such that this value would be reached before the end of an additional step.

After that,

— the volume measuring device shall be zeroed by adjusting the volume of liquid whilst keeping the centre of the measuring cell at the level of the pressure measuring device;

— the acquisition and recording device, i.e. the data logger, shall be initialised (types B and C control units);

— the initial reading of each transducer shall be checked and, if appropriate, recorded.

B.4.3 Equipment volume loss calibration test

B.4.3.1 General

The probe, either simply clad by its rubber cover or fitted with its slotted tube, shall be placed into the volume loss calibration cylinder as described in 4.4.2.4 and Figure B.1. The probe shall be pressurized by increments Δp initially of 100 kPa until the probe cover or the slotted tube comes into contact with the calibration cylinder. After this point, equal increments shall be applied up to the expected maximum pressure of the tests to be performed. During the second part of this test each pressure level shall be applied within 20 s and held for 60 s.

The pressure in the guard cells shall fulfil the conditions given in B.4.5.

B.4.3.2 Obtaining the volume loss correction for the equipment

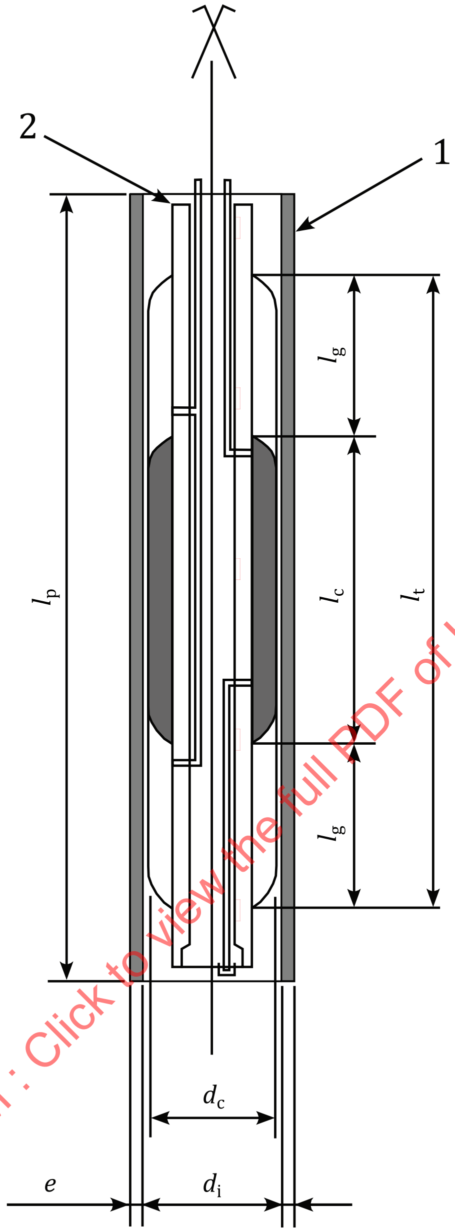
The injected volume at the end of each pressure step shall be recorded and used to plot a graph of $V_r = f(p_r)$ resulting in the volume loss correction curve.

The volume loss factor a and V_p are respectively the slope and the intercept of the straight line best fitting the points after the probe comes into contact with the calibration cylinder, according to the following formula and Figure B.2.

$$V_r = V_p + a.p_r$$

Excessively high a values suggest inadequate liquid filling, a leak in the liquid circuit or other problem. The whole equipment, including control unit, lines and probe shall be checked again.

NOTE A maximum value of 6 cm^3/MPa has been historically considered for the 60 mm pressuremeter probe.



Key

1 calibration cylinder

2 pressuremeter probe

Figure B.1 — Calibration cylinder for volume loss correction (example of a tri-cell probe)

B.4.3.3 Obtaining central measuring cell volume V_c

The initial external volume of the central measuring cell, for a probe with a flexible cover with or without rigid protection, shall be obtained from the following formula:

$$V_c = 0{,}25\ \pi\ l_c\ d_i^2 - V_p$$

where

V_p is in B.4.3.2;

l_c is the length of the central measuring cell measured when the cell membrane is fixed on the probe steel core, as shown in Figure B.1 and in Table A.1;

d_i is the inside diameter of the calibration cylinder. This value shall be recorded on the pressuremeter test report.

For a probe in a slotted steel tube, the initial external volume of the central measuring cell shall be obtained from the following formula:

$$V_c = 0{,}25\ \pi\ l_c\ (d_i^2 - (d_c^2 - d_{ci}^2)) - V_p$$

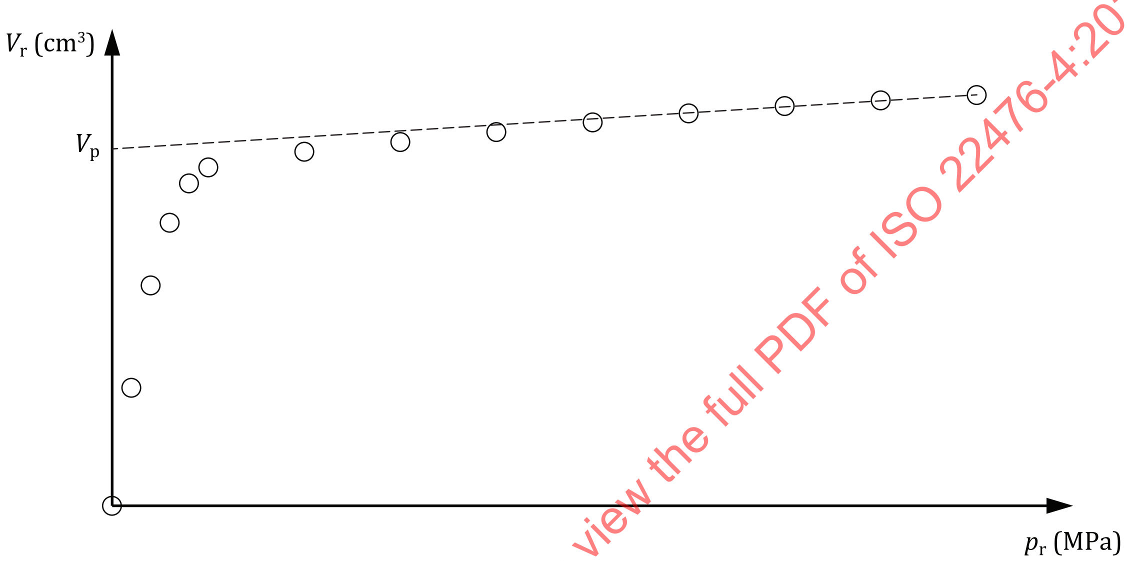


Figure B.2 — Volume loss calibration – Example

B.4.4 Probe pressure loss calibration test

The probe shall be placed close to the pressure measuring device, as shown on Figure B.3, and in the open air. The probe shall be inflated as if it were in the ground, with pressure increments Δp equal to 1/5 of the expected pressure loss of the probe p_{el}. Each pressure increment shall be held for 60 s. A volume of at least 700 cm^3 shall be injected in the central measuring cell.

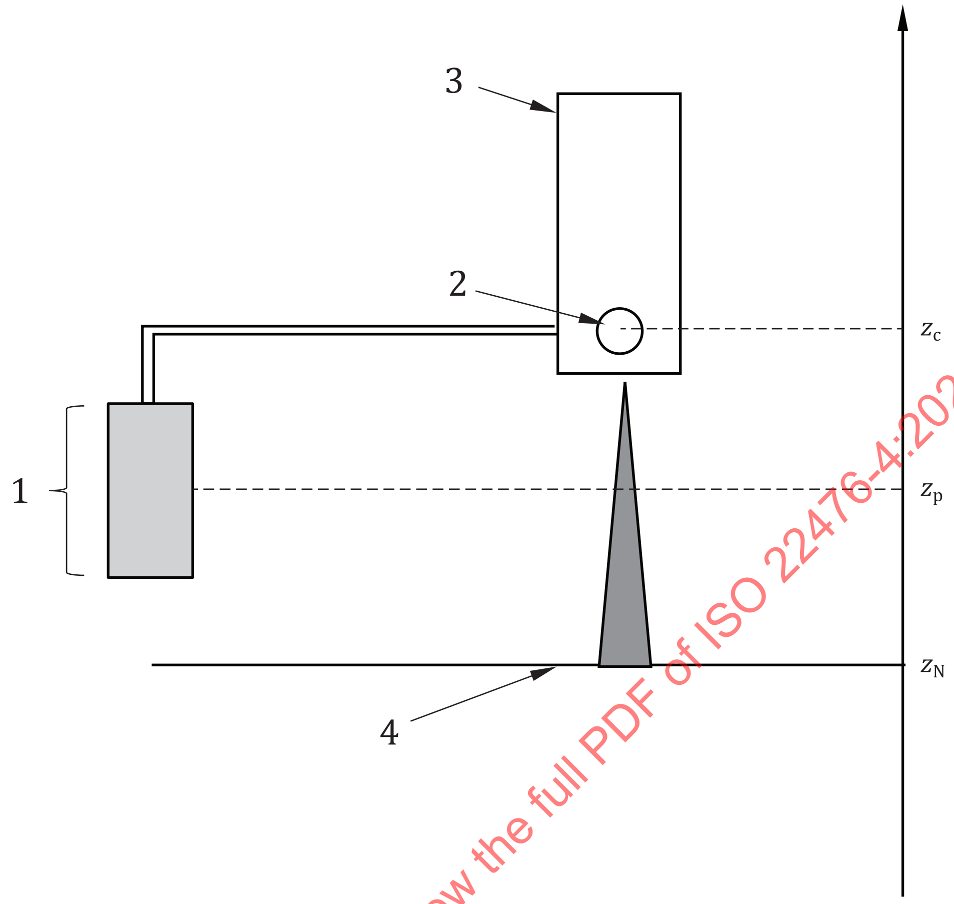
The volumetric strain rate of the pressure loss test should not significantly differ from the one imposed during the pressuremeter test. Alternatively, the pressure loss calibration can be made by volume steps, with a total duration equal to the pressuremeter test.

NOTE The pressure loss p_{el} of the probe is a function of the type of membrane, cover and slotted tube, if any, which are used. It is essentially adapted to the type of ground to be tested. It can vary between 0,05 MPa and 0,3 MPa.

The resulting pressure versus volume curve, $V_{60} = f(p_e)$ is illustrated in Figure B.4.

The pressure values obtained from this curve for each pressure step shall be used for the pressure loss correction (see D.1.3).

The ultimate probe pressure loss p_{el} (Figure B.4) shall be the pressure reading for an injected volume of liquid equal to 1,2 times the volume of the probe V_c (around 700 cm^3 for a 60 mm pressuremeter probe).



Key

1 pressuremeter probe
2 pressure measuring device
3 pressure regulator
4 ground surface
z elevation

NOTE For z_c , z_s and z_N, refer to Figures B 5 and D.1.1.

Figure B.3 — Elevation of probe and pressure regulator during a pressure loss calibration

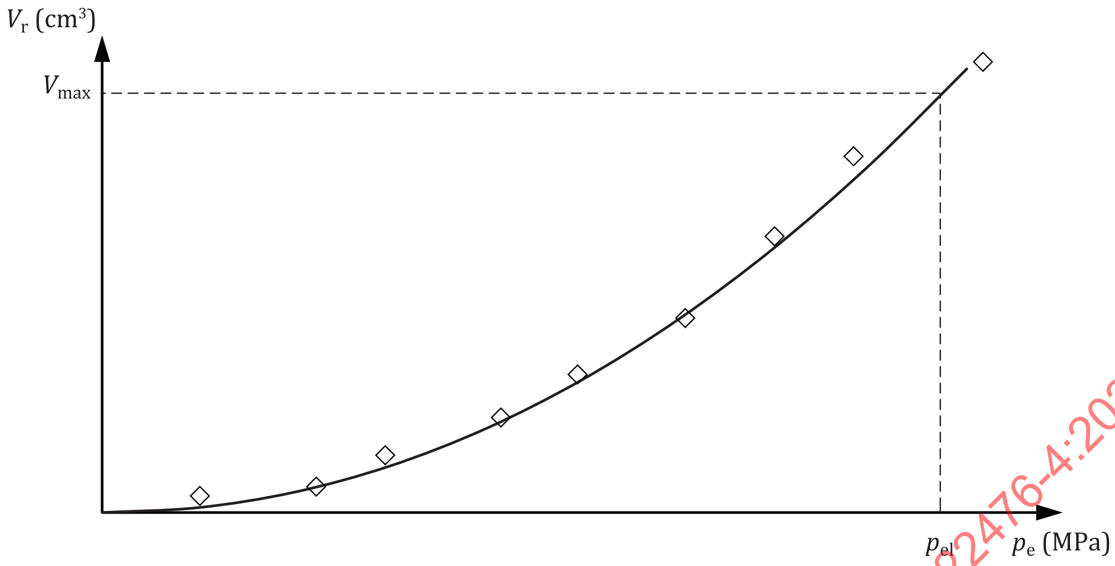


Figure B.4 — Example of pressure loss plot for a pressuremeter probe

B.4.5 Estimation of gas pressure in guard cells for a given test

The gas pressure p_k in the guard cells shall not be higher than the pressure in the central measuring cell p_c. The difference between the pressure at the measuring cell and the guard cells shall be such as to ensure a correct inflation (quasi-cylindrical) of the measuring cell during the test. In general, for G type probes, this difference is comprised between two or three times the central cell pressure loss.

This can be verified if the following relationship is respected, at the probe level:

$$(p_c - p_k) = Kp_m$$

$$p_k = 0 \quad \text{if} \quad p_c < Kp_m$$

$$2 \leq K \leq 3$$

The central cell pressure loss p_m and the coefficient K to be adopted are parameters that depend on the membrane being used for the central cell. These parameters shall be given by fabricant or determined by the contractor before any testing.

The difference between the pressure at the measuring cell and the guard cells shall be determined before each test as a function of the testing depth and fixed at the first pressure step. This value shall not vary during the test.

At the CU level, operator shall adjust the differential pressure $p_{diff,CU} = (p_r - p_g)$ according to the following rules:

For conditions in which the self-weigh of gas can be neglected: (considering $p_k \approx p_g$ and given that $p_c = p_r + p_h$):

$$p_{diff,CU} = \left(p_r - p_g\right) = Kp_m - p_h$$

For conditions in which the self-weigh of gas cannot be neglected, p_k shall be corrected as follows:

$$p_k = p_g + \lambda_g \left(z_{CU} - z_p\right) p_g$$

Where:

p_c is the liquid pressure in the central measuring cell, obtained with $p_c = p_r + p_h$;

p_m is the central measuring cell membrane pressure loss;

p_k is the gas pressure in the guard cells. Since the unit weight of the gas changes with the gas pressure:

$(z_{CU} - z_p)$ is the vertical distance between probe cells and measuring device in the control unit,

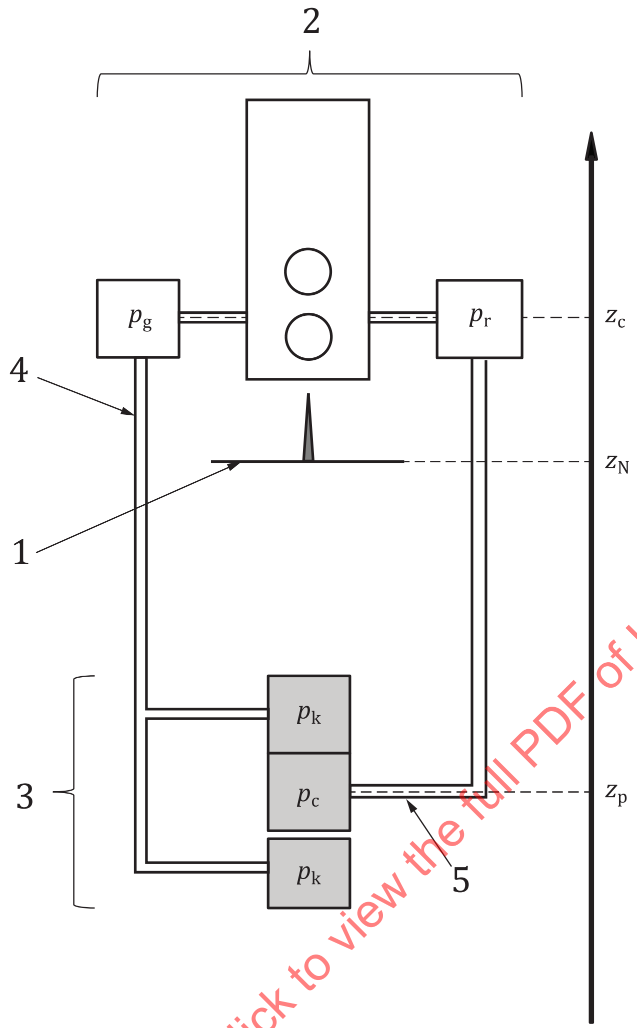
p_h is the head in the liquid line between the liquid pressure transducer and the central measuring cell,

p_g is the pressure reading at the control unit of the gas in the guard cells.

λ_g is the rate of change of pressure head of gas at pressure p_k per meter depth. When no data is available, λ_g = 1,15 10^{-4} m^{-1} may be used.

NOTE For practical purposes, the gas unit weight change can be ignored when the vertical distance between the control unit and the probe is less than 30 m and the gas pressure less than 5 MPa.

For type G tri-cell probes, at the jobsite, and before carrying out the tests, the operator shall be given a table exhibiting guard cells pressures as a function of the depth according to the type of probes used.



Key

1 ground surface
2 CU
3 pressuremeter probe
4 gas line
5 liquid line

NOTE z_c and z_{cg} are positive; z_p is negative.

Figure B.5 — Details of pressures and elevations during a Ménard pressuremeter test

Annex C
(normative)

Placing the pressuremeter probe in the ground

C.1 General considerations

C.1.1 Overview

Pressuremeter testing and the production of the pressuremeter series of pockets shall be considered together. The quality of each pocket wall governs the quality of each test. In order to place the probe in the ground and to obtain valid Ménard pressuremeter parameters, the pressuremeter test pocket formation techniques shall be adapted as specified in C.2 and C.3 according to the type of soil (see Table C.2). Alternative techniques may be chosen depending on the actual site conditions and on the evaluation of the operator. When the soil conditions are unknown, equipment for several different techniques shall be brought to the site so as to cover unexpected cases.

If any placing technique other than those listed in C.2 is used, the contractor shall be able to demonstrate upon request that the technique yields pressuremeter results of satisfactory quality (see D.2.2).

C.1.2 Spacing between tests and the minimum depth of probe in the ground

In any pressuremeter sounding, the minimum spacing between two successive tests shall not be less than ten times the probe diameter (> $10d_c$). The spacing between the locations of the central section of the probe for two successive tests should be 1 m.

The minimum depth z_c below the ground level for a test in a pressuremeter sounding shall be ten times the probe diameter.

The probe shall be placed in the pocket so that the top of its expanding length is at least 0,5 m from the pocket entry.

If the pressuremeter test pocket is created from the bottom of a larger borehole no test shall take place at a depth of the central cell less than 0,75 m below the conventional borehole foot.

The bottom of the expanding length of the probe shall also not be closer than 0,3 m from the bottom of the pocket.

C.1.3 Maximum length of the drilling stage before placing pressuremeter probe

When the pocket is obtained by drilling, the pressuremeter probe shall be installed in the pocket as soon as possible after drilling has been completed (see C.1.4) and in the same working day. Drilling or driving should be advanced between every test. However, drilling or driving stages enough for several tests may be allowed if ground conditions and time permit, as shown in Table C.1.

Table C.1 — Maximum continuous drilling or driving stage length before testing

Ground type	Maximum continuous drilling or tube driving stage length (m)
Sludge and soft clay, soft clayey soil	1[a]
Firm clayey soils	3

[a] Or the required interval between two successive tests.

Table C.1 *(continued)*

Ground type	Maximum continuous drilling or tube driving stage length (m)
Stiff clayey soils	5
Silty soils: - above ground water table - below water table	 4 2
Loose sandy soils: - above ground water table - below water table	 3 1[a]
Medium dense and dense sandy soils	5
Coarse soils: gravels, cobbles	5
Coarse soils with cohesion	5
Loose non homogeneous soils, other soils not specified above (e.g. tills)	3 to 5
Weathered rock, weak rock	5
Medium hard and hard rock	5

[a] Or the required interval between two successive tests.

Maximum continuous drilling stage lengths before testing may not apply to STDTM technique (see C.2.4.7). These lengths shall be chosen according to agreed specifications.

C.1.4 Time between forming the pressuremeter test pocket and testing

When pockets are obtained through drilling or tube pushing, pressuremeter testing shall be carried out immediately after the pressuremeter test pockets have been drilled and during the same drilling phase.

When the pressuremeter probe is directly driven or pushed into the ground inside a slotted tube, two ways to carry out the tests are permitted:

— after stopping driving at each depth of test, or

— after completing the driving or pushing, by lifting the string of casing or rods between tests.

NOTE 1 The first way implies that some delay can be required between the end of driving or pushing and the start of the test to ensure equilibration of the pore water pressure.

NOTE 2 The second way is only possible if the casing string diameter is the same as that of the slotted tube. This technique helps equilibration of the pore water pressure for the upper tests without further delay.

C.2 Probe placement techniques without ground displacement

C.2.1 General

When a pressuremeter test pocket is drilled, the primary concern shall be the quality of the pocket wall obtained. The second concern is that this pocket diameter shall be adapted to the pressuremeter probe diameter.

Drilling parameters should be measured according to ISO 22476-15.

Localisation of ground units may be based on ground profile derived from measuring while drilling (MWD) according to ISO 22476-15.

NOTE 1 Use of MWD or further analysis of discontinuities in rock based on core samples results can help to solve potential anomaly in interpretation of the pressuremeter sounding.

The guidelines given in Table C.2 shall be considered when selecting the proper method and the appropriate equipment.

When selecting the method and equipment, it shall be considered that the wall of the pressuremeter test pocket shall be as smooth as possible and that its diameter shall be as constant as possible over the length of the pressuremeter test pocket.

When inserting the probe, it shall be checked that shoe and hollow probe body are not obstructed.

NOTE 2 If the pressuremeter test pocket diameter varies significantly, because of ravelling for example or if the pocket is not cylindrical, the quality of the test is impaired.

C.2.2 Cutting tool diameter for the pocket

When determining the diameter of the necessary cutting tool for a bored pressuremeter test pocket, three factors shall be considered:

— the diameter of the pocket required;

— the over cutting of the pocket resulting from either wobble of the cutting tool or wall erosion by the mud circulation or both; and

— the inward yielding that occurs between the removal of the cutting tool and the probe placement.

Inward yielding or swelling can be reduced by the use of an appropriate drilling fluid.

The tool diameter shall not be more than 1,1 d_c.

When selecting equipment for the site, several bits of various sizes should be available so as to adjust the size of the tool depending on whether over cutting or inward yielding occurs.

One of the techniques described in C.2.4, potentially including the provisions described in C.2.3, may be used to prepare the test cavity for the pressuremeter probe, depending on the type of ground (see Table C.2).

C.2.3 Methods to stabilize the borehole

C.2.3.1 General

When the walls of the borehole are likely to be unstable or subject to decompression, stabilizing fluid and/or casing shall be used.

In case of stabilizing fluid, it is recommended to use a fluid of sufficient viscosity and density, based on bentonite, possibly weighed down by additives.

A fluid may be used as a flushing medium to transport the excavated material and cool the drilling tool.

Water or air can be used as drilling fluid but cannot be considered as a stabilizing fluid. Water is the preferred drilling fluid in rotary core drilling technique but shall be avoided in open holes and rotary percussive drilling techniques.

Other drilling fluids, also called muds, may be used as stabilizing fluids on the basis of experience of previous cases in comparable or worse geotechnical conditions, such as:

— bentonite suspensions,

— polymers and other, or

— other products.

The fluids shall be prepared by suspending the respective particles in water, with or without the use of admixtures. The suspensions shall be prepared, maintained and controlled in accordance with the manufacturer's instructions.

To avoid erosion during drilling and increasing of the borehole diameter, or damaging of the borehole, the flow rate shall be limited. If a liquid is used as drilling fluid, a value of 15 l/min should not be exceeded to limit the upward speed to 30 m/min to 60 m/min.

NOTE Oversized drilling diameters can be identified with the pressuremeter curve.

The flow should also be adapted so that the fluid pressure (measured in the drilling rig at ground level) remains lower than 500 kPa.

The operator shall check that the fluid ensures a proper recovery of the fluid itself and the excavated material.

C.2.3.2 Bentonite suspensions

Properties of bentonite suspensions, when fresh, shall be obtained by mixing on average 40 kg of dry bentonite in 1 m^3 of water.

Higher densities are permitted during the drilling process for the re-use case.

Specific additives may be added to increase density for specific purposes.

NOTE The value of 40 kg of bentonite in 1 m^3 corresponds to a mean density of 1,1 g/cm^3.

C.2.3.3 Polymers and other suspensions

Other suspensions or drilling fluids, for instance containing

— polymers,

— polymers with bentonite as an admixture,

— other clays.

may be used as stabilizing fluids on the basis of experience of

— previous cases in comparable or worse geotechnical conditions, or

— full-scale trial excavations on the site.

C.2.4 Different probe placement techniques without ground displacement

C.2.4.1 General

The down thrust force shall be adjusted in order to limit the downward penetration rate V_A to 90 m/h (150 "cm/min"). The rotation rate should also be limited to maintain a constant drilling diameter.

NOTE Oversized drilling diameters can be identified with the pressuremeter curve.

C.2.4.2 Rotary open hole drilling (OHD)

Rotary open hole drilling consists in rotating a cutting bit, applying a downward force from the ground surface with a drill rig and washing the resulting cuttings to the surface with a flow of fluid.

The selected bits should be drag bits or rock roller bits with specially designed axial bottom discharge nozzles.

The rotating drill bit shall be advanced into the soil while satisfying the following conditions:

— low vertical pressure on the drilling tool, slow rotation (less than 60 revolutions per minute), and

— low and controlled drilling fluid flow appropriate for the material being drilled.

C.2.4.3 Hand auger (HA)

Above water table, a hand auger may be used to drill the pressuremeter test pocket. It consists of two tubular steel segments with a cutting edge, or auger blades, welded at the top to a common rod to form a nearly complete tube, but with diametrically opposed longitudinal slots. The auger blades are connected at the bottom by a helical point or tapered screw. The blades also block the escape of the contained soil. A handle is fitted to the top extension rod.

NOTE Depending on the stiffness and the grading of the soil, the use of a hand auger can become difficult. The pocket walls can be damaged by too many removals of the cutting tool. This technique is used for testing at shallow depths (4 m to 6 m).

Care shall be taken that the auger does not simply displace very soft soil.

C.2.4.4 Continuous flight auger drilling (CFA)

A flight auger consists of a short helical length of steel welded to a slender solid stem with a cutting head connected either to drill rods or to additional auger sections over the length of the drilling string. The cutting head shall be slightly greater in diameter than the auger flight to prevent smearing the cavity wall. Rotation speed should not exceed 60 revolutions per minute. The auger shall be rotated during withdrawal, in the same direction as during the penetration phase.

C.2.4.5 Rotary core drilling (RCD)

Equipment and tool should be selected in a way that the mud circulation does not erode the pressuremeter test pockets.

This technique permits a detailed description of lithology and thickness of the various soil layers. In addition, the core sample can be tested but the priority shall be given to pocket wall quality.

C.2.4.6 Rotary percussive drilling (RP & RPM)

In the case of soils in which this technique is acceptable (see Table C.2 for guidance), rotary percussive drilling consisting in advancing the pressuremeter sounding by dropping and raising a drilling bit by pneumatic or hydraulic pressure may be used. The disintegrating action of the drilling bit is increased by rotation.

If air is used as a drilling fluid, this technique may mostly be used for testing at shallow depths due to the limitation of available air pressure.

C.2.4.7 Slotted tube with inside disintegrating tool and mud circulation (STDTM)

The STDTM technique consists in creating the pocket using an open slotted tube which is an integral part of the casing close to its lower end. One of the two following methods may be chosen.

— The casing is driven minimizing soil displacement by using a cutting shoe with an inside bevel. The soil inside the casing is removed by an appropriate drilling bit.

— The casing is lowered using a rapid reciprocating hammering action. The drilling proceeds simultaneously with the advancement of a casing. The cutting tool associated with fluid injection is either slightly protruding from the casing shoe or flush with it.

Before each series of pressuremeter tests, the drilling string shall be pulled up. Then the probe shall be centred in the slotted section.

C.2.5 Pushed, hammered or vibro-driven tubes (OS-T/W, OS-TK/W and VDT)

C.2.5.1 General

For certain ground conditions, a tube with a circular cross section may be pushed, hammered or vibro-driven into the ground. The tube shall be fitted with an inward bevel cutting edge to minimise pre-stressing of the test cavity wall before testing, in contrast to samplers described in ISO 22475-1. A minimum distance of three times the tool diameter should be applied between the probe and the driving point, in order to avoid disturbance cause by the additional stresses near the bottom of the tool.

C.2.5.2 Pushed tubes (OS-T/W)

In soft to medium stiff clayey soils and in silty soils above water table pushed tubes may be used to create the pressuremeter test pocket. If the pocket cannot be obtained in one single push another method of preparing the pressuremeter test pocket shall be chosen. Full core recovery is required so as to avoid disturbance of the pocket wall and to be able to test the underlying layers.

The tube shall be withdrawn slowly to limit inward yielding of the pocket wall due to suction.

In sludge and soft clay, thin wall tubes shall be used.

C.2.5.3 Hammered tubes (OS-TK/W) or vibro-driven tubes (VDT)

For stiffer soils, thick wall tubes shall be used. They may be driven by ramming or by a vibrating hammer.

C.3 Probe placement techniques with ground displacement

In buoyant granular material, if it appears impossible to prevent the pressuremeter test pocket wall from caving in, the probe may be:

— pushed directly into the soil (PP);

— hammered or vibro-driven into the soil (DST) inside its slotted tube;

with either a driving point or a cutting shoe.

Between the probe and either the point or the cutting shoe, an extension tube at the diameter of the probe or the slotted tube shall be included, so as to prevent compaction effect at the level of the probe.

In certain cases, drilling a pilot hole much smaller in diameter than the pressuremeter probe may be necessary to help probe placing. The pilot hole may be drilled with possible pre-boring techniques: OHD, RP and RPM. Once this smaller size open hole is completed, the pocket is trimmed to the proper diameter by pushing the probe or driving the slotted tube.

Table C.2 — Guidelines for pressuremeter probe placement techniques

Probe placing		Without ground displacement										With ground displacement	
		Boring technique											
Soil and rock types ↓ according to ISO 14688 (all parts), and ISO 14689		$1 < d_t/d_c \leq 1{,}1$ (V_A < 90 m/h; P_I< 500 kPa; Q_I < 15 l/min; V_r < 60 revolutions per minute)[a]										$d_t/d_c \leq 1$	
		Rotary drilling				Rotary percussion			Driven tube			Driven probe	
		OHDM	HA/ HAM	CFA	RCD	RP	RPM	STDTM	OS-T/W P	OS-TK/W H VDT		PP	DST
Fine soils	Very soft and soft clay	**	***	*	*		-	*	***	-		*	-
	Soft to firm clayey soils	***	***	**	**	-	*	**	**	*			
	Stiff clayey soils	***	*	***	***	*	**	**	*	*			
	Silty soils: - above water table	***	***	***	**	-	*	**	**	*		-	-
	- below water table	***	**	-	*	-	*	**	-	-		*	*
Coarse soils	Loose sandy soils: - above water table	***	***	**	*	-	**	**	-	-		-	-
	- below water table	***	**	-	-	-	**	**	-	-		*	*
	Medium dense and dense sandy soils	***	**	***	**	*	***	***	-	*		-	**
	Gravels	**	-	-	*	*	***	***		*		-	***
Very coarse soils	Cobbles, cobbles with gravels, boulder	**			**	**	***	**		-		-	**
Intermediate soils	Cohesive non homogeneous soils (e.g. boulder clay)	**	-	*	**	*	***	**		*		-	*
	Loose non homogeneous soils, other soils not specified above (e.g. tills, some alluvial deposits, man-made soils, treated or untreated fills)	**	*	*	*	*	**	**	-	*		*	**
Hard soils	Chalk	***	*	**	**	**	**	**		*			

Table C.2 *(continued)*

Probe placing		Without ground displacement										With ground displacement	
		Boring technique											
Soil and rock types ↓ according to ISO 14688 (all parts), and ISO 14689		1< d_t/d_c ≤ 1,1 (V_A < 90 m/h; P_I< 500 kPa; Q_I < 15 l/min; V_r < 60 revolutions per minute)[a]										d_t/d_c ≤ 1	
		Rotary drilling				Rotary percussion			Driven tube			Driven probe	
		OHDM	HA/ HAM	CFA	RCD	RP	RPM	STDTM	OS-T/W P	OS-TK/W H VDT		PP	DST
soft rocks	Weathered and weak rock masses	***	-	*	***	**	**	**		-	-		
Rocks	Medium hard and hard rocks	**		-	***	***	***	*		-	-		

***	Recommended	OHDM	Open hole drilling with mud	OS-T/W-P	Pushed tube
**	Permitted	HA	Hand auger	OS-TK/ WH	Hammered thick tube
*	Possible	HAM	Hand auger and mud	VDT	Vibro-driven tube
-	Not allowed	CFA	Continuous flight auger	PP	Pushed probe
		RCD	Rotary core drilling	DST	Driven slotted tube
a	For the driller's guidance.	RP	Rotary percussion		
		RPM	Rotary percussion with mud		
		STDTM	Slotted tube with inside disintegrating tool and mud circulation		

Annex D
(normative)

Obtaining pressuremeter parameters

D.1 Obtaining a corrected pressuremeter curve

D.1.1 General

Values of pressures and volumes readings during the test shall be corrected for:

— hydraulic head p_h;

— probe pressure loss p_e;

— volume loss of the whole equipment during pressurization V_e.

D.1.2 Probe hydraulic head correction

During a test at a given elevation z_s, the pressure in the central cell shall be equal to the pressure regulator pressure plus the hydraulic head, p_h, between the elevation of the pressure measuring device and the centre of the pressuremeter probe (see Figure D.1).

$$p_h = \gamma_i (z_p - z_s)$$

D.1.3 Probe pressure loss correction

This pressure correction involves the pressuremeter probe pressure loss p_e as a function of V_r (see B.4.4 and Figure B.4). After having discarded erratic points if any, one of the following methods may be used:

— power law type interpolation:

$$p_e(V_r) = bV_r^{\,c}$$

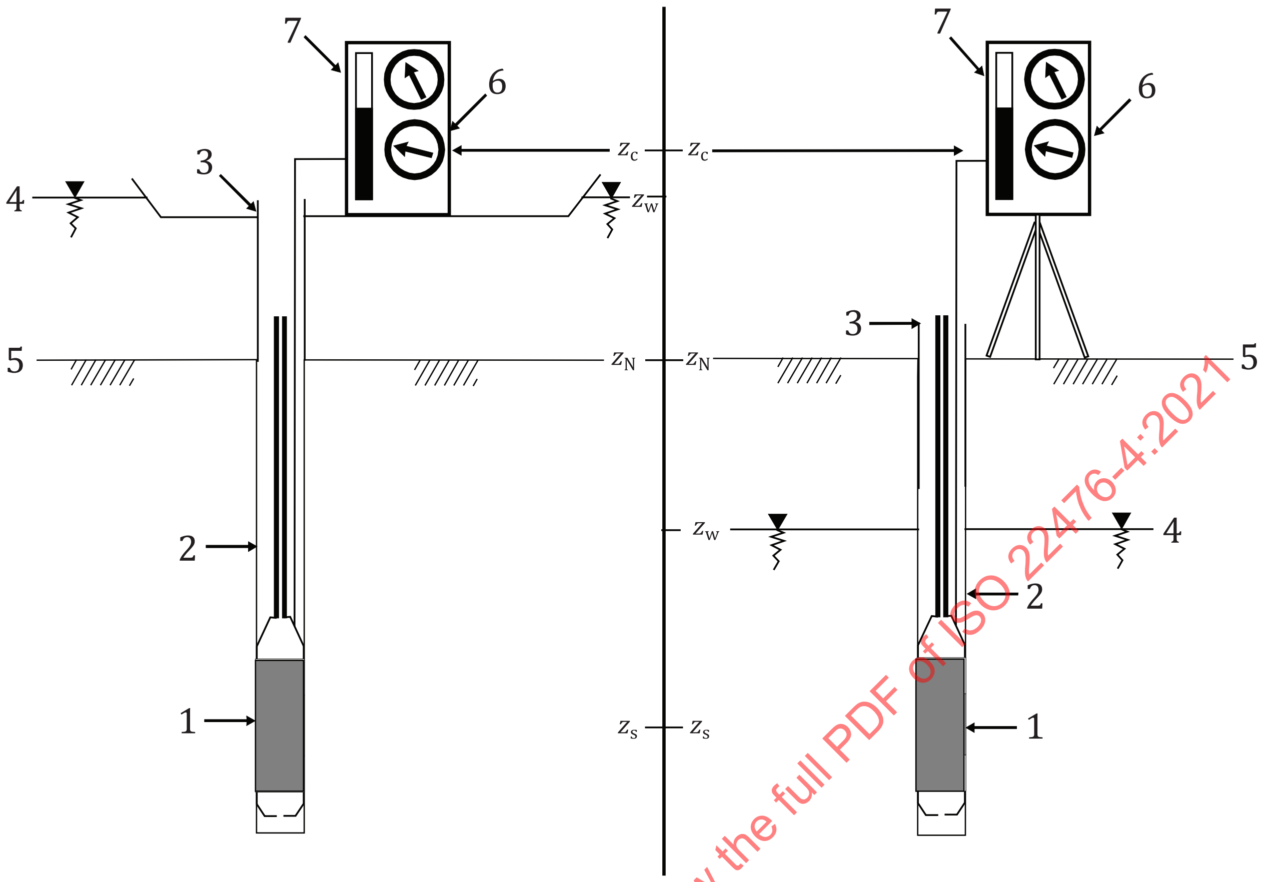
where b and c are obtained by the mean square regression method;

— double hyperbolic adjustment (see D.4.3.3);

— linear interpolation between experimental points.

As this pressure loss is a function of the type of membrane and cover, of the slotted tube if any, and of the injected fluid volume, the corrected pressure shall be:

$$p = p_r(V_r) - p_e(V_r)$$



a) In a marine or river environment

b) In a land environment

Key

1 pressuremeter probe
2 pressuremeter borehole
3 casing
4 water table
5 ground surface
6 liquid pressure measuring device
7 control unit (CU)

Figure D.1 — Elevation of probe and control unit during test

D.1.4 Volume loss correction

The volume loss correction involves the experimental pressuremeter probe volume loss curve obtained in a thick steel tube in B.4.3.2, in order to take into account the volume losses of the probe, the connecting lines and the measuring system.

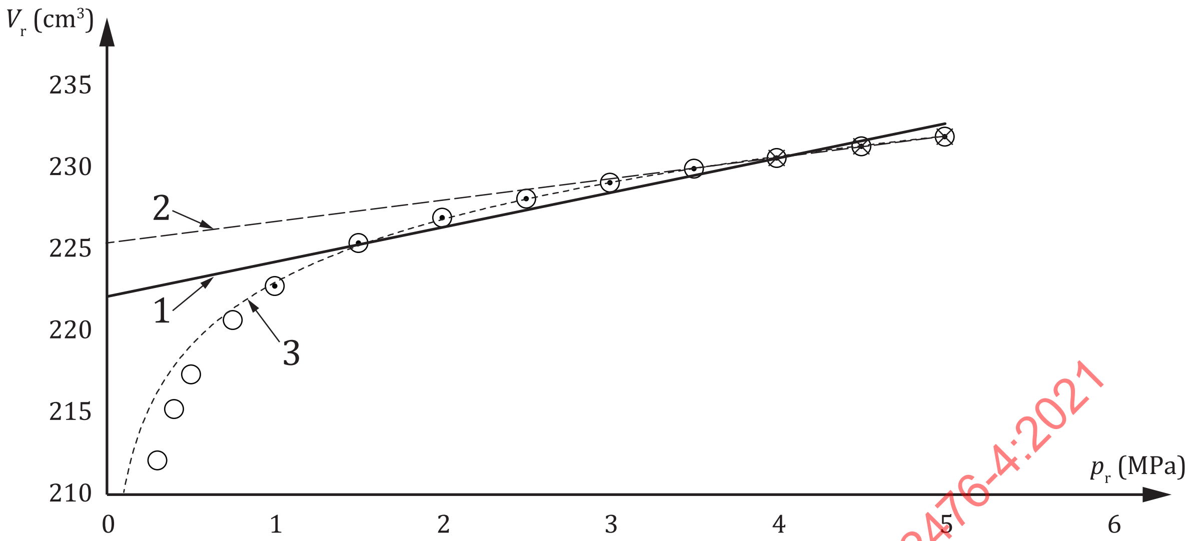
This curve shall be used for volume loss correction by one of the following methods (see Figure D.2):

— volume correction by direct linear adjustment between experimental points;

— volume correction using a factor obtained by linear regression (see B.4.3.3); for a given value of pressure p_r, the volume V_r shall be corrected as $V = V_r\ (p_r) - a.p_r$;

— volume correction using more elaborated methods than linear regression: hyperbolic model as used in D.4.3.3 or logarithmic regression $V = d + e.\ln(p_r)$.

NOTE In stiff or dense soils and rocks, the more elaborated methods (third method) are preferred.



Key

1 linear regression for all points after the contact with the calibration tube

2 linear regression on the last 3 points

3 logarithmic regression for all points after the contact with the calibration tube

NOTE The volume loss correction in soft to medium stiff grounds can be negligible.

Figure D.2 — Volume loss correction

D.1.5 Corrected pressuremeter curve

The corrected values of volume and pressure, read at each pressure level for an elapsed time of 60 s are obtained from the following formulae:

$$p = p_r + p_h - p_e(V_r)$$

$$V = V_r - V_e(p)$$

The pressuremeter test data points or curve shall be plotted with pressures on the horizontal axis and volumes on the vertical axis.

D.2 Assessing the quality of the pressuremeter test

D.2.1 Analysis of a pressuremeter test

The corrected pressuremeter curve shall be analysed together with the corrected pressuremeter creep curve, considering m_i slopes and $V_{60/30}$ pressuremeter creep values at each pressure step (see Figures 5 and D.3), considering slopes m_i of straight line segments between data points:

$$m_i = \frac{(V_i - V_{i-1})}{(p_i - p_{i-1})}$$

In a completed test, the sequence of readings can be divided into three successive groups:

— the first group consists of the sets of readings obtained during probe expansion up to the contact between the surface of the probe and the pocket wall and a first recompression stage; they usually exhibit high pressuremeter creep values;

— the second group in the lower pressure range includes readings which exhibit low slopes m_i and low pressuremeter creep values; this group identifies the pseudo-elastic section of the curve;

— the third group in the higher pressure range exhibits increasingly higher slopes and higher pressuremeter creep values; this group identifies the plastic phase.

Pressuremeter creep pressure p_f shall be found in the transition zone between the last two groups (see D.3).

Ménard pressuremeter modulus E_M shall be obtained from the second group of readings (see D.5).

Ménard pressuremeter limit pressure p_{LM} shall be obtained from the third group of readings (see D.4).

On the pressuremeter curve, the region between the first and the second group is used to define the contact of the probe against the pocket wall.

D.2.2 Quality of the pressuremeter test

The magnitude of scatter of the test points and the shape of the pressuremeter curve shall give an indication of the pressuremeter test pocket quality.

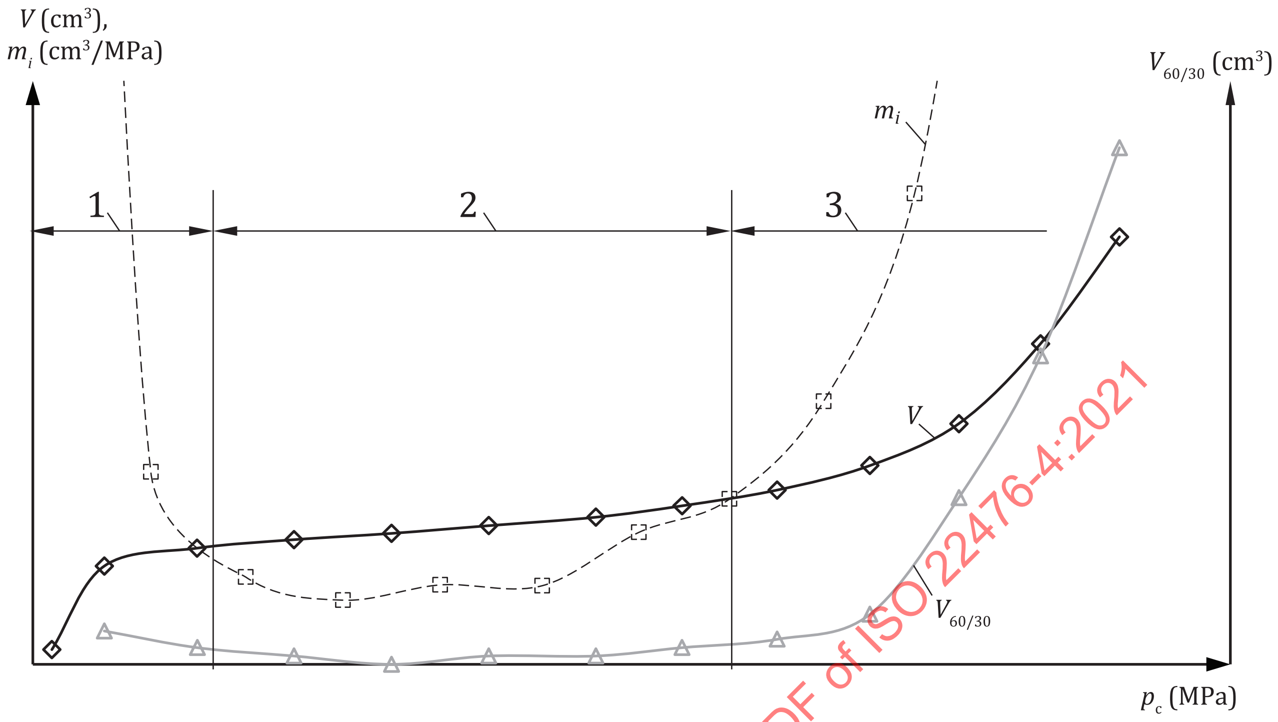
At least three data points in the second group of readings and three data points in the third group shall be available to determine all three parameters p_f, p_{LM} and E_M.

If in a test, one group of readings is incomplete or missing, the following effects on the determination of the three parameters shall be considered:

— when the pressuremeter curve includes only the second and third groups of readings and with fewer than two data points in the second group, values of E_M and p_f cannot be obtained;

— when the pressuremeter curve includes only the first and second groups of readings (i.e. only one or no points in the third group), p_{LM} and p_f cannot be obtained.

NOTE A pressuremeter curve that includes only the last two groups of readings can result from a test performed in swelling ground or in too small a pocket. A too large pocket can result in a pressuremeter test curve which includes only the first two groups of readings.



Key

1 first group of readings

2 second group of readings

3 third group of readings

Figure D.3 — Pressuremeter test data points analysis – Example

D.3 Pressuremeter creep pressure

If there are at least two sets of readings both in the second and in the third group, the creep pressure p_f shall be estimated, using the following graphical analysis of the (p, $V_{60/30}$) diagram: 2 straight lines shall be drawn on the (p, $V_{60/30}$) graph, one involving the data points in the second group, the second one involving the data points in the third group, as illustrated on Figure D.4; the abscissa of the intersection of the 2 straight lines give p_f .

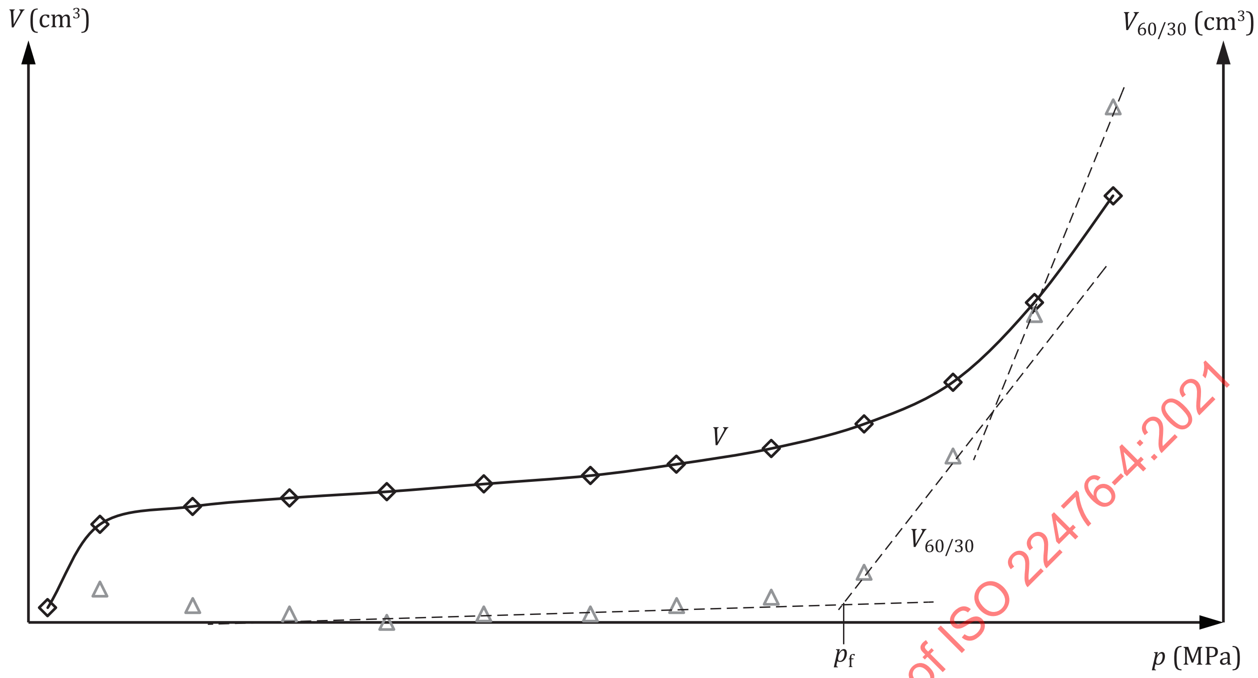


Figure D.4 — Pressuremeter creep pressure determination

This value shall be confirmed during the final check (see D.6) when considering the values of p_{LM} and E_M obtained in D.4 and D.5, and the whole pressuremeter curve.

If there is only the first set of readings, the pressuremeter creep pressure value shall be reported as $p_f > p$, p being the last corrected pressure applied.

D.4 Ménard pressuremeter limit pressure

D.4.1 Definition

The Ménard pressuremeter limit pressure is conventionally defined as the pressure leading to the doubling of the initial volume of the pocket.

It can be either obtained by direct measurement or determined using extrapolation methods (Figure D.5).

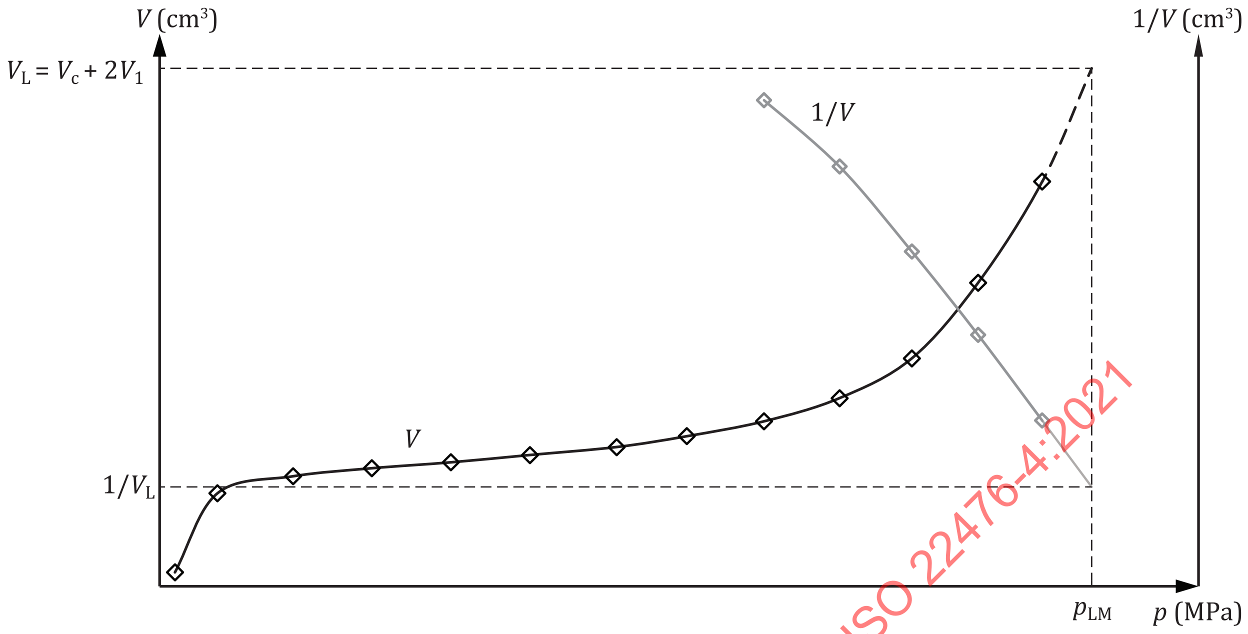


Figure D.5 — Ménard pressuremeter limit pressure, with reciprocal fitting and extrapolation method

D.4.2 Direct solution

When, during a test, the injected volume is such that the pressuremeter central cell volume becomes bigger than

$$V_c + 2V_1$$

the Ménard pressuremeter limit pressure shall be then obtained by interpolation.

D.4.3 Curve fitting and extrapolation methods

D.4.3.1 General

When, during an expansion test, the injected liquid volume is not enough to reach the Ménard pressuremeter limit pressure, it is impossible to use the direct method. Therefore, the limit pressure shall be extrapolated.

Different extrapolation methods may be applied to test results. The final value of the limit pressure which has to be reported shall be determined according to D.4.4. Examples of curve fitting and extrapolation methods are given in D.4.3.2 and D.4.3.3.

For these methods, extrapolation is only permitted when the number of pressure steps applied beyond pressure p_f is at least three.

Special care should be taken when a ratio $p_{lM}/p_f > 2,5$ is observed.

If the limit pressure is not obtained either by the direct method or by extrapolation methods, the Ménard pressuremeter limit pressure value shall be reported as $p_{lM} > p$, p being the maximum corrected pressure.

D.4.3.2 Reciprocal (1/*V*) method

The (p, V) pairs of readings shall be transformed into (p, $1/V$) values and plotted. A linear regression shall then be performed using the last three readings.

This extrapolation shall be obtained by the following transformation:

$$1/V = Ap + B$$

where A and B are coefficients obtained by a least squares regression of $1/V$ on p.

D.4.3.3 Hyperbolic methods

A single hyperbolic segment may be used when applicable for the second and third groups of points.

$$V = A_1 + A_2 p + \frac{A_3}{(A_4 - p)}$$

The entire pressuremeter curve shall be approximated by a straight line tangential to two hyperbolic segments as defined by the following formula:

$$V = A_1 + A_2 p + \frac{A_3}{(A_4 - p)} + \frac{A_5}{(A_6 - p)}$$

NOTE Reference for the mathematical modelling can be found in Bibliography.

D.4.4 Limit pressure by extrapolation, final step

The sum of the errors for each fitting curve obtained by at least two methods shall be calculated and divided by the number of data points beyond p_f used. The Ménard pressuremeter limit pressure p_{LM} retained shall be the one obtained by the method giving the lowest mean error.

D.5 Obtaining the Ménard pressuremeter modulus

D.5.1 General

The Menard pressuremeter modulus shall be derived from the corrected pressuremeter test data points or the fitting curve as defined in D.5.2 on a pseudo-elastic range.

D.5.2 Choice of the pseudo-elastic range

The analysis of a corrected pressuremeter curve shall begin by calculating the slope m_i (see D.2.1).

The lowest m_i value, always positive, is called m_E. The coordinates of the origin of this segment (p_E, V_E) and of its end (p'_E, V'_E) shall be used to calculate the coefficient β as follows:

$$\beta = 1 + \frac{1}{100} \cdot \frac{p'_E + p_E}{p'_E - p_E} + \frac{2\delta V}{V'_E - V_E}$$

where δV is a tolerance for V taken as 3 cm^3 initially.

