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Geotechnical investigation and testing — Field testing —

Part 4: Ménard pressuremeter test

Reconnaissance et essais géotechniques — Essais en place —

Partie 4: Essai au pressiomètre de Ménard

Reference number
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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 22476-4 was prepared by the European Committee for Standardization (CEN) Technical Committee CEN/TC 341, *Geotechnical investigation and testing*, in collaboration with Technical Committee ISO/TC 182, *Geotechnics*, Subcommittee SC 1, *Geotechnical testing*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

ISO 22476 consists of the following parts, under the general title *Geotechnical investigation and testing — Field testing*:

— *Part 1: Electrical cone and piezocone penetration test*

— *Part 2: Dynamic probing*

— *Part 3: Standard penetration test*

— *Part 4: Ménard pressuremeter test*

— *Part 5: Flexible dilatometer test*

— *Part 7: Borehole jack test*

— *Part 9: Field vane test*

— *Part 10: Weight sounding test* [Technical Specification]

— *Part 11: Flat dilatometer test* [Technical Specification]

— *Part 12: Mechanical cone penetration test (CPTM)*

Geotechnical investigation and testing — Field testing —

Part 4: Ménard pressuremeter test

1 Scope

This part of ISO 22476 specifies the equipment requirements, execution of and reporting on the Ménard pressuremeter test.

NOTE 1 This part of ISO 22476 fulfils the requirements for the Ménard pressurermeter test, as part of the geotechnical investigation and testing according to EN 1997-1 and EN 1997-2.

This part of ISO 22476 describes the procedure for conducting a Ménard pressuremeter test in natural soils, treated or untreated fills and in weak rocks, either on land or off-shore.

The pressuremeter test results of this part of ISO 22476 are suited to a quantitative determination of ground strength and deformation parameters. They may yield lithological information. 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 1997-2:2007, 2.4.1.4(2) P, 4.1 (1) P and 4.2.3(2) P).

The Ménard pressuremeter test is performed by the radial expansion of a tricell probe placed in the ground (see Figure 1). During the injection of the liquid volume in the probe, the inflation of the three cells first brings the outer cover of the probe into contact with the pocket wall and then presses on them resulting in a soil displacement. Pressure applied to and the associated volume expansion of the probe are measured and recorded so as to obtain the stress-strain relationship of the soil as tested.

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 14689-1 obtained during the pressuremeter test operations, the test results of this part of ISO 22476 are suited to the quantitative determination of a ground profile, including

— the Ménard E_{M} modulus,

— the Ménard limit pressure p_{LM} and

— the Ménard creep pressure p_{fM}.

This part of ISO 22476 refers to a probe historically described as the 60 mm G type probe. This part of ISO 22476 applies to test depths limited to 50 m and test pressure limited to 5 MPa.

NOTE 2 Ménard pressuremeter tests are carried out with other probe diameters and pocket dimensions such as shown below.

Probe		**Drilling diameter** (mm)	
Designation	**Diameter** (mm)	**min**	**max**
AX	44	46	52
BX	58	60	66
NX	70/74	74	80

Two alternative methods of measurement are provided as follows.

— Procedure A: data are recorded manually.

— Procedure B: data are recorded automatically.

2 Normative references

The following referenced documents are indispensable for the application 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 14689-1, *Geotechnical investigation and testing — Identification and classification of rock — Part 1: Identification and description*

ISO 22475-1, *Geotechnical investigation and testing — Sampling methods and groundwater measurements — Part 1: Technical principles for execution*

ENV 13005:1999, *Guide to the expression of uncertainty in measurement*

3 Terms, definitions and symbols

3.1 Terms and definitions

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

3.1.1
pressuremeter
whole equipment which is used to carry out a Ménard pressuremeter test, excluding the means necessary to place the pressuremeter probe into the ground

NOTE 1 A pressuremeter includes a pressuremeter probe, a pressure and volume control unit, called CU, lines to connect the probe to the CU and, in the case of procedure B, a data logger which is either built into the CU or linked to it.

NOTE 2 See Figure 2.

3.1.2
pressuremeter test pocket
circular cylindrical cavity formed in the ground to receive a pressuremeter probe

3.1.3
pressuremeter borehole
borehole in which pressuremeter pockets with circular cross sections are made in the ground, and into which the pressuremeter probe is to be placed

3.1.4
pressuremeter test
process during which a pressuremeter probe is inflated in the ground and the resulting pocket expansion is measured by volume as a function of time and pressure increments according to a defined programme

NOTE See Figure 4 and F.1.

3.1.5
pressuremeter sounding
whole series of sequential operations necessary to perform Ménard pressuremeter testing at a given location, i.e. forming pressuremeter test pockets and performing pressuremeter tests in them

NOTE See F.2.

3.1.6
pressuremeter pressure reading, p_r
pressure p_r as read at the CU elevation in the liquid circuit supplying the central measuring cell

3.1.7
pressure loss
difference between the pressure inside the probe and the pressure applied to the pocket wall

3.1.8
volume loss
difference between the volume actually injected into the probe and the volume read on the measuring device

3.1.9
raw pressuremeter curve
graphical plot of the injected volumes recorded at time 60 s, V_{60}, versus the applied pressure at each pressure hold, p_r

3.1.10
corrected pressuremeter curve
graphical plot of the corrected volume V versus the corrected pressure p

NOTE See Figure 5.

3.1.11
Ménard creep
difference in volumes recorded at 60 s and at 30 s at each pressure hold: $V_{60} - V_{30} = \Delta V_{60/30}$

3.1.12
corrected Ménard creep curve
graphical plot of the corrected Ménard creep versus the corrected applied pressure at each pressure hold

NOTE See Figure 5.

3.1.13
pressuremeter log
graphical report of the results of the pressuremeter tests performed in pockets at a succession of depths in the same pressuremeter borehole, together with all the information gathered during the drilling

NOTE See Annex F.

3.1.14
Ménard pressuremeter modulus, E_M
E-modulus obtained from the section between (p_1, V_1) and (p_2, V_2) of the pressuremeter curve

NOTE See Figure 5 and Annex D.

3.1.15
Ménard pressuremeter limit pressure, p_{LM}
pressure at which the volume of the test pocket at the depth of the measuring cell has doubled its original volume

NOTE See Annex D.

3.1.16
pressuremeter creep pressure, p_{fM}
pressure derived from the creep curve

NOTE See Annex D.

3.1.17
operator
qualified person who carries out the test

3.1.18
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 given in Table 1 apply.

Table 1 — Symbols

Symbol	Description	Unit
a	Apparatus volume loss coefficient	cm^3/MPa
d_{ci}	Outside diameter of the inner part of the probe with slotted tube	mm
d_i	Inside diameter of the calibration cylinder used for the volume loss calibration	mm
d_c	Outside diameter of the central measuring cell, including any additional protection such as a slotted tube	mm
d_t	Drilling tool diameter	mm
e	Wall thickness of the calibration cylinder used for the volume loss calibration	mm
l_p	Length of the calibration cylinder used for the volume loss calibration	mm
l_g	Length of each guard cell	mm
l_{gs}	Length of each guard cell for a short central measuring cell pressuremeter probe	mm
l_{gl}	Length of each guard cell for a long central measuring cell pressuremeter probe	mm
l_m	Length along the tube axis of the slotted section of the slotted tube	mm
l_c	Length of the central measuring cell of the probe, measured after fitting the membrane	mm
l_{cs}	Length of the short central measuring cell after fitting the membrane	mm
l_{cl}	Length of the long central measuring cell after fitting the membrane	mm
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 by the probe to the ground after correction	MPa
p_e	Correction for membrane stiffness usually called pressure loss of the probe	MPa
p_E	Pressure at the origin of the segment exhibiting the slope m_E	MPa
p_{el}	Ultimate pressure loss of the probe	MPa
p_{fM}	Pressuremeter creep pressure	MPa
p_g	Gas pressure applied by the control unit indicator to the guard cells of the pressuremeter probe	MPa
p_h	Hydrostatic pressure between the control unit indicator and the central measuring cell of the pressuremeter probe	MPa
p_k	Gas pressure in the guard cells	MPa
p_{LM}	Ménard pressuremeter limit pressure of the ground	MPa
p_{LM}^*	Ménard net pressuremeter limit pressure of the ground	MPa
p_{LMH}	Ménard pressuremeter limit pressure as extrapolated by the hyperbolic best fit method	MPa
p_{LMDH}	Ménard pressuremeter limit pressure as extrapolated by the double 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 reading at the CU transducer elevation in the central measuring cell liquid circuit	MPa
p_c	Liquid pressure in the central measuring cell of the pressuremeter probe	MPa
p_t	Target pressure for each pressure hold according to loading programme	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_i	Time required for incrementing to the next pressure hold	s
t_h	Time the loading pressure level is held	s

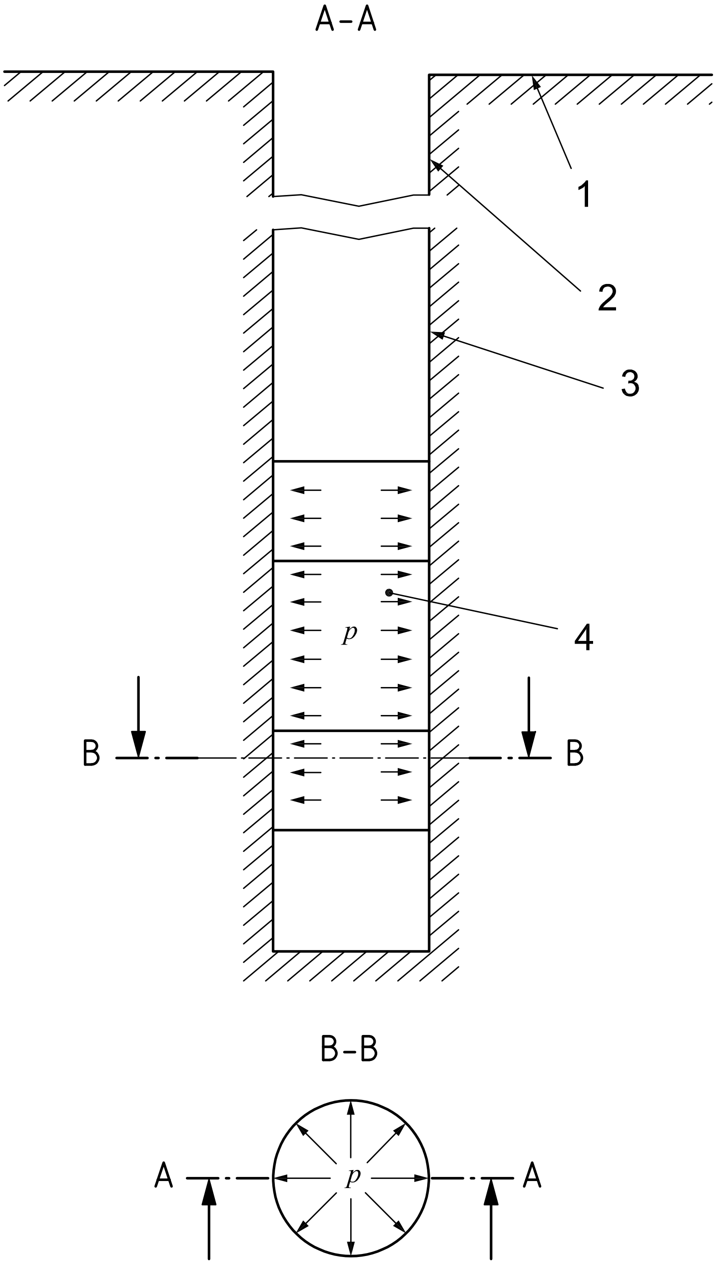
Table 1 *(continued)*

Symbol	Description	Unit
u_s	Pore water pressure in the ground at the depth of the test	MPa
z	Elevation, positively counted above datum	m
z_c	Elevation of the pressure measuring device for the liquid injected in the measuring cell	m
z_{cg}	Elevation of the pressure measuring device for the gas injected in the guard cells of the pressuremeter 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
CU	Pressure and volume control unit	—
E	Type of pressuremeter probe where the three cells are formed by three separate membranes in line	—
E_M	Ménard pressuremeter modulus	MPa
G	Type of pressuremeter probe where the central measuring cell is formed by a dedicated membrane over which an external membrane is fitted to form the guard cells (see Figure 2)	—
K_o	Coefficient of earth pressure at rest at the test depth	—
V	Value, after zeroing and data correction, of the volume injected in the central measuring cell and measured 60 s after starting a pressure hold	cm^3
V_c	Original volume of the central measuring cell, including the slotted tube, if applicable	cm^3
V_m	The average corrected volume between V_1 and V_2	cm^3
V_p	Volume obtained in the volume loss calibration test (see Figure B.2)	cm^3
V_E	Value, after data correction, of the volume injected in the central measuring cell for pressure p_E	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_r	Volume injected in the probe as read on the CU, before data correction	cm^3
V_t	Volume of the central measuring cell possibly including the slotted tube	cm^3
V_1	Corrected volume at the origin of the pressuremeter modulus pressure range (see Figure 5)	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 hold	cm^3
V_{60}	Volume injected in the central measuring cell as read 60 s after the beginning of the pressure hold	cm^3
β	Coefficient used to determine the pressuremeter modulus pressure range	—
γ	Unit weight of soil at the time of testing	KN/m^3
γ_l	Unit weight of the liquid injected in the central measuring cell	KN/m^3
γ_w	Unit weight of water	KN/m^3
λ_g	Rate of change of pressure head of gas at p_k per metre depth	m^{-1}
ν	Poisson's ratio	—
σ_{vs}	Total vertical stress in the ground at test depth	kPa
σ_{hs}	Total horizontal stress in the ground at test elevation	kPa
Δp	Loading pressure increment	MPa
Δp_1	Initial pressure increment	MPa
$\Delta V_{60/30}$	Injected volume change from 30 s to 60 s after reaching the pressure hold − the Ménard creep	cm^3
$\Delta V_{60/60}$	60 s injected volume change between successive pressure holds	cm^3

4 Equipment

4.1 General description

The principle of the Ménard pressuremeter test is shown in Figure 1.



Key

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

Figure 1 — Principle of a Ménard pressuremeter test

The pressuremeter as shown schematically in Figure 2 shall include:

— tri-cell probe;

— string of rods to handle the probe;

— control unit (CU);

— lines connecting the control unit to the probe.

The control unit (CU) 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;

— device which permits the direct reading and, in the case of procedure B, the automatic recording of the parameters to be measured: time, pressure and volume.

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

— above the ground surface, or

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

In the first case, the CU shall be provided with means to check the stabilized pressure value at the probe.

Some means of measuring the depth of the test with appropriate accuracy shall be provided.

4.2 Pressuremeter probe

Two types of probe shall be used according to ground type and condition:

— probe with a flexible cover;

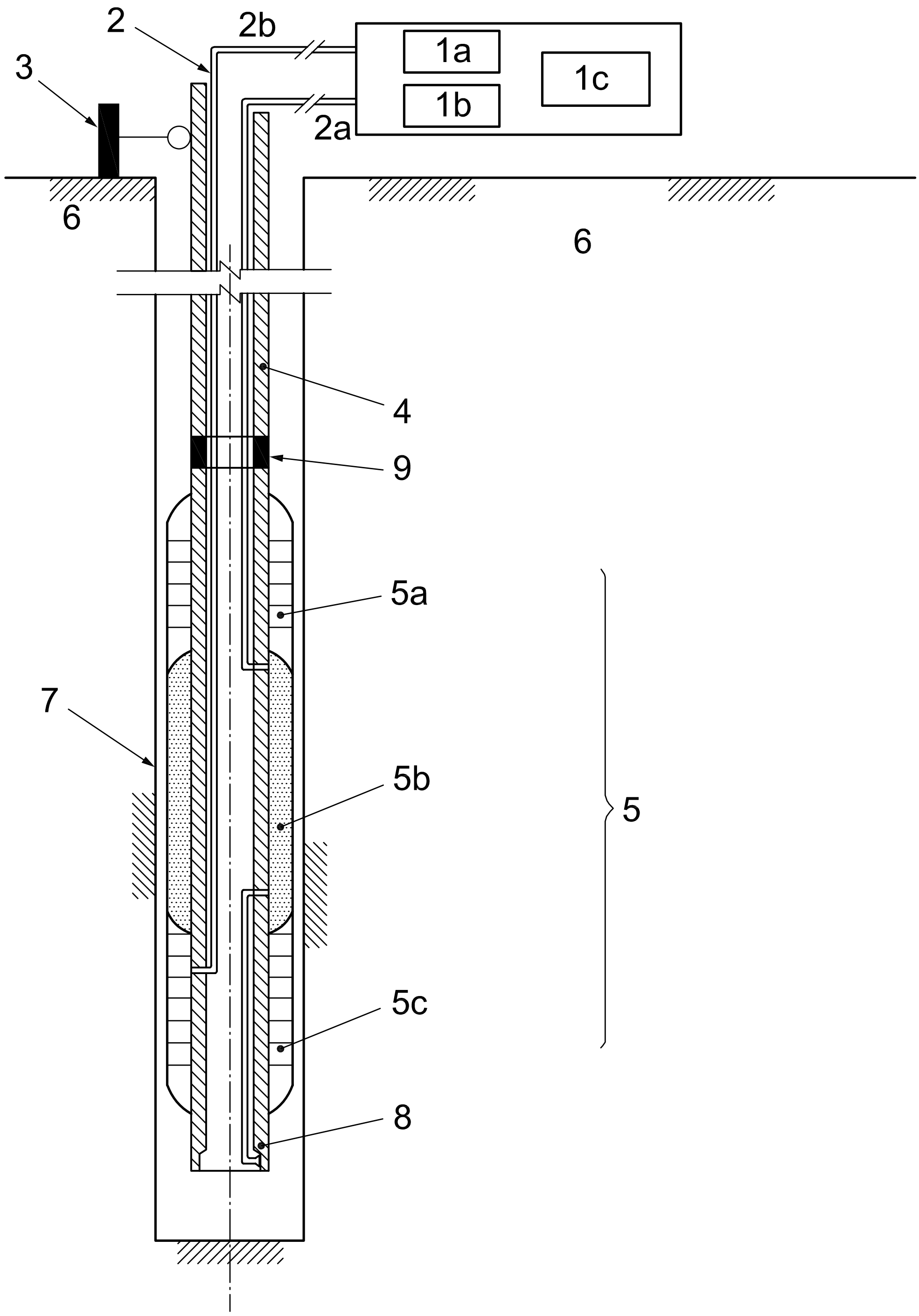
— probe with a flexible cover and either an additional more rigid protection or a slotted steel tube.

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

When the probe is driven or pushed into the ground (see C.3), it shall be fitted with the more rigid protection or a slotted tube together with a extension tube completed by either a point or a cutting shoe.

NOTE If no slotted tube is involved, the probe body must be designed to withstand driving or pushing.

The probe shall be capable of a volumetric expansion of at least 700 cm^3 (550 cm^3 for a probe with a short central measuring cell within a slotted tube).



Key

1 control unit (CU):

1a pressurization, differential pressurization and injection devices

1b pressure and volume measuring devices

1c acquisition, storage and printing out of the data (required for procedure B)

2 connecting lines:

2a line for liquid injection

2b line for gas injection

3 depth measurement system

4 rods

5 pressuremeter probe:

5a upper guard cell

5b central measuring cell

5c lower guard cell

6 ground

7 pressuremeter test pocket

8 probe body, hollow

9 probe rod coupling

Figure 2 — Diagram of a Ménard pressuremeter

4.2.1 Probe with flexible cover

The probe shall be made up of three cylindrical cells of circular cross-section along the same axis (see Figure A.1). During a test these cells shall expand simultaneously against the pocket wall. The probe includes:

— one central measuring cell, with an outside diameter d_c and a length l_c (l_{cl} for a “long probe” or l_{cs} for short probe – see Table A.1), which shall expand radially in a pocket and shall apply a uniform stress to the pocket wall. This cell shall be inflated by injecting a liquid which is assumed to be incompressible;

— two guard cells with an outside diameter d_g and a length l_g (l_{gl} or l_{gs}) located above and below the central measuring cell. These cells shall be designed to apply to the pocket wall a stress close to, but not greater than, the stress induced by the central measuring cell. These cells shall be inflated by gas pressure.

The probe shall consist of a hollow steel core with passages to inject the proper fluids to inflate the cells. The probe shall be fitted with a central measuring cell membrane and a flexible cover sleeve. The steel core, on its outside curved surface, shall usually bear a network of grooves which uniformly distribute the liquid in the central measuring cell under the membrane. To this core shall be fixed the membrane and the flexible cover. The top of the core shall be threaded and coupled to the string of rods handling the probe from ground level; the central measuring cell membrane shall isolate the fluid in the central measuring cell from the gas of the guard cells. The flexible cover which overlies the central measuring cell membrane shall give form to the guard cells. A flexible protection made of thin steel strips usually 17 mm wide either overlapping (up to half-way) or isolated, running between fixing rings (see Figure A.1) may be added over the cover. Fluid lines shall connect the probe cells to the pressure and volume control unit (CU). The drain tap of the measuring cell shall protrude from the bottom of the steel core.

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

4.2.2 Probe with slotted tube

This probe shall consist of two parts:

— an inner part which shall be an assembly of three cylindrical cells of circular cross-section along the same axis; and

— an outer part which shall be made of a slotted steel tube (see Figure A.1). 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 inner part includes:

— one central measuring cell, with an outside diameter d_c and a length l_c (l_{cl} for a “long probe” or l_{cs} for short probe – see Table A.1), which shall expand radially in the slotted tube and shall apply a uniform stress to the tube wall. This cell shall be inflated by injecting a liquid which is assumed to be incompressible;

— two guard cells with an outside diameter d_g and a length l_g (l_{gl} or l_{gs}), located above and below the central measuring cell. These cells shall be designed to apply to the slotted tube wall a stress close to, but not greater than, the stress induced by the central measuring cell. These cells shall be inflated by gas pressure.

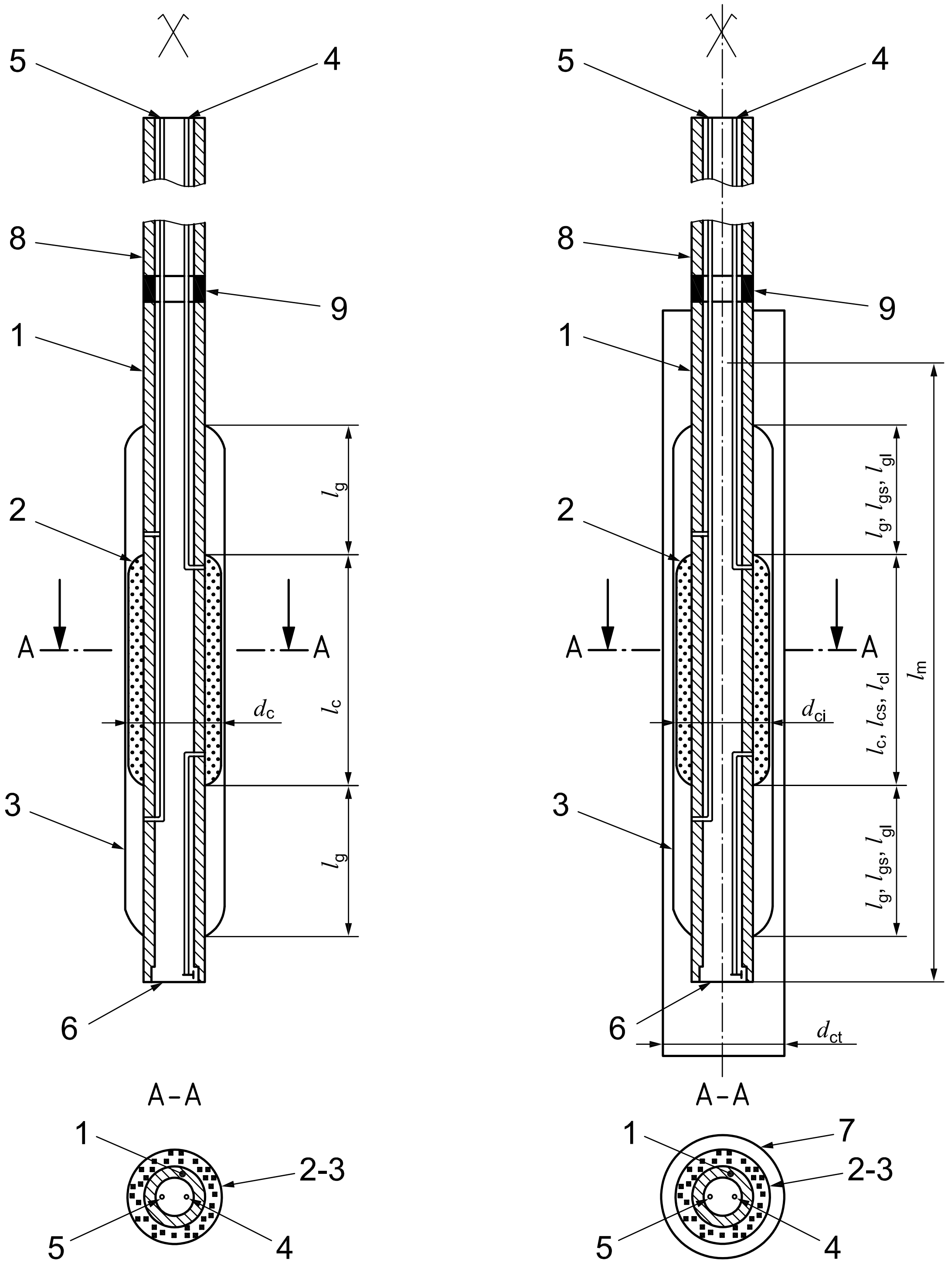
During a test these cells shall act simultaneously on the inside wall of the slotted tube, which shall transfer the stresses to the pocket wall.

The outside steel tube shall carry at least six axial or helical slots evenly distributed round the circumference (Figure 3 b).The tube slotted length l_m is measured along the tube axis. This length shall be the greater of:

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

Before and after expansion, the opening of each slot of the tube shall be less than or equal to 0,4 mm. After expansion the slotted tube and the slots shall be able to recover their original shape and size.

The assembly within the slotted tube shall be located by flexible spacers so as to allow the probe to expand radially with a minimum of resistance.



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
6 measuring cell drain outlet
7 slotted tube
8 rods
9 probe–rod coupling

Dimensions are given in Annex A.

Figure 3 — Pressuremeter probe (diagrammatic)

4.3 Pressure and volume control unit (CU)

The control unit (CU) shall be built around a cylindrical volumeter fitted with a pressurizing device and a set of measuring devices. The CU shall control the probe cell expansion and permit the simultaneous reading of liquid and gas pressures and injected liquid volume as a function of time.

The pressurizing device shall allow:

— reaching the pressuremeter limit pressure or a pressure p_r at least equal to 5 MPa;

— 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 CU;

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

— injecting a volume of liquid in the measuring cell larger than 700 cm^3.

Further, in the control unit a valve between the volumeter and the pressure measuring device shall allow stopping the injection.

4.4 Connecting lines

The flexible lines shall connect the pressure and volume control unit (CU) 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.

4.5 Injected liquid

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.

4.6 Measurement and control

4.6.1 Time

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

4.6.2 Pressure and volume

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

4.6.3 Display of readings

At the site the pressure and volume control unit (CU) 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 and pressure of the gas in the guard cell circuit.

4.6.4 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 66 mm;

— wall thickness e not less than 8 mm;

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

4.7 Data logger

The data logger, the device to acquire and record the data under procedure B, shall be fitted with

— an internal clock,

— a printer, and

— a memory device readable by a computer.

The data logger shall be designed to record the raw data from the transducers, the zeros, calibration coefficients and identification of each and the resulting calibrated data of pressure and volume.

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: date, hour, minute, second, CU number, data logger number, memory device number;

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

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

The data logger shall include an alarm device or a special display for the following events:

— no memory device in place;

— no test identification parameters recorded according to 5.4;

— no electric power.

5 Test procedure

5.1 Assembling the parts

The cover, the membrane and possibly the slotted tube if required shall be selected according to the expected stress-strain parameters 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.

5.2 Calibration and corrections

Calibration and correction shall be performed according to Annex B. Copies of the calibration results shall be available at the testing location.

5.3 Pressuremeter pocket and probe placing

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

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 test pocket:

— the equipment and method used to prepare the 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.1.2 and C.1.3)

NOTE An indication of the quality of the test pocket is given by the shape of the pressuremeter curve and the magnitude of scatter of the test readings (see D.2).

5.4 Preparation for testing

The pressure and volume control unit (CU) 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 next step, for each sounding:

— the acquisition and recording device, i.e. the data logger, shall be initialized (procedure B);

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

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

— test operator identification;

— file number;

— sounding number;

— type of probe;

— technique of pocket drilling (see Annex C);

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

— method of probe setting;

— calibrations 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

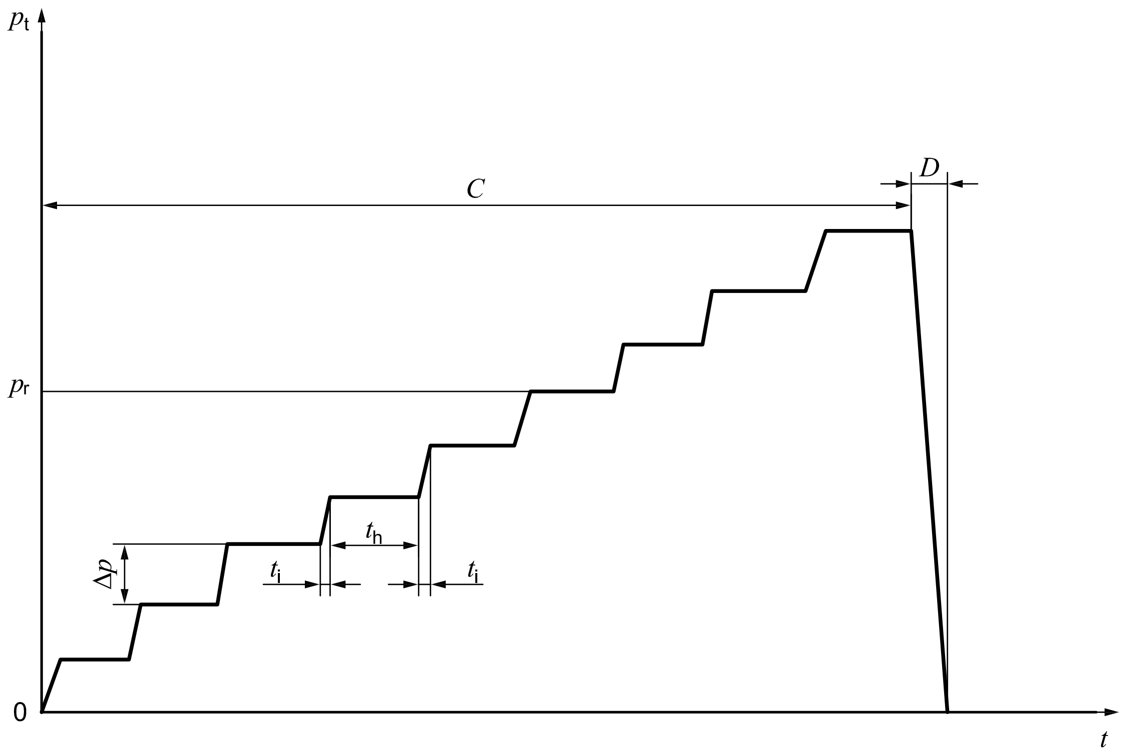
The loading programme of a pressuremeter test shall be the relationship between time and pressure as applied by the probe to the ground (Figure 4).

At each pressure hold the pressure shall be held constant in the central measuring cell and in the guard cells for a time t_h of 60 s. In procedure A, if a variation in p_r during a pressure hold exceeds the greater of 25 kPa or 0,5 % of the current pressure value p_r, the final value of pressure 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. Once the initial readings have been recorded, the operator shall observe the creep parameter $\Delta V_{60/30}$ and the differences $\Delta V_{60/60}$ 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

— reach the end of the test (see 5.7.2).



Key

p_t target pressures

Δp pressure increment

p_r pressure hold during th

C loading phase

t time

t_i pressure increment time

t_h duration of a pressure hold

D unloading phase

Figure 4 — Loading programme for a Ménard pressuremeter test

The time t_i for raising the pressure by the next step Δp shall be less than 20 s when the line length is less than 50 m. Appropriate adjustment to t_i shall be made for the case of the line length exceeding 50 m (when in coil). Once the test is completed as described in 5.7.2, unloading shall be performed steadily and without stopping.

5.6 Establishing the differential pressure

The pressure of the gas in the guard cells shall be lower than the pressure in the central measuring cell by at least twice the central measuring cell membrane pressure loss p_m as defined in B.2.

At the elevation of the control unit (CU), the pressure difference which is necessary to keep the above-mentioned equilibrium is called the differential pressure. It shall be calculated according to B.4.4. This differential pressure shall be set before the start of the test and checked at each pressure hold.

At the jobsite, before carrying out the tests, the operator shall be given a table exhibiting differential pressures as a function of the depth according to the type of probes used.

5.7 Expansion

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.

5.7.1 Readings and recordings

At each pressure hold the following readings shall be taken:

— in procedure A, the liquid pressure 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. The liquid and gas pressures, the differential pressure and their variations shall be checked. Excessive variation shall be noted (see also 5.5);

— in procedure B, the applied liquid pressure and the injected volumes in the probe shall be displayed and recorded 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 hold shall be taken at the end of the corresponding pressure increment period t_i.

5.7.2 End of test

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

— when the pressure p_r reaches at least 5 MPa, or

— when the volume of liquid injected into the central measuring cell exceeds 600 cm^3 (450 cm^3 for a short probe within a slotted tube) or

— when the probe bursts.

NOTE In the event that these conditions are not met, the test can still be fully analysed when three pressure holds beyond p_{fM} are obtained.

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 and national regulations, technical or authority requirements, and shall take into consideration 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

National safety regulations shall be 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 22475-1 when applicable.

6 Test results

6.1 Data sheet and field print-out

6.1.1 Data sheet in procedure A

All the data as shown in F.1 shall be fully and carefully recorded except readings at 1 s.

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

6.1.2 Site print-out in procedure B

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

a) before the start of the test:

   1) the operator's identification;

   2) a statement that the test will comply with the present standard: ISO 22476-4;

   3) the data logger parameters;

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

      — memory device number;

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

b) at the start of the test:

   1) date (year, month, day, hour and minute) at the start of the test.

c) at the end of each pressure hold:

   1) loading pressure step number in the series;

   2) 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;

   3) injected volume readings 30 s and 60 s after the start of the pressure hold rounded to the nearest cm^3;

   4) the difference between these two readings i.e. $\Delta V_{60/30}$;

   5) the difference between the 60 s injected volume readings of the current and preceding pressure hold $\Delta V_{60/60}$.

d) at test completion:

   1) date and time at completion of test;

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

   3) 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 CU readings V_r versus p_r, each at 60 s.

In procedure B, the raw pressuremeter curve shall be provided by the data logger printer.

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:

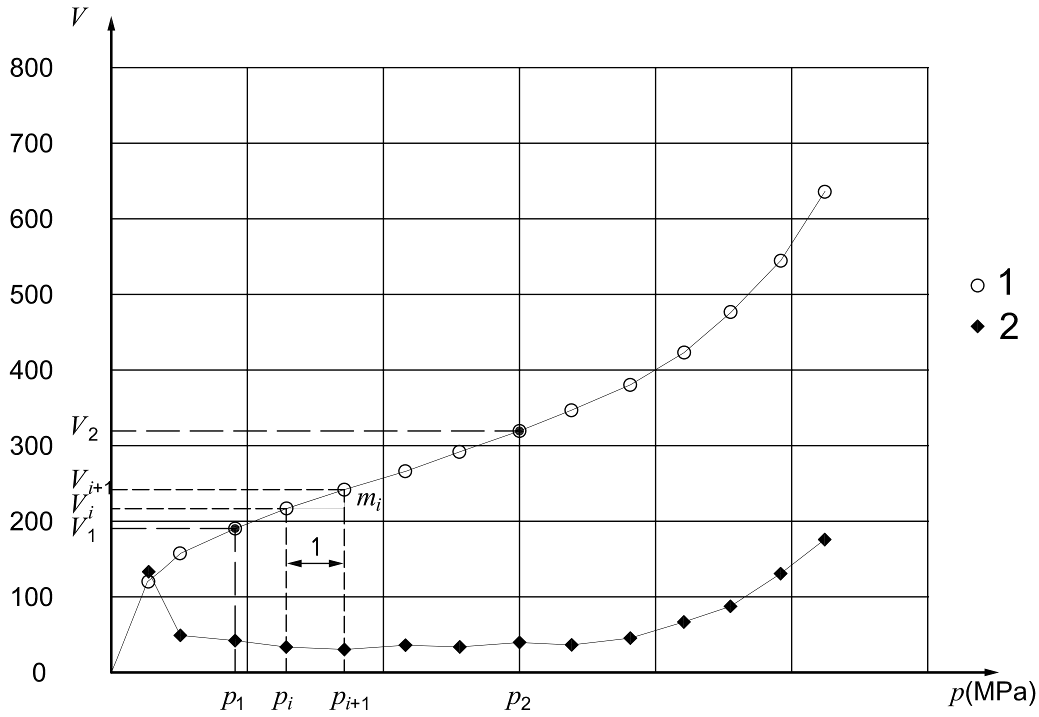
$$V = f(p)$$

where

p is the pressure at 60 s applied by the outer cover of the probe on the pocket wall, after correction for hydrostatic head and pressure loss (see D.1.2 and D.1.3);

V is the corresponding volume of liquid injected into the probe, after zeroing (see B.4.1) and after correction for volume loss (see D.1.4).

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. The slope of the pressuremeter curve shall then be sensibly constant. After the end of this stage, the probe radial expansion rate shall increase rapidly as the pressure increases.



Key

1 corrected pressuremeter curve

2 corrected creep curve

Figure 5 — Plot of a Ménard pressuremeter test

The creep curve shall be plotted as shown in the lower part of Figure 5, (according to D.3). Changes in the creep rate can identify important events in the test.

6.3 Calculated results

The pressuremeter test parameters shall be obtained from the information recorded on the data sheet (procedure A) or either on the print-out or on the memory device (procedure B).

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_{fM} (D.3),

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

— to calculate the Ménard pressuremeter E-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 be signed by the operator in charge (6.1.1 and 6.1.2).

7.3 Test report

The test report shall include the pressuremeter test identification parameters (see 5.4) and the Ménard pressuremeter test files (see 6.1). The test report shall be signed by the field manager responsible for the project.

7.3.1 Ménard pressuremeter test file

The file for a single pressuremeter test shall include, as shown in Annex F, the corrected data, the pressuremeter curve and the pressuremeter test parameters.

It shall also contain the field reports including a copy of either the signed data sheet (see 6.1.1) or of the signed print-out (see 6.1.2) and in the case of procedure B the corresponding readable electronic data recorded on the memory device as described in 4.7.

The file shall include the following data as a minimum:

a) reference to this part of ISO 22476;

b) type of procedure used for the test: A or B;

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 test pocket, correct to the 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 (E or G) and its details (slotted tube, short probe, long probe), the volume loss and the pressure loss calibration test results as defined in Annex B;

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

l) table of the liquid pressure and volume readings at 1 s (procedure B 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.1 and Figure D.1;

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

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_{fM} and the method used to obtain it;

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

7.3.2 Pressuremeter tests log

A pressuremeter tests log, as shown in F.2, shall include as a minimum:

a) reference to this part of ISO 22476;

b) type of procedure used: A or B;

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 hole in the ground 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) 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_{fM}.

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

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

j) 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 4.1 and Figures 3 and A.1.

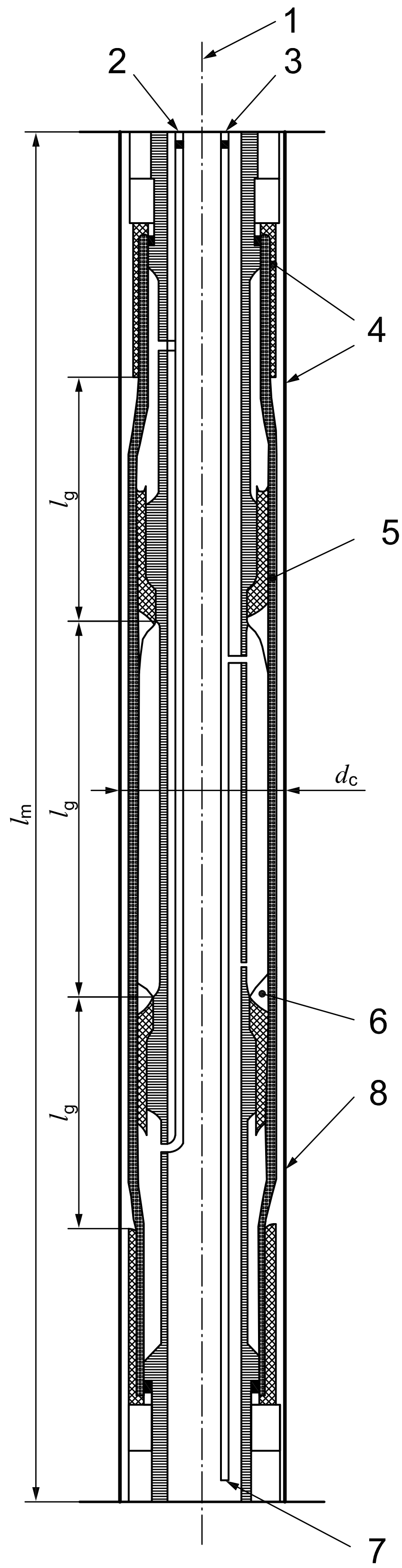
Table A.1 — Geometrical specifications for probes

Parameter			Symbol	Unit	Value	Tolerance
Probe 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	58	±2
Probe with slotted tube [see Figures 3 b) and A.1]	Inner part: short central measuring cell	Central measuring cell length	l_{sc}	mm	210	$^{+2}_{0}$
		Guard cell length	l_{gs}	mm	200	±5
		Central measuring cell outside diameter	d_{ci}	mm	44	±2
	Inner part: long central measuring cell	Central measuring cell length	l_{ci}	mm	370	±5
		Guard cell length	l_{gl}	mm	110	±5
		Central measuring cell outside diameter	d_{ci}	mm	44	±2
	Slotted tube	Outside diameter	d_c	mm	59	±5
		Slot length (along tube axis)	l_m	mm	≥ 800	–

NOTE It may occur that the inner part of the slotted tube described above is used as a 44 mm outside diameter probe with flexible cover in smaller diameter borehole. Conversely, 76 mm diameter probes can be used. They consist either of a 74 mm flexible cover probe or of a 58 mm flexible cover probe used as inner part of a slotted tube probe.

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.



Key

1 probe axis

2 gas supply pipe

3 liquid supply pipe

4 membrane and cover fixing rings

5 rubber cover

6 central measuring cell rubber membrane
7 drain valve
8 slotted tube

Figure A.1 — Components of the pressuremeter probe (here shown as a probe protected by a slotted tube – see 4.2.2)

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

a) for the central cell membrane

$p_{\mathrm{m}} \leq 80$ kPa

b) for the whole probe

when $p_{\mathrm{LM}} \leq 900$ kPa, then $p_{\mathrm{el}} \leq p_l/4 + 25$ kPa

when $p_{\mathrm{LM}} \geq 900$ kPa, then $p_{\mathrm{el}} \leq \min \{ [p_l/18 + 200 \text{ kPa}]; 350 \text{ kPa} \}$

Annex B
(normative)

Calibration and corrections

B.1 Measuring devices

All control and measuring devices shall be periodically checked and calibrated against reference standards (ENV 13005:1999) to show that they provide reliable and accurate measurements. The calibration interval shall be such that the resolution required can be verified.

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

The uncertainties of measurements summarized in E.2 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 is not given by the supplier, then it must be independently measured as given in B.2.

NOTE 2 Pressure loss is due to the added stiffness of the central measuring cell membrane, 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 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

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.2.1 and B.2.2.

The membrane pressure loss value shall be known before testing so as to set the correct pressure difference between the central measuring cell and the guard cells.

B.2.1 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 equal to 700 cm^3 (or 550 cm^3 for a short probe used within a slotted tube).

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.2.2 Measurement of central cell membrane pressure loss

The membrane shall be inflated in pressure increments Δp equal to 10 kPa. Each pressure level shall be held constant for 60 s. 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 equal to 700 cm^3 (550 cm^3 for the short probe in a slotted tube).

B.3 Checking measuring devices at site

Readings of the analogue and digital indicating instruments of the control unit (CU) shall be compared with any other available measuring device (e.g. 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 the case of procedure B between 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 either

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

  — 1 % of the full scale measurement, whichever is the larger;

b) for volumes: 3 cm^3.

B.4 Reading corrections

The stiffness of the membrane and cover assembly decreases during their first expansions and this decrease shall be minimized by some preliminary exercising as described in B.4.1.

The operations described in B.4.2 and B.4.3 shall then be carried out as follows:

— at each change of pressuremeter probe configuration;

— at each change of lines between the probe and the pressurizing and read-out 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 pocket, that is when the correct tube lines are fitted and gas bubbles have been purged from the central measuring cell and the liquid circuit.

B.4.1 Probe pre-inflation and zeroing of the volume measuring device

Before use, any probe shall first be inflated at least three times in the open air by injecting 700 cm^3 of liquid into the central measuring cell (550 cm^3 in a short probe fitted with a slotted tube).

After that:

— the volume measuring device shall be zeroed by adjusting the volume of liquid while 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 initialized (procedure B);

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

B.4.2 Equipment volume loss calibration test

The probe, either simply clad by its rubber cover or fitted with its slotted tube, shall be placed into the pressure loss calibration cylinder as described in 4.6.4 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 maximum pressure rating of the probe. 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.4.4 below.

B.4.2.1 Obtaining the volume loss correction for the equipment

The injected volume at the end of each pressure hold 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, referred to in D.1.4, shall be the slope of the straight line which is the best fit for the part of this graph that appears after the probe comes into contact with the calibration cylinder (see Figure B.2):

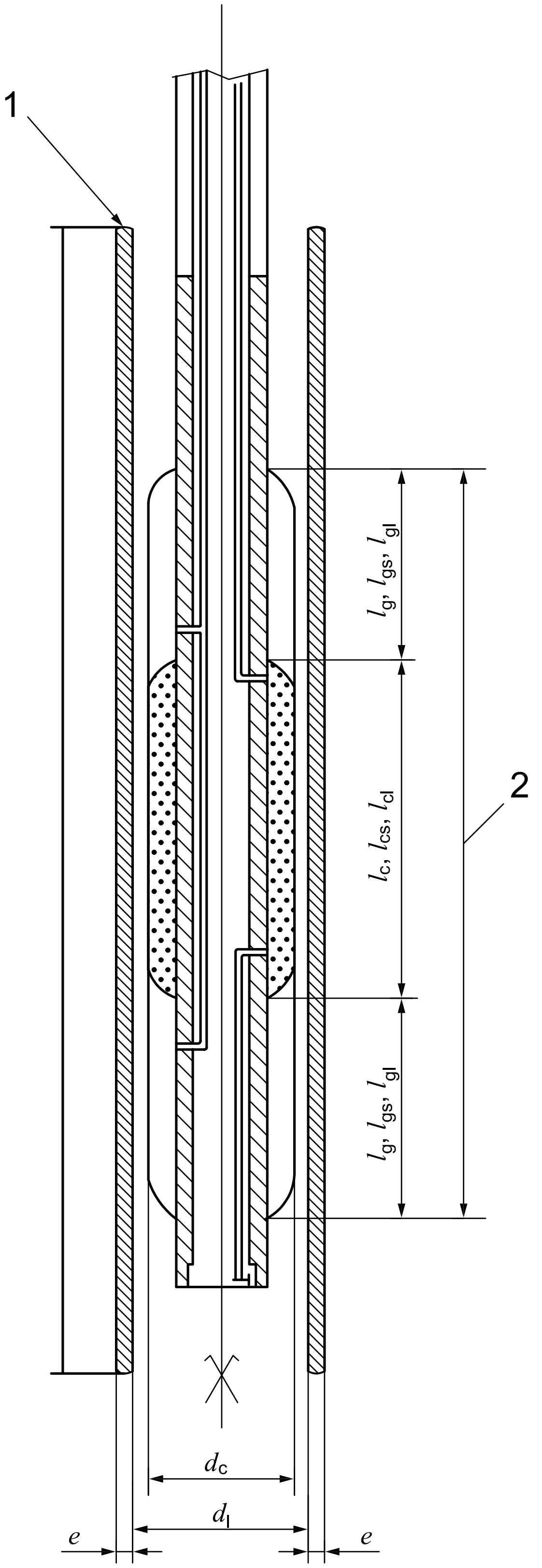
$$V_r = V_p + a p_r$$

where

V_p is the intercept on the volume axis of the straight line best fitting the data points.

The value of a shall be less than 6 cm^3/MPa (when the pressuremeter is fitted with not more than 50 m long lines).

Higher 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.



Key

1 calibration cylinder

2 pressuremeter probe

Figure B.1 — Calibration cylinder for volume loss correction

B.4.2.2 Obtaining central measuring cell volume V_c

The initial external volume of the central measuring cell shall be obtained from the following equation:

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

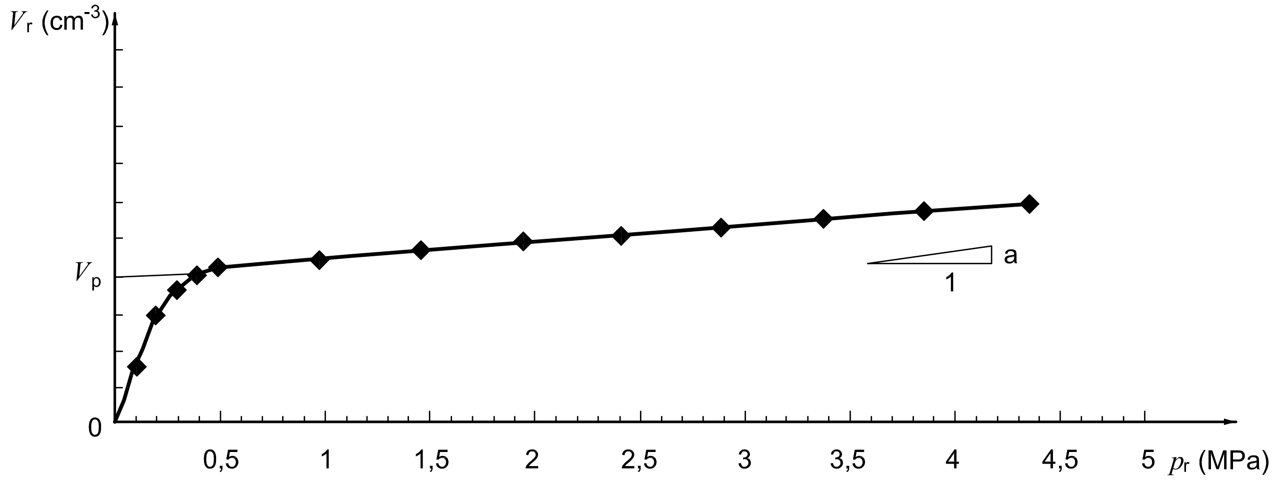
where

V_p is the intercept on the volume axis of the straight line best fitting obtained in B.4.2.1;

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;

when the probe is fitted with a slotted tube, l_c is equal to l_{cs} for a short probe or to l_{cl} for a long probe;

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



Key

V_r Injected liquid volume at the end of each pressure hold

p_r Pressure in the measuring cell

V_p Intercept of the straight line $V_r = V_p + ap_r$

Figure B.2 — Volume loss calibration — Example

B.4.3 Probe pressure loss calibration test

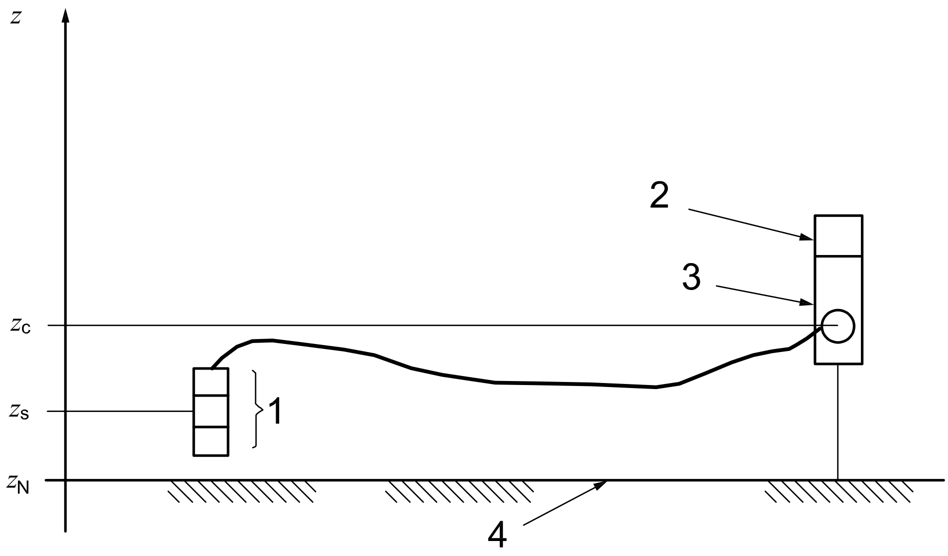
The probe shall be placed close to the pressure measuring device, as shown on Figure B.3, and in the open air. The probe shall be inflated as if it were in the ground, with pressure increments Δp equal to 1/5 of the expected pressure loss of the probe p_{el}. Each pressure increment shall be held for 60 s. A volume of at least 700 cm^3 shall be injected in the central measuring cell (550 cm^3 for the short probe fitted with a slotted tube).

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 0,2 MPa.

The resulting pressure versus volume curve, $V_{60} = f(p_e)$ is illustrated in Figure B.4. The value $z_c - z_s$ must be minimized so as to neglect any correction on the pressure readings (see D.1.1 and Figure D.1)

The pressure values obtained from this curve for each pressure hold 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 700 cm^3 (or 550 cm^3 for the short probe in a slotted tube).



Key

1 pressuremeter probe

2 pressure measuring device

3 pressure regulator

4 ground surface

z elevation

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

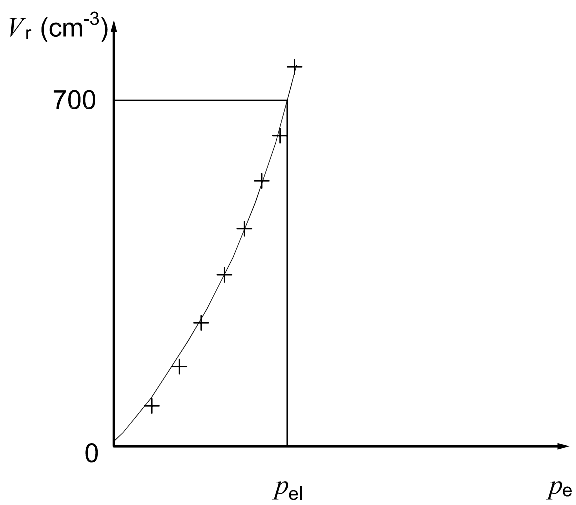


Figure B.4 — Example of pressure loss plot for a pressuremeter probe

B.4.4 Estimation of gas pressure in guard cells for a given test

The gas pressure in the guard cells shall not be higher than the pressure in the central measuring cell. The value of the guard cell pressure shall be determined before each test and fixed at the first pressure hold.

During the application of the pressure p_C in the central measuring cell, the gas pressure p_K in the guard cells shall be regulated according to the following rules (see Table 1 in 3.2, Figures B.5 and D.1 for the meaning of symbols).

For the G type probe, where the guard cells are created by the overall cover, the gas pressure p_k in the guard cells shall be lower than the pressure in the central measuring cell, but high enough to maintain the pressuremeter probe cover in a cylindrical shape:

$$p_c - 3p_m \le p_k \le p_c - 2p_m$$

or

$$p_r + (p_h - 3p_m) \le p_k \le p_r + (p_h - 2p_m)$$

and $p_k = 0$ as long as $p_r + (p_h - 2p_m) = 0$

p_c is the liquid pressure in the central measuring cell: $p_c = p_r + p_h$;

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 :

$$p_k = p_g\,[1+ \lambda_g(z_{cg} - z_p)]$$

Since values of z_c and z_{cg} will normally be positive, value of z_p shall be negative and $(z_{cg} - z_p)$ is the sum of absolute values $\left|z_{cg}\right|$ plus $\left|z_p\right|$.

p_r is the liquid pressure reading at the CU at the elevation z_c;

p_h is the head in the liquid line between the liquid pressure transducer and the central measuring cell, $p_h = \gamma_l\,(z_c - z_s)$ as explained in D.1.1;

p_g is the pressure reading at the CU of the gas in the guard cells. The measuring device in the CU elevation is z_{cg} and the probe elevation is z_s;

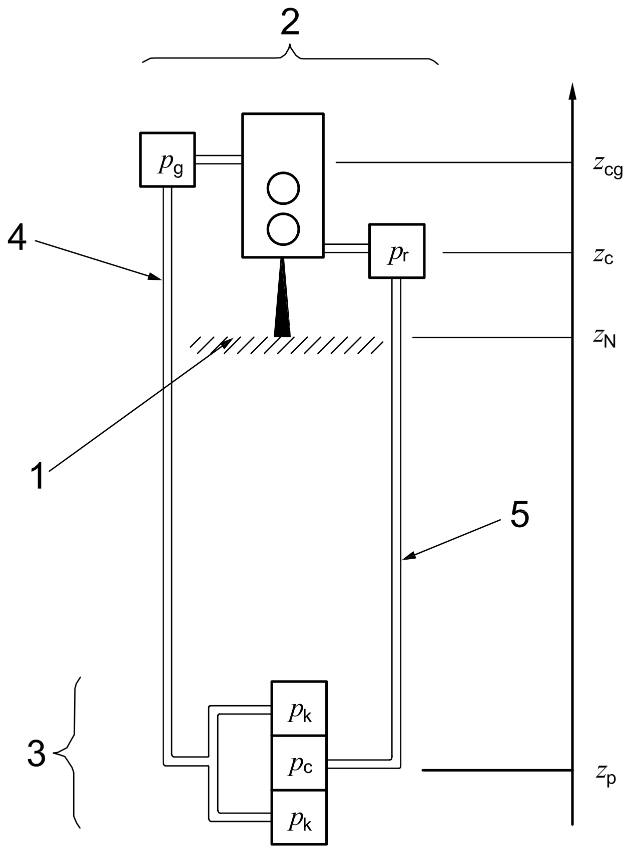
λ_g is the rate of change of pressure head of gas at pressure p_k per metre depth.

When no data on λ is known, it is recommended to use: $\lambda_g = 1{,}15 \times 10^{-4}$ per metre,

or $\lambda_g = 1{,}15 \times 10^{-4}\ m^{-1}$

NOTE 1 For practical purposes, the gas unit weight change can be ignored when the elevation difference between the CU and the probe is less than 30 m and the gas pressure less than 5 MPa. If this is the case then $p_k = p_g$.

NOTE 2 For most purposes, the assumption $z_{cg} = z_c$ is valid.



Key

1 ground surface

2 CU

3 pressuremeter probe

4 gas line

5 liquid line

z_c and z_{cg} will be positive and z_p will be 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

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 pocket formation techniques shall be adapted as listed below to the type of soil (see Table C.2). 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 or C.3 is used, the operating organization shall be able to demonstrate upon request that the technique yields pressuremeter results of satisfactory quality (see D.2.2).

C.1.1 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 0,75 m. 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 0,75 m

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 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.1.2 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.1.3). 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

Soil type	Maximum continuous drilling or tube driving stage length (m)		
	Adapted rotary drilling[b]	Rotary percussive drilling[b]	Smooth tube pushing, driving and vibrodriving[c]
Sludge and soft clay, soft clayey soil	1[a]	—	1[a]
Firm clayey soils	2	2	3
Stiff clayey soils	5	4	4
Silty soils:			
— above ground water table	4	3	3
— below water table	2[a]	1[a]	—
Loose sandy soils:			
— above ground water table	3	2	—
— below water table	1[a]	1[a]	—
Medium dense and dense sandy soils	5	5	4
Coarse soils: gravels, cobbles	3	5	3
Coarse soils with cohesion	4	5	3
Loose non-homogeneous soils, other soils not specified above (e.g. tills, etc.)	2	3	2
Weathered rock, weak rock	4	5	3

a Or the required interval between two successive tests.

b Refer to Table C.2 for acceptable techniques.

c Not applicable to STDTM technique (see C.2.6.3).

C.1.3 Time between forming the test pocket and testing

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

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 will possibly 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 soil displacement

C.2.1 General

When a 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. For any requirement apart from soil sampling techniques, soil sampler features and borehole diameters, reference to ISO 22475-1 is mandatory

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 test pocket shall be as smooth as possible and that its diameter shall be as constant as possible over the length of the test pocket.

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

C.2.2 Cutting tool diameter for the pocket

When determining the diameter of the necessary cutting tool for a bored 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;

— 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 1,08 d_c (see Table A.1 and NOTE 2 of Clause 1).

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 following techniques 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 Rotary drilling (OHD)

C.2.3.1 Open hole drilling

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.

NOTE This method is not listed in ISO 22475-1 (see C.2.1 and C.2.2).

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

Above water table, a hand auger may be used to drill the 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.

Hand augering (HA) gives good results in soft and medium stiff soil.

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).

Conversely, a hand auger with axial bottom discharge of slurry (HAM for “hand auger with drilling mud”) may be used to stabilize the pressuremeter pocket wall too, It may be used in clays exhibiting limit pressures lower than 0,5 MPa, as long as:

— the auger blades are very sharp, and

— the auger diameter is slightly larger than the pressuremeter probe diameter, but still smaller than 1,08 times the probe diameter.

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

C.2.3.2 Advancement specifications

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 rotations per minute) and

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

The drilling fluid shall cause the minimum damage to the pressuremeter pocket wall. The fluid should have a viscosity high enough to remove the cuttings at low pumping rates.

C.2.4 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 must be slightly greater in diameter than the auger flight to prevent smearing the cavity wall. The auger shall be rotated during withdrawal.

NOTE This method is not listed in ISO 22475-1 (see C.2.1)

When a hollow stem flight auger is used for simultaneous drilling and casing of the initial hole the auger end shall be kept closed. Great care shall be taken when this closer is withdrawn that the test zone is not damaged by the suction caused.

C.2.5 Rotary core drilling (CD)

Core drilling uses a core barrel sampler and rotary drilling.

Equipment and tool should be selected in a way that the mud circulation does not erode the pressuremeter test pockets. Application of ISO 22475-1 is limited (see C.2.1 and C.2.2)

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.2.6 Rotary percussive drilling (RP and RPM)

C.2.6.1 General

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.

C.2.6.2 Rotary percussive dry drilling (RP)

The removal of cuttings is by air flush. When using this technique one shall bear in mind the water content, the clay content and the hardness of the ground. This technique may mostly be used for testing at shallow depths due to the limitation of available air pressure.

C.2.6.3 Rotary percussive drilling using drilling fluids (RPM)

In this technique the pocket should be advanced by a rapid reciprocating and rotating hammering action. Fluid circulation should remove the cuttings so formed.

C.2.7 Pushed, driven or vibrodriven tubes (PT, TWT, DT and VDT)

C.2.7.1 General

For certain ground conditions (see Table C.2 for guidance), a tube with a circular cross section may be pushed, driven or vibrodriven into the ground. The tube shall be fitted with an inward bevel cutting edge to minimize pre-stressing of the test cavity wall before testing.

NOTE The samplers described in the following are not in accordance with ISO 22475-1 but they can be classified as sampling methods corresponding to sampling category C of ISO 22475-1.

C.2.7.2 Pushed tubes (PT and TWT)

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

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.2.7.3 Driven tubes (DT) or vibro-driven tubes (VDT)

For stiffer soils (see Table C.2 for guidance) thick wall tubes shall be used. They may be driven by ramming or by a vibrating hammer.

C.2.8 Slotted tube with inside disintegrating tool and mud circulation (STDTM)

In certain ground conditions (see Table C.2 for guidance), the STDTM technique may be used. It 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.3 Probe placing by driven slotted tube (DST)

In buoyant granular material, if it appears impossible to prevent the test pocket wall caving in, the probe may be pushed or driven into the soil directly or 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. Once this smaller size open hole is completed, the pocket is trimmed to the proper diameter by pushing or (vibro) driving the probe.

Table C.2 — Guidelines for pressuremeter probe placement technique

Boring technique → / Soil Type ↓	Probe placing without soil displacement										Probe placing by direct driving
	1< $d_t/d_c \leq$ 1,08										$d_t/d_c \approx 0$
	Rotary drilling				Rotary percussion			Tube pushing, driving or vibrodriving			Driven slotted tube.
	OHD *	HA/HAM *	CFA	CD	RP	RPM	STDTM	PT	DT	VDT	DST
Sludge and soft clay	✸✸°	✸✸✸°	—	—■		—	—■	✸✸✸ TWT	—		✸■
Soft to firm clayey soils	✸✸✸°	✸✸✸°	✸✸■	✸✸■	—	✸■°	✸°	✸■	✸	—	
Stiff clayey soils	✸✸✸°	✸✸■°	✸✸✸	✸✸✸ °	✸■	✸✸°	✸✸■°	—	✸■	—	
Silty soils: — above water table	✸✸°	✸✸✸°	✸✸	✸✸■°	—	✸°	✸✸°	✸■	✸	✸	—
— below water table	✸■°	✸✸■°	—	✸■°	—	✸°	✸✸▴°	—	—	—	✸■
Loose sandy soils: — above water table	✸✸°	✸✸✸■°	✸✸	✸	—	✸°	✸°	—■	—	—	—
— below water table	✸■°	✸✸°	—	—■	—	✸°	✸▴°	—■	—	—	✸■+
Medium dense and dense sandy soils	✸✸✸°	✸✸✸°	✸✸✸	✸ °	✸	✸✸°	✸✸▴°	—	✸	✸	✸✸■+
Gravels, cobbles	✸✸ °	—■°	—■	—■	✸	✸✸✸°	✸■°		✸	✸	✸✸✸■+
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)	✸✸°	✸°	✸	✸ °	✸	✸✸°	✸✸■°	—	✸	✸	✸✸■+
Weathered rock, weak rock	✸✸✸°	✸✸°	✸✸	✸✸■°	✸ ■	✸✸°	✸✸■°		✸■	✸■	

Table C.2 (*continued*)

Key					
✸✸✸	Recommended	OHD	Open hole drilling.	PT	Pushed tube
✸✸	Suited	HA	OHD performed with a hand auger	TWT	Thin wall tube, pushed
✸	Acceptable	HAM	OHD performed with a hand auger and mud	DT	Driven tube
—	Not suited	CFA	Continuous flight auger	VDT	Vibrodriven tube
	Not covered by this standard	CD	Core drilling	DST	Driven slotted tube
		RP	Rotary percussion		
		RPM	Rotary percussion with mud		
		STDTM	Slotted tube with inside disintegrating tool and mud circulation		
▪	Depending on the actual site conditions and on the evaluation of the operator				
*	Rotation speed should not exceed 1 s^{-1} and tool diameter not be more than 1,15 d_c				
°	Slurry circulation: pressure should not exceed 500 kPa and the flow rate 15 l/min. The flow can be temporarily interrupted if necessary.				
+	Pilot hole with possible preboring techniques: DST, RP and RPM				
ˆ	Needs special care: add a guard tube at the toe of the slotted tube; carry out the tests while going down; keep slurry level in casing higher than water table level				

Annex D
(normative)

Obtaining pressuremeter parameters

D.1 Obtaining a corrected pressuremeter curve

D.1.1 General

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

— hydraulic head p_h;

— probe pressure loss p_e;

— volume loss of the whole equipment during pressurization.

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 hydrostatic head, p_h, between the elevation of the pressure measuring device and the centre of the pressuremeter probe (see Figure D.1).

$$p_h = \gamma_l (z_c - z_s)$$

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.4.3 and Figure B.4). This experimental curve shall be modelled by one of the following mathematical functions, depending on the purpose of the test analysis. The methods are listed from the less elaborated (rough analysis) to the more elaborated one (research work):

— First method: linear interpolation between experimental points.

— Second method: power law type interpolation

$$p_e(V_r) = b(V_r)^m + c$$

where

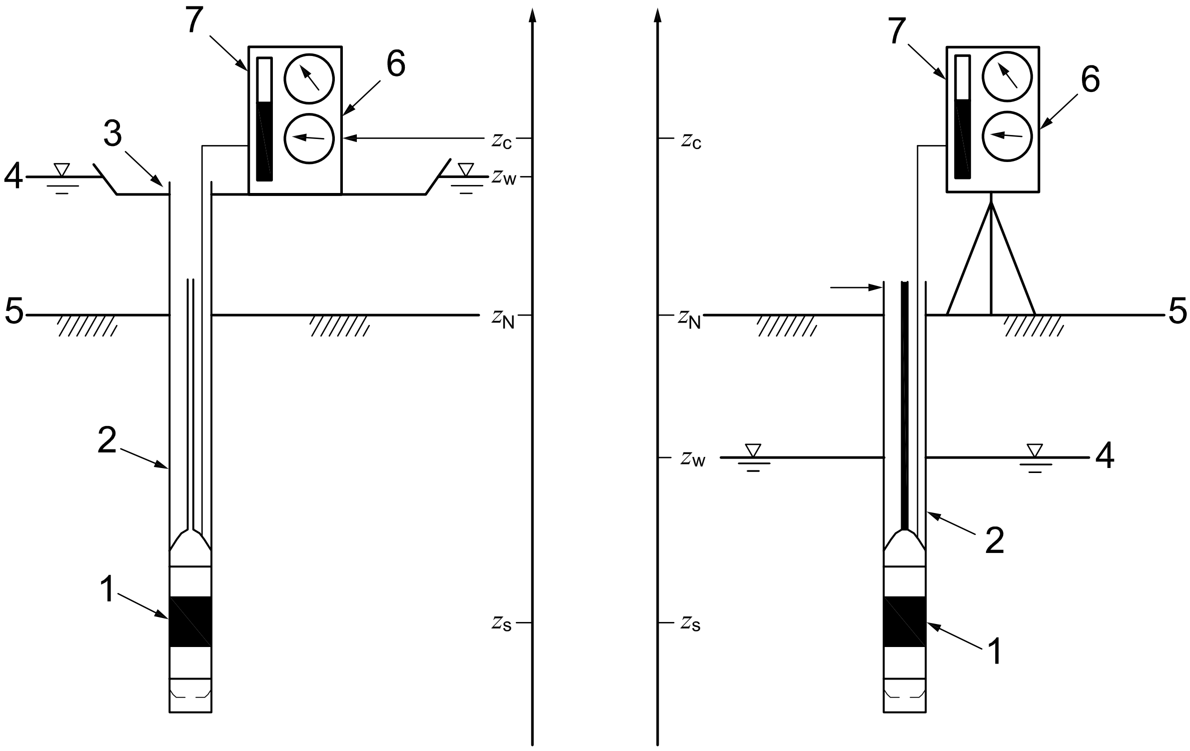
m is chosen between 0 and 1,

b and c are obtained by the mean square regression method.

— Third method: double hyperbolic adjustment (see D.4.3.3).

As this pressure loss is a function of the type of membrane and cover, of the slotted tube if any, and of the injected liquid 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)
z elevation

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

D.1.4 Volume loss correction

The volume loss correction involving the experimental pressuremeter probe volume loss curve obtained in B.4.2.2 shall be applied using the a factor obtained by linear regression (see B.4.2.1).

For a given value of pressure p_r, the volume V_r shall be corrected so as to take into account the volume losses of the probe, the lines and the measuring system:

$$V = V_r\ (p_r) - ap_r$$

NOTE 1 The volume loss correction is not necessary in soft to medium stiff soils.

It is possible to use more elaborated methods than linear regression, such as hyperbolic model, or direct linear links between experimental points.

D.1.5 Corrected pressuremeter curve

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

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

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

The pressuremeter curve shall be plotted with pressures on the horizontal axis and volumes on the vertical axis (EN 1997-2:2007, 4.4.3(5), Table 4.1).

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 creep curve, considering

— slopes m_i of straight line segments between data points

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

— and $\Delta V_{60/30}$ Ménard creep values (see Figures 5 and D.2).

The corrected pressuremeter curve shall be analysed together with the corrected creep curve, considering m_i slopes and $\Delta V_{60/30}$ Ménard creep values at each pressure hold (see Figures 5 and D.2). 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; they usually exhibit high Ménard creep values.

— The second group in the lower pressure range includes readings which exhibit low m_i slopes and low Ménard 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 Ménard creep values. This group identifies the plastic phase.

Ménard creep pressure p_{fM} shall be found in the transition zone between the last two groups (see D.3).

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

Ménard 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 test pocket quality.

If the test pocket wall is almost perfect and the test performed in ideal conditions, the first group shall be limited to the readings of the first pressure hold, indicating a high quality test.

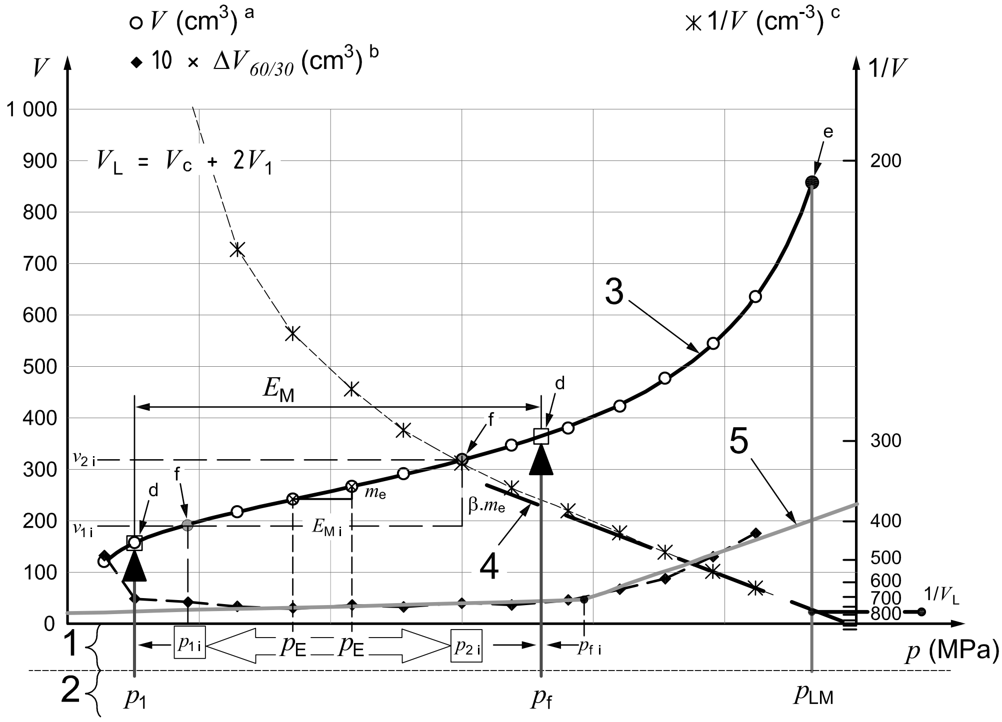
At least two data points in the second group of readings and two data points in the third group shall be available to determine all three parameters p_{fM}, p_{LM} and E_M.

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_{fM} 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_{fM} 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. Too large a pocket can give a pressuremeter curve which includes only the first two groups of readings.



Key

1 initial evaluation

2 final check

3 double hyperbolic fitted curve

4 inverse volume straight line fitting the last three values

5 example of creep data points fitting

a Corrected pressuremeter test data points fitted with double hyperbolic curve.

b Pressuremeter creep data points (volume scale enlarged 10 times).

c Corrected pressuremeter test data points on $1/V$ scale (volume reciprocal scale on the vertical axis, right hand side).

d Points retained to obtain E_M after final check for p_{LM} and p_{fM}.

e The black point retained for p_{LM} (D.4.2).

f The 2 grey points initially limiting the pseudo-elastic range (D.5.1).

“i” stands for “initial”.

Figure D.2 — Pressuremeter test curve 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_{fM} shall be estimated, using the following two graphical analyses.

— A graphical analysis of the (p, $\Delta V_{60/30}$) diagram: 2 straight lines shall be drawn on the (p, $\Delta V_{60/30}$) 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.2; the abscissa of the intersection of the 2 straight lines shall give a first value for p_{fM}: call it p_{fMi}.

— A graphical analysis of the (p, V_{60}) diagram: the borderline between the second group of readings (pseudo-elastic phase) of the pressuremeter curve and the third group of readings (large strains) shall be determined: call p_{2i} its abscissa.

The creep pressure value shall lay between p_{fMi} and p_{2i} . The closer p_{fMi} and p_{2i} are, the better is the quality of the test.

This value shall be confirmed during the final check (see D.6) when considering the values of p_{LM} and E_M obtained in the next sections.

D.4 Pressuremeter limit pressure

D.4.1 Definition

Since the pressuremeter limit pressure is obtained when the volume of the central measuring cell, which is also called the volume of the pocket, is doubled and since the volume readings do not involve the original volume V_c of the central measuring cell (see B.4.2.1), the limit pressure shall be the corrected pressure for which the corrected injected volume in the probe central cell is such that (see Figure D.2):

$$V_L = V_c + 2V_1$$

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 limit pressure shall be then obtained by linear interpolation.

D.4.3 Extrapolation methods

D.4.3.1 General

When, during an expansion test, the injected liquid volume is smaller than $V_c + 2V_1$ it is impossible to use the direct method. Therefore, the limit pressure shall be extrapolated.

Each of the two extrapolation methods described in D.4.3.2 and D.4.3.3 shall be applied to test results The final value of the limit pressure which is to be reported shall be determined using the method given in D.4.4.

For these methods, extrapolation is only permitted when the number of pressure holds applied beyond pressure p_{fM} is at least two (see D.6).

If the limit pressure is not attained either by the direct method or by extrapolation methods, the limit pressure value shall be reported as $p_{LM} > p$, p being the last corrected pressure applied.

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:

$$Y = Ap + B$$

with

$$Y = V^{-1}$$

where

A and B are coefficients obtained by a least square regression of Y on p.

The limit pressure shall be determined by the following equation:

$$p_{\text{LMR}} = -\frac{B}{A} + \frac{1}{\left[A\left(V_{\text{c}} + 2V_1\right)\right]}$$

D.4.3.3 Double hyperbolic method

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

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

The coefficients A_5 and A_6 are the abscissae of the vertical asymptotes to each hyperbola.

The matrix of four coefficients $\left[A\right] = \left[A_1, A_2, A_3, A_4\right]$ shall be obtained for values of the asymptotic limits A_5 and A_6, by the following matrix transformation.

$$\left[A\right] = \left[X^{\text{t}} \times X\right]^{-1} \times \left[X^{\text{t}} \times V\right]$$

where

$$\left[V\right] = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}, \qquad \left[X\right] = \begin{bmatrix} 1 & p_1 & 1/(A_5 - p_1) & 1/(A_6 - p_1) \\ 1 & p_i & 1/(A_5 - p_i) & 1/(A_6 - p_i) \\ 1 & \cdots & \cdots & \cdots \\ 1 & p_n & 1/(A_5 - p_n) & 1/(A_6 - p_n) \end{bmatrix}$$

A_5 and A_6 are found by a least square analysis on V based on the Gauss/Newton method.

The limit pressure p_{LMDH} shall be determined for $V_{\text{L}} = V_{\text{c}} + 2V_1$ as derived from the double hyperbolic equation above, using the analytical expression given by the unique positive solution such as $0 < p_{\text{LMDH}} < A_6$, in the third degree equation:

$$-A_2 \times p_{\text{LMDH}}^3 + \left[V - A_1 + A_2(A_5 + A_6)\right] \times p_{\text{LMDH}}^2 + \left[\left(A_1 - V\right)\left(A_5 + A_6\right) - A_5 \times A_6 \times A_2 + A_3 + A_4\right] \times p_{\text{LMDH}}$$
$$+ \left[\left(V - A_1\right) \times A_5 \times A_6 - A_3 \times A_6 - A_4 \times A_5\right] = 0$$

NOTE Reference for the mathematical modelling can be found in references [2]–[4] in the Bibliography.

D.4.4 Limit pressure by extrapolation, final step

The sum of the errors Σ_i $|V_{calculated} - V_{measured}|$ for each extrapolated curve obtained by the two methods described in D.4.3.2 and D.4.3.3.shall be calculated and divided by the number of data points used. The 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 Choice of the pseudo-elastic range

The analysis of a corrected pressuremeter curve shall begin by calculating the slope m_i of each linear segment between two adjacent data points (see Figure 5).

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

with

p_i, V_i the coordinates of the beginning of segment No. i ($i \geq 1$).

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 a coefficient β as follows:

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

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

In a first approach, the pseudo-elastic range along which the pressuremeter modulus shall be obtained by including all the consecutive segments which exhibit a slope less than or equal to β times the lowest non-zero m_E gradient. This range shall then extend in both directions from the origin of the first such segment to the end of the latest segment. The coordinates of the origin of the pseudo-elastic range shall be denoted (p_1, V_1) and those of its end (p_2, V_2). If the number n of intervals becomes too low (for example $n < 3$) the tolerance interval δV shall be increased. Engineering judgment shall be exercised, for example by considering p_2 closer to or equal to p_{fMi}.

NOTE At any time of the test reading and test reporting, quick approximation of the pseudo-elastic range boundaries (p_1, V_1), (p_2, V_2), can be obtained by an analysis of the variation of DV/DP between pressure holds.

D.5.2 Ménard pressuremeter modulus EM

D.5.2.1 General

According to the type of probe cover, the pressuremeter modulus shall be obtained by using the corresponding equations given in D.5.2.2 or D.5.2.3.

D.5.2.2 Flexible cover

$$E_M = 2(1+\upsilon) \left[V_c + \left(\frac{V_1 + V_2}{2} \right) \right] \frac{(p_2 - p_1)}{(V_2 - V_1)}$$

where

υ is the Poisson's ratio, conventionally taken as 0,33.

The E_M modulus shall be given in MPa.

D.5.2.3 Slotted tube

When using the slotted tube, E_M shall be obtained either from the equation given in D.5.2.2, or from the following equation:

$$E_M = 2(1+\upsilon)\sqrt{(V_m + V_c)(V_m + V_t)}\ \frac{(p_2 - p_1)}{(V_2 - V_1)}$$

where

$V_c = \pi \frac{d_c^2}{4} l_c$ is the volume of the central measuring cell after calibration;

$V_t = \pi \frac{d_{ci}^2}{4} l_c$ is the volume of the central measuring cell, including the slotted tube;

$V_m = (V_1 + V_2) / 2$.

NOTE For further information on the equation, see reference [4] in the Bibliography.

The corresponding equation according to either D.5.2.2 or D.5.2.3 used shall be reported.

D.6 Final check on pressuremeter parameters

Before finalizing the interpretation of a pressuremeter test, the p_1, p_2, p_{fM} and p_{LM} values shall be marked on the horizontal axis of the pressumeter test curve (Figures 5 and D.2) and the fit checked with the corrected curve so as to detect any error or incorrect extrapolation and to check the choice of boundaries for the trio of results [p_{fM}, p_{LM}, E_M].

When the limit pressure is obtained by extrapolation, the limit pressure p_{LM} stated in the test report shall not be smaller than the last corrected pressure hold applied to the ground.

Annex E
(normative)

Resolution and uncertainties

E.1 Resolution of the measuring devices

Since readings for pressure and volume are either recorded manually or by transducers, it shall be considered that their resolution depends on either the display (for procedure A - data recorded manually) or the data logger (for procedure B - data recorded automatically).

The minimum requirements for the measuring devices of a Ménard pressuremeter test as shown in Table E.1 shall be adhered to.

Table E.1 — Measuring range and resolutions for the Ménard pressuremeter measuring devices.

Measuring device for	Units	Minimum measuring range	Allowable minimum resolutions Procedure A	Allowable minimum resolutions Procedure B
Depth	m	—	0,2	0,2
Time	s	—	1	0,5
Pressure	kPa	0 – 5 000	1 % or 25[a]	1 % or 15[a]
Volume	cm^3	0 – 700	2	1

a The allowable minimum resolution shall be the larger value of the two quoted. The relative resolution shall apply to the measured value and not to the measuring range.

E.2 Uncertainties of the measurements

The dependence of the accuracy of the measurements on the equipment and the type of measuring devices of pressure and volume included in the equipment shall be considered.

The uncertainty is defined as the interval within which the true measure of the magnitude will be encountered. It can be calculated by reference to ENV 13005.

The uncertainties in pressuremeter testing shall be calculated according to the following possible sources amongst others:

— ambient and transient temperature effects;

— poor de-airing of the equipment;

— data acquisition;

— zero shifts of the measuring device during testing;

— quality of the test pocket;

— soil variability;

— operator.

Annex F
(normative)

Pressuremeter test records

While the contents of the records in F.1 and F.2 are normative minimum requirements, the format may be freely chosen.

F.1 Ménard pressuremeter test data sheet

NAME / ADDRESS	MENARD PRESSUREMETER TEST DATA according to ISO 22476-4 procedure A ☐ procedure B ☐	SITE	
		File	
		Country	
		Job site identification	
		Location plan ref.	
		Sounding No.	

PROBE	CELL PARAMETERS				TUBING AND FLUID PARAMETERS						PRESSURE LOSS PARAMETERS	
	Code				Type	Co-axal		Liquid	Nature		Calibration sheet reference No.	
	Length		Cover			Twin Lines			Unit weight γ_l/γ_w		Ultimate pressure loss p_{el} (MPa)	
	310 mm		Rubber		Total length (m)			Gas	Nature		VOLUME LOSS PARAMETERS	
	370 mm		Nylon canvas						Compressi-bility γ_g m^{-1}		Calibration sheet reference No.	
	Type		Steel canvas		MEMBRANE PARAMETERS						Calibration cylinder diameter d_i (mm)	
	E		With metal strips		Supplier type and code						Calibration coefficient a (cm^3/MPa)	
	G		Slotted tube		Pressure loss p_m (MPa)						Probe volume V_c (cm^3)	

TEST		
	Test No. & depth	
	Test date and time	
	Control unit No.	
	Data logger No.	
	Operator's name	
	Differential pressure (MPa)	
	Observations	
	(Weather, etc.)	

SITE READINGS									CORRECTED DATA			
Pres-sure Hold No.	PRESSURE p_r (MPa)				VOLUMES V_r (cm^3)				PRES p	VOL V	SLOPE m_i $\Delta V/\Delta p$	CREEP $\Delta V_{60/30}$
	1 s	15 s	30 s	60 s	1 s	15 s	30 s	60 s	(MPa)	cm^3	cm^3/MP^a	(cm^3)
0												
1												
2												
3												
4												
5												
6												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												

LEVELS	DATUM	Levels	Relative levels
			0 (bore-hole top)

PRESSUREMETER SOUNDING			
	Localization system	X =	
		Y =	
	Drilling rig		
	Drilling technique		
	Use (table C.2 abbreviations)		
	Drilling tool	type	
		Diameter (mm)	
	Casing foot at (m depth)		
	Drilling fluid		
	Length drilled before testing	from level (m)	
		to level (m)	
		Time (hr + min) completed	

UNITS			
	Elevations	Metre	
	Time	second	
	Volumes	Cubic centimetre	
	Pressures	Megapascal	

(continued overleaf)

F.1 Ménard pressuremeter test data sheet (*continued*)

FIRM LOGO / NAME / ADDRESS	**MENARD PRESSUREMETER REPORT AND INTERPRETATION** according to ISO 22476-4 procedure A ☐ B ☐	
		File
		Test reference
		Job site identification
		sounding No.
		Test depth

(Pressuremeter data plots)

CALCULATED NORMATIVE RESULTS	
σ_{hs}	
p_1	
p_2	
p_f	
p_{LM}	
p_{LM}^*	
E_M	
E_M / p_{LM}	
E_M / p_{LM}^*	

EXTRAPOLATION METHODS PARAMETERS		
Inverse volumes — — —	A	
	B	
	Average error (cm^3)	
Double hyperbolic curve ———	A1	
	A2	
	A3	
	A4	
	A5	
	A6	
	Average error (cm^3)	

COMMENTS	
Calculation program reference and version No.	**Date**

NOTE In case of procedure A, where pressure and volume at 1 second are not measured, the corresponding columns are disregarded.

F.2 Ménard pressuremeter log

Pressuremeter log According to ISO 22476-4 procedure A ☐ procedure B ☐	Pressuremeter sounding inclination if any	File No.
Grid reference x = y = z_N =	Sounding North direction	Pressuremeter sounding No. Layout Drawing No.

Elevation z (m)	Depth below GL (z_N) (m)	Information on the ground strata	Water levels	Drill tools Pocket formation technique & dates Casings dates		Pressuremeter limit pressure p_{LM} [a] • Pressuremeter creep pressure p_f [a] o (MPa)	Ménard pressuremeter modulus E_M [a] (MPa)
	⓪					0 1 2 3 4 5	0 10 20 30 40 50
	①				①		
	②				②		
	③				③		
	④				④		
	⑤				⑤		
	⑥				⑥		
	⑦				⑦		
	⑧				⑧		
	⑨				⑨		
	⑩				⑩		

Comments	Company	Name Signature

[a] Arithmetic or logarithmic scales are acceptable.

Bibliography

[1] ISO 10012, *Measurement management systems — Requirements for measurement processes and measuring equipment*

[2] General document: Ménard, L., The Interpretation of Pressuremeter Tests Results, *Sols-Soils No.26*, Paris, 1975. (texts in French and German available)

[3] Modelling the pressuremeter curve: BAUD J.-P., GAMBIN M., UPRICHARD S.T. Modeling and Automatic Analysis of a Ménard Pressuremeter Test, in: *Géotechnique et Informatique*, Proceedings of a Symposium Organised by ENPC in Paris, Presses des Ponts, Paris, 1992.

[4] Alternative method to derive E_M from slotted tube tests: HANSBO S., PRAMBORG G. Experience of the Ménard pressuremeter in foundation design, in: *Pressuremeters*, Proceedings of ISP3 Symposium organised by BGS in Oxford, Thomas Telford Limited, London, 1990.

[5] EN 1997-1, *Eurocode 7: Geotechnical design — Part 1: General rules*

[6] EN 1997-2, *Eurocode 7: Geotechnical design — Part 2: Ground investigation and testing*

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