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Geotechnical investigation and testing — Field testing —

Part 5: Prebored pressuremeter test

Reconnaissance et essais géotechniques — Essais en place —

Partie 5: Essai au pressiomètre en préforage

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Foreword

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

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

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

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

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

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

This second edition cancels and replaces the first edition (ISO 22476-5:2012), which has been technically revised.

The main changes are as follows:

— the title of the part has been modified;

— a reference loading programme with cyclic loading has been added;

— calibration procedures have been developed.

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

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

Geotechnical investigation and testing — Field testing —

Part 5:
Prebored pressuremeter test

1 Scope

This document is applicable to pressuremeter tests using cylindrical flexible probes placed in pre-existent boreholes using testing procedures other than the Menard procedure.

Pressuremeter tests following the Menard procedure are provided in ISO 22476-4.

NOTE A high-pressure flexible pressuremeter probe which contains transducers for the measurement of radial displacements is also known as flexible dilatometer probe or high-pressure dilatometer probe.

This document applies to tests performed in any kind of grounds, starting from soils, treated or untreated fills, hard soils and soft rocks, up to hard and very hard rocks, either on land or offshore.

The parameters derived from this test can include stiffness, strength, initial in-situ stress state and consolidation properties.

2 Normative references

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

EN 16228-1, *Drilling and foundation equipment – safety – Part 1:Common requirements*

EN 16228-2, *Drilling and foundation equipment – safety – Part 2: Mobile drill rigs for civil and geotechnical engineering, quarrying and mining*

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

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

ISO 22475-1, *Geotechnical investigation and testing — Sampling methods and groundwater measurements — Part 1: Technical principles for the sampling of soil, rock and groundwater*

ISO 22476-4, *Geotechnical investigation and testing — Field testing — Part 4: Prebored pressuremeter test by Ménard procedure*

3 Terms, definitions and symbols

3.1 Terms and definitions

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

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

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

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

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

Note 1 to entry: Pressuremeter probes contains means of measurement of its radial displacements or volume.

3.1.2
flexible dilatometer probe
high-pressure dilatometer probe
high-pressure flexible pressuremeter probe which contains transducers for the measurement of radial displacements

3.1.3
pressuremeter control unit
set of suitable devices capable of supplying fluid and/or gas pressure to the probe, to control and take readings of the probe’s pressure, radial displacements or volume of the measuring cell

3.1.4
connecting line
cable that connects the control unit to the probe, delivers fluid and/or gas pressure in the measuring and guard cells

3.1.5
pressuremeter test pocket
circular cylindrical cavity formed in the ground to receive a *pressuremeter probe* (3.1.1)

3.1.6
pressuremeter test
process of expanding the pressuremeter probe so as to pressurize the flexible membrane against the pocket wall and so measure pressure, radial displacements or volume as a function of time during the expansion test

Note 1 to entry: See Figure 1.

3.1.7
pressuremeter sounding
series of pressuremeter tests in a borehole

3.1.8
seating pressure
pressure during the expansion of the pressuremeter at which the pressuremeter membrane contacts the pocket wall

3.1.9
controlling parameter
variable used to define the loading programme of the test according to a pre-determined programme and recorded in the control unit

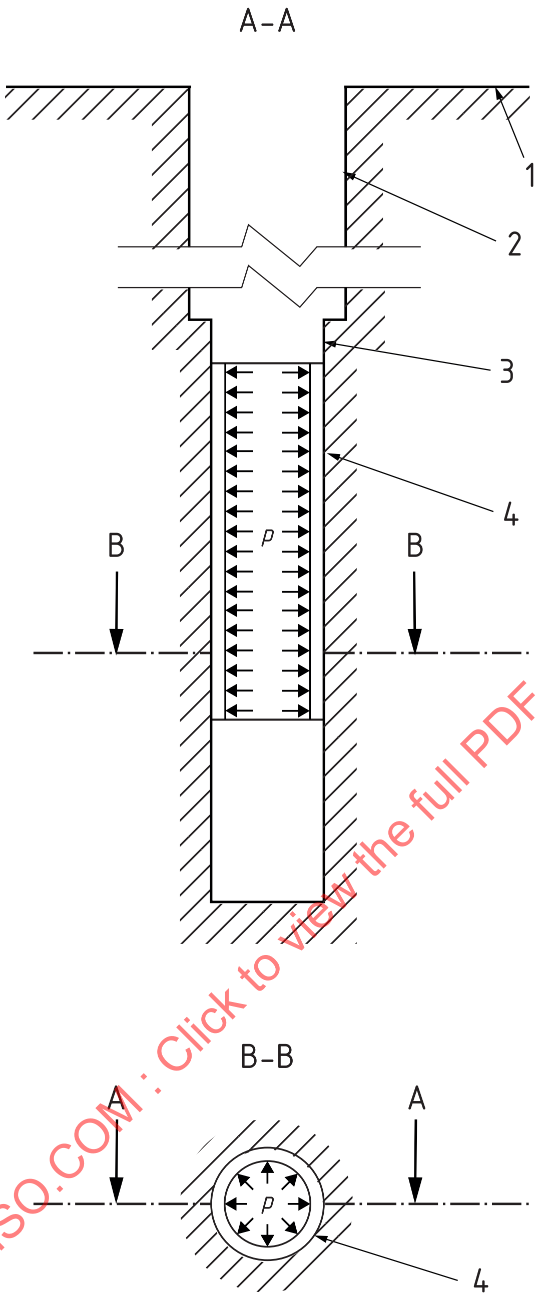
Note 1 to entry: This variable can be the pressure, the radius displacement or the injected volume.

3.1.10
radial displacement
change in pressuremeter probe radius/diameter or in cavity wall displacement

3.1.11
pressuremeter curve
graphical plot of pressure versus the associated cavity wall displacement or measuring cell volume

3.1.12
pressuremeter shear modulus
G_{PBP}
shear modulus obtained from the pressuremeter curve

Note 1 to entry: See 6.3



Key

1 ground surface
2 borehole wall
3 pocket
4 expanding pressuremeter probe
P applied pressure
A-A axial section
B-B cross section

Figure 1 — Example of a prebored pressuremeter test

3.1.13
depth of test
distance between the ground level and the centre of the expanding length of the pressuremeter probe measured along the borehole axis

Note 1 to entry: See Figure 2.

3.1.14
operator
qualified person who carries out the test

3.1.15
phase
section of the loading or expansion program characterized by a controlling parameter, a loading rate and a loading direction

3.1.16
loop
sequence of the loading or expansion program including at least an unloading phase and a reloading phase, and possibly an intermediate hold phase

3.2 Symbols and abbreviations

For the purposes of this document, the symbols in Table 1 apply.

Table 1 — Symbols

Symbol	Description	Unit
a	Corrected equipment radial displacement or volume loss coefficient, taking into account calibration cylinder self-deformability	$mm.MPa^{-1}$ or $cm^3.MPa^{-1}$
a_r	Raw equipment radial displacement or volume loss coefficient	$mm.MPa^{-1}$ or $cm^3.MPa^{-1}$
a_{cc}	Radial displacement or equivalent volume loss taking into account calibration cylinder self-deformability	$mm.MPa^{-1}$ or $cm^3.MPa^{-1}$
d_{cc}	Calibration cylinder inside diameter	mm
d_c	Initial external diameter of the pressuremeter probe	mm
E_{PBP}	A Young modulus derived from a prebored pressuremeter test	MPa
G	Shear modulus	MPa
G_{L1}	First loading pressuremeter shear modulus	MPa
G_{PBP}	Pressuremeter shear modulus	MPa
G_{Ri}	A reloading pressuremeter shear modulus	MPa
G_{sys}	Apparent shear modulus of the equipment or system during unloading-reloading loops	MPa
G_{Ui}	An unloading pressuremeter shear modulus	MPa
G_{URi}	An unloading/reloading pressuremeter shear modulus	MPa
k_f	Creep parameter in reference loading programme C	mm
L_{FD}	Expanding length of the pressuremeter probe	mm
p	Corrected pressure	MPa

Table 1 *(continued)*

Symbol	Description	Unit
$p_{1.1}$	Constant full relief pressure for loops in reference loading programme A	MPa
p_e	Pressure loss associated with membrane stiffness	
p_i	Corrected reversal pressure before loop *i*	MPa
p_{mean}	Average corrected pressure in reference loading programme D	MPa
p_{min}	Minimum corrected pressure in reference loading programme D	MPa
p_{max}	Maximum corrected pressure in reference loading programme D	MPa
p_r	Pressure as read at the measuring unit	MPa
p_s	Seating pressure	MPa
r	Corrected radius	mm
r_1	Corrected radius at time t_1 in reference loading programme C	mm
r_2	Corrected radius at time t_2 in reference loading programme C	mm
r_e	Radius correction	mm
r_s	Nominal cavity radius	mm
t	Time	min
T	Period in reference loading programme D	min
t_1	Time 1 in reference loading programme C	min
t_2	Time 2 in reference loading programme C	min
ΔV	Corrected injected volume	cm^3
ΔV_e	Injected volume correction	cm^3
ΔV_r	Injected volume, as read at the control unit	cm^3
V	Total volume	cm^3
z	Test depth	m
δ	Corrected radial displacement	mm
δ_e	Radial displacement correction	mm
δ_r	Radial displacement, as read at the control unit	mm
δ_s	Radial displacement corresponding to the seating pressure	mm
Δd_r	Increase of diameter, as read at the control unit	mm
Δd	Corrected diameter increase	mm
Δp_r	Pressure increment, as read at the control unit	MPa
Δp	Corrected pressure increment	MPa
ε_c	Cavity strain	-
ν	Poisson's ratio	-

4 Equipment

4.1 General

The test with the pressuremeter is performed by the expanding of a pressuremeter membrane placed in the ground (see Figure 1). The pressure and the associated expansion of the probe are measured and recorded so as to obtain a pressure-expansion relationship for the ground as tested.

The equipment to carry out pressuremeter tests shall consist of the components shown in Figure 2.

The following components are mandatory:

— pressuremeter probe (no. 8 in Figure 2);

— connecting line (no. 6 in Figure 2);

— signal cable (no. 5 in Figure 2);

— displacement or volume measuring unit (no. 2 in Figure 2);

— pressure control unit (no. 3 in Figure 2);

— pressure source (no. 4 in Figure 2).

— setting rods (no.1 in Figure 2).

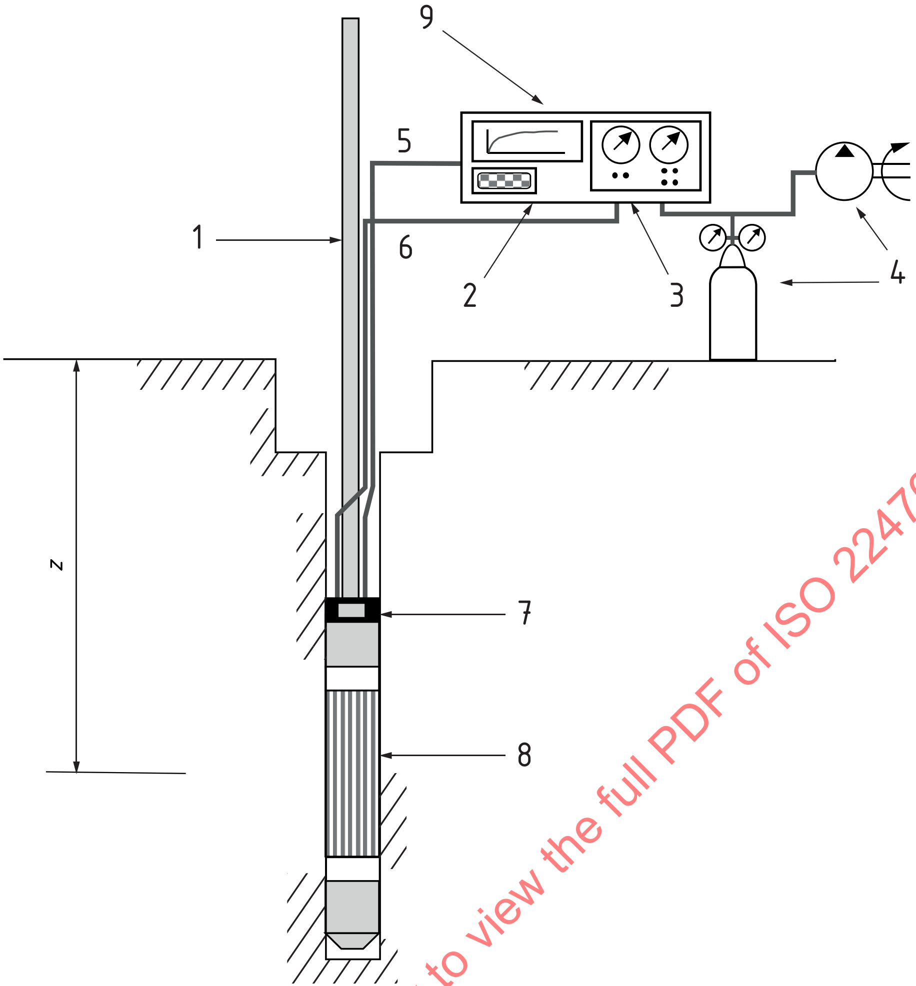
The following components may be added to allow orientation of the instrument if needed:

— data logger (no. 9 in Figure 2);

— sediment collection tube (no. 14 in Figure 3);

— pore pressure measuring system;

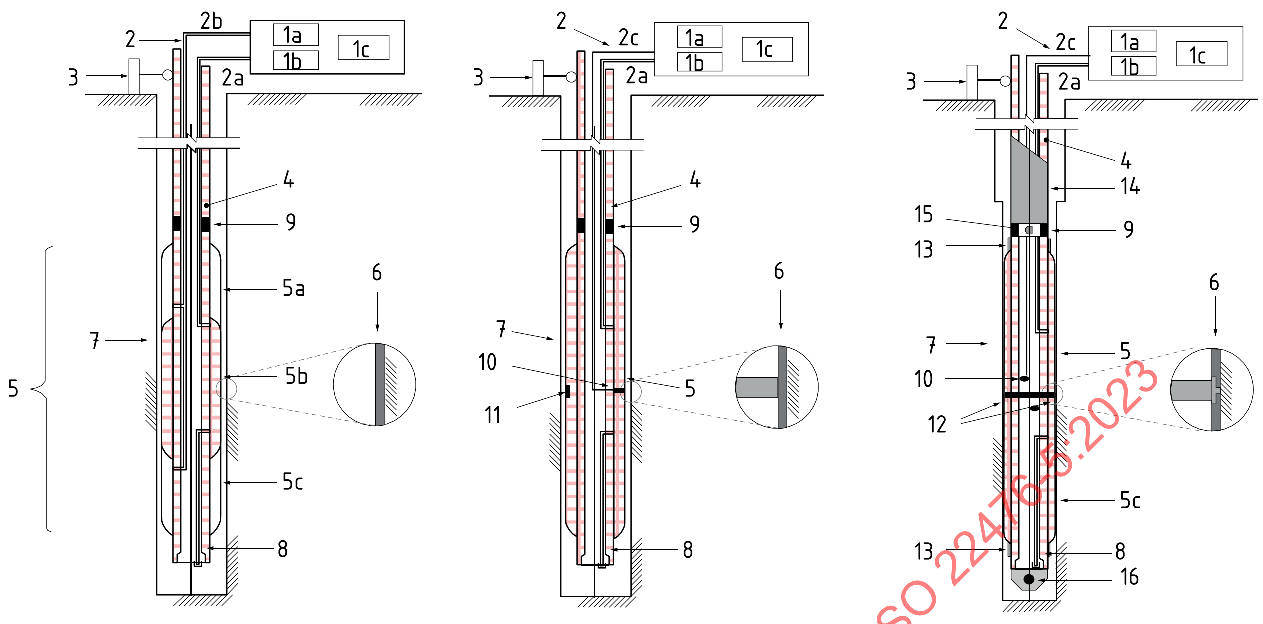
— accelerometer or geophones to perform shear wave velocity measurements.



Key

1 setting rods
2 displacement or volume measuring unit
3 pressure control unit
4 pressure source
5 signal cable
6 connecting line
7 probe rode coupling sediment collection tube
8 pressuremeter probe
9 data logger
z test depth

Figure 2 — Schematic diagram of pressuremeter equipment



a) Tri-cellular or monocellular probe with expansion followed through the volume of central cell

b) Monocellular probe with displacement measured inside the membrane

c) Monocellular probe with displacement measured at the cavity wall

Key

1	control unit (CU):	1a	pressurization, differential pressurization (if any) and injection devices
		1b	pressure and displacement or volume measuring devices
		1c	acquisition, storage and printing out of the data (required for CU type B and C)
2	connecting lines:	2a	line for liquid injection
		2b	line for gas injection
		2c	signal cable
3	depth measurement system		
4	setting 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		
10 and 11	displacement transducers		
12	metal insert at the extremities of the displacement transducers		
13	membrane clamping ring		
14	sediment collection tube		
15	pressure transducer (if applicable)		
16	compass (if applicable)		

Figure 3 — Sketch of pressuremeter probes

Preparation of pressuremeter test pocket shall be performed according to ISO 22476-4. The annular space between borehole wall and the probe, if any, shall be chosen taking into account the measuring range of the displacement transducers if any. Drilling parameters should be recorded according to ISO 22476-15. Borehole log should be recorded according to ISO 22475-1 and ISO 14689.

4.2 Pressuremeter probe

The probe expansion shall be monitored by radial displacement [see Figure 3 b) and c)] or volume measurement [see Figure 3 a)].

The probe shall have a cover in a shape of monocellular or be tricellular. When small strain measurement (as defined in EN 1997-2) is needed, local displacement measurement can be implemented in the probe.

Radial displacements shall be measured by electrical transducers on two or more points, placed in the vicinity of the mid plane [see Figure 3 b) and c)].

NOTE The arrangement shown in Figure 3 a) and b) with measurement at the inner wall of the membrane is primarily used in soils. The arrangement shown in Figure 3 c) with measurement on inserts that penetrate the membrane and directly bear on the cavity walls is primarily used in rocks.

In arrangement shown in Figure 3 a) and b), because membrane compression influences the readings of pressure and displacement, proper corrections shall be determined by corresponding calibration (see A.3).

The slenderness of the pressuremeter probe (ratio between expanding length L_{FD} and initial external diameter d_c) shall at least be equal to 6.

If included, pore pressure may be measured in the mid plane of the probe.

4.3 Connecting lines

The pressure connecting line and signal cable connect the control unit to the probe. The pressure connecting line conveys the fluid to the probe and may be either parallel or coaxial with the signal cable.

The injected fluid and inner diameter of the connecting lines shall be selected so that the pressure differential between the CU and the probe remains limited.

4.4 Control unit (CU)

The control unit shall control the probe expansion and permit the reading of liquid or gas pressure and displacement or volume as a function of time.

The pressurizing system (3 and 4 in Figure 2) shall allow:

— reaching a pressure defined by the project;

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

— stopping the injection when necessary.

The control unit shall include:

— equipment to apply the controlling parameters, and so to inflate or deflate the probe, and to maintain constant pressures as required during the test;

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

— a device that allows, according to the type defined in Table 2, the reading and recording of the parameters to be measured: time, pressure and displacement or volume.

Table 2 — Types of pressuremeter control unit

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

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

4.5 Measurement and control accuracy

4.5.1 Time

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

4.5.2 Pressure and expansion

The pressure measuring devices for the liquid or for the gas in the measuring cell shall be located:

— at least in the control unit;

— if relevant, also inside the probe, in this case at less than 1 m above the centre of the measuring cell.

The maximum uncertainty of measurement of the devices measuring pressure and probe expansion shall be as specified in Annex C.

4.5.3 Display of readings

On site, the pressure control and probe expansion measuring units shall give a simultaneous and instantaneous display of the following readings: time, pressure of the fluid injected into the probe and radial displacements or injected volume.

4.5.4 Expansion calibration cylinder

The main dimensions of the steel calibration cylinder serving the calibration for membrane compression and additional effects shall be as follows:

— a known inside diameter which closely fits the deflated instrument;

— a thickness appropriate to the maximum pressure to be applied;

— a length appropriately greater than the expanding length of the instrument.

5 Test procedures

5.1 Assembly of parts

The cover, the membrane and possibly the rigid protection or the slotted tube if required shall be selected according to the planned loading programme and type of the ground in which the probe is to be used.

Then the probe shall be linked to the control unit through the connecting lines and cables. The whole system shall be filled with working fluid and purged to remove air bubbles if relevant.

5.2 Calibration of the testing device and corrections of readings

Before testing, the operator shall make sure that:

— all measuring components have been calibrated according to ISO 10012;

— calibration of the whole system has been performed according to Annex A and reading corrections are available.

Copies of the calibration documents shall be available on request.

5.3 Pressuremeter test pocket and probe placing

The test location is usually determined from design requirements. The position of the borehole into which the probe is to be inserted shall be marked on a drawing and identified by its location details.

The pocket shall be drilled and the pressuremeter probe placed in the test location with the minimum of disturbance to the borehole wall to be tested.

The pocket and the probe placing shall be performed, and samples shall be taken according to ISO 22476-4, with the exception of techniques involving ground displacement (e.g. pushed probe, driven slotted tube).

NOTE Pressuremeter testing for which placement of probes involves ground displacement is dealt by ISO 22476-8.

If necessary, the instrument may be orientated in the pocket by rotating the setting rods.

The uncertainty on the probe depth measurement shall follow Annex C.

5.4 Test execution

5.4.1 Test loading programmes

The test loading programme shall be specified and available before the start of the test.

NOTE The test loading programme can take into account or cover the expected loading caused by the structure, if known.

The test loading programme should include:

— the sequence of phases in the test, including any loops, if present;

— the controlling parameter that applies in each phase: pressure, displacement or volume;

— the mode of application of the controlling parameter by a continuous ramp or in steps:

  — in case of a continuous ramp, its rate and interval;

  — in case of steps, their magnitude and duration;

— the amplitude of any loop, if present;

— readings and recordings frequency;

— any additional stopping criteria.

The loading programme specification can be simplified by using or adapting any of the reference loading programmes laid out in 5.4.2.

The parameters laid out in a test specification may be changed during the test if the operator has reason to believe that the specified loading programme will jeopardize the test result or damage the instrument. Any adaptation to the test specification by the operator and the reasons for it shall be recorded.

5.4.2 Reference loading programmes

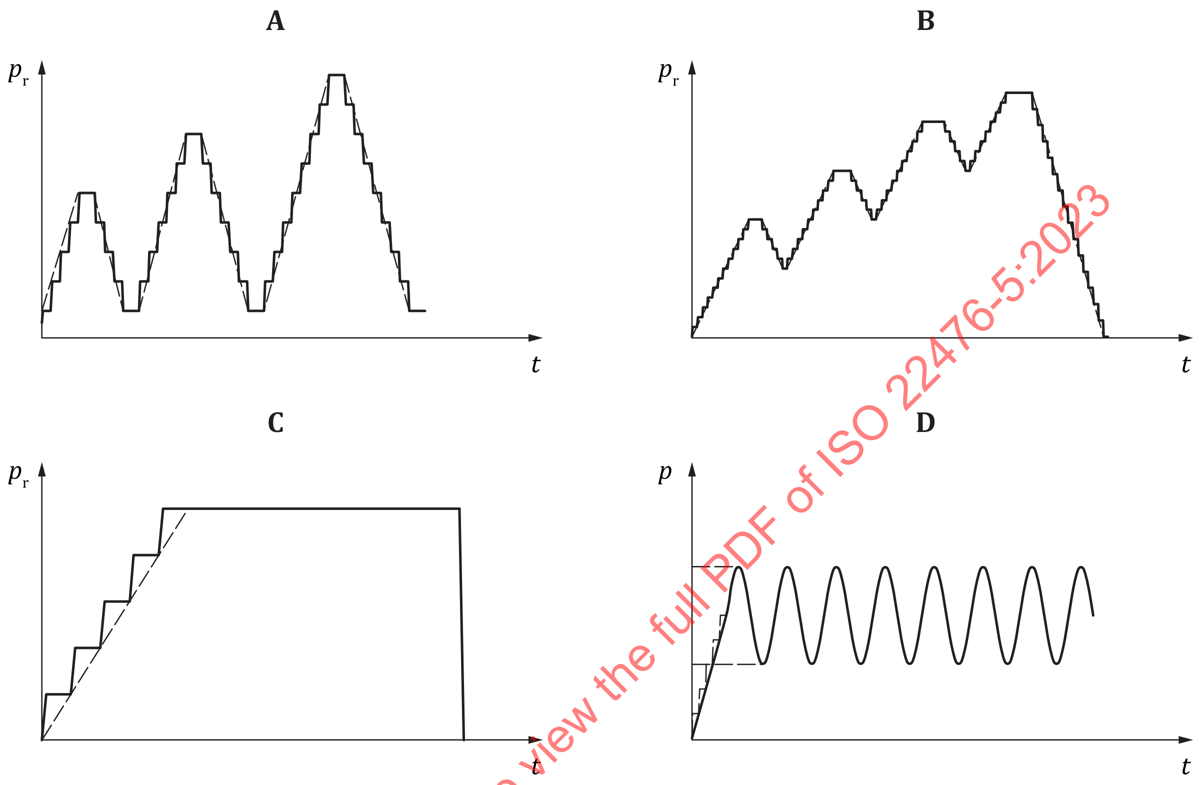


Figure 4 — Reference loading programmes A, B, C and D

One of the following reference loading programmes provided in Figure 4 may be employed as templates to specify the test. These reference loading programmes, which are fully described in Annex B, are:

— reference loading programme A: at least two loops with (almost) full unloading, and final unloading;

— reference loading programme B: at least three loops with partial unloading;

— reference loading programme C: a hold after a preliminary loading phase;

— reference loading programme D: a specified number of loops or cycles, after a preliminary loading phase.

NOTE In Figure 4, the pressure is used as controlling parameter only for illustration purposes. The same reference loading programme can be applied using either radial displacement δ_r or injected volume ΔV_r.

5.4.3 Readings and recordings before and during the test

During the test, the operator shall record:

— the effective applied loading programme, including any deviation from the specification;

— the response of all measuring sensors during the loading programme.

A comprehensive number of data (see 7.2) shall be reported.

5.4.3.1 During the test

At the end of each pressure hold or sequence:

— loading pressure or hold number in the series;

— any changes in the pressure and volume or displacement occurring during the hold or sequence.

Graphical representation of loading program (control variable according to time) and raw measurement should be displayed to the operator.

5.4.3.2 At test completion

— date and time at completion of test;

— the uncorrected pressure-expansion curve;

— the full print-out authentication by the operator who signs and gives his full name in capital letters.

5.4.3.3 Data sheet and print out

Data sheets or, in case of the use of a data logger, print outs, shall be available.

5.5 End of test

The test shall be stopped when any of the following occur:

— the specified test loading programme has been carried out;

— the maximum admissible expansion of the pressuremeter membrane is reached;

— the measuring range of any of the transducers is exceeded;

— the operator considers there is a risk to jeopardize the test result or to damage the equipment.

5.6 Backfilling of borehole

After completion of a pressuremeter sounding, the borehole shall be backfilled and the site restored according to the specifications given in ISO 22475-1.

5.7 Safety requirements

The user of this document should be aware of national safety regulations, for instance for:

— personnel health- and safety equipment;

— clean air if working in confined spaces;

— ensuring the safety of the equipment.

Drilling rigs shall be in accordance with EN 16228-1 and EN 16228-2.

6 Test results

6.1 General

All the derived parameters shall be obtained from the corrected pressure (corresponding to the pressure at the cavity walls), and the corrected radius or volume (corresponding to the radius or volume of the cavity).

The cavity radius and volumes shall be obtained considering the corrected radial displacement and corrected injected volumes respectively.

Corrected pressure, corrected radial displacement and corrected injected volume shall be obtained from measured values through the application of corrections described in 6.2.

The parameters derived from the pressuremeter test can include:

— shear moduli;

— undrained shear strength;

— at rest total horizontal stress;

— consolidation or creep parameters.

The interpretation assumptions shall be referenced explicitly.

6.2 Corrected pressure, radial displacement and volume

The corrected pressure p shall be obtained from Formula (1) or (2):

$$p = p_r(\delta_r) - p_e(\delta_r) + p_h \tag{1}$$

$$p = p_r(\Delta V_r) - p_e(\Delta V_r) + p_h \tag{2}$$

where

p_h is the hydraulic head, due to the difference of elevation between the measurement of the pressure in the measuring cell and the probe;

p_e is the pressure correction due to membrane resistance (see Clause A.2).

The corrected radial displacement δ or injected volume ΔV shall be obtained from Formula (3) or (4):

$$\delta = \delta_r - \delta_e(p_r, \delta_r) \tag{3}$$

$$\Delta V = \Delta V_r - \Delta V_e(p_r, \Delta V_r) \tag{4}$$

where

δ_e is the radial displacement correction (see Clause A.3);

ΔV_e is the injected volume correction (see Clause A.3).

6.3 Apparent pressuremeter moduli

The apparent secant shear modulus of a prebored pressuremeter test, G_{PBP} can be obtained through Formula (5) or (6):

$$G_{PBP} = \frac{1}{2} r_s \frac{\Delta p}{\Delta \delta} \tag{5}$$

$$G_{PBP} = V_s \frac{\Delta p}{\Delta V} \tag{6}$$

where

r_s	is the radius of the cavity corresponding to the seating pressure p_s;
V_s	is the volume of the cavity corresponding to the seating pressure p_s;
Δp	is either the change of pressure above the seating pressure p_s, the reversal pressure of a given loop or the minimal pressure of a given loop;
ΔV	is the change of corrected injected volume due to Δp;
$\Delta\delta$	is the change of corrected radial displacement due to Δp.

NOTE 1 The pressuremeter shear modulus G_{PBP} corresponds to the secant shear modulus considering that the ground follows a linear elastic behaviour during the pressuremeter test, independent from strain and stress level. If the linear elastic behaviour is not met, especially for soils, the shear modulus G will also vary with the distance to the probe and the use of the previous formulae only yields an apparent shear modulus.

NOTE 2 Procedures to derive the shear modulus G from the pressuremeter shear modulus G_{PBP} obtained with Formula (5) or (6) can be found in Reference [12].

6.4 Results

6.4.1 Determination of moduli

Pressuremeter shear moduli G_{PBP} should be determined from Formula (5) or (6).

In case of radial displacement measurements, pressuremeter shear moduli G_{PBP} shall be determined using the average value of radial displacements. However, if the values differ much from each other indicating anisotropy of the rock or soil mass, the pressuremeter shear moduli G_{PBP} should be determined separately for each pair of opposing displacement transducers and reported accordingly.

When evaluating pressuremeter tests, Δp shall only be selected within a range of any loading or unloading phase. Whichever is selected determines whether the modulus measured is a loading or an unloading one. Distinction shall be made between the first loading modulus and various reloading moduli. All shear moduli shall be derived and quoted individually. Shear moduli values should be quoted to three significant digits.

6.4.2 Reference loading programme A

The prebored pressuremeter shear moduli G_{PBP} should be calculated as follows (see Table 3 and Figure 5):

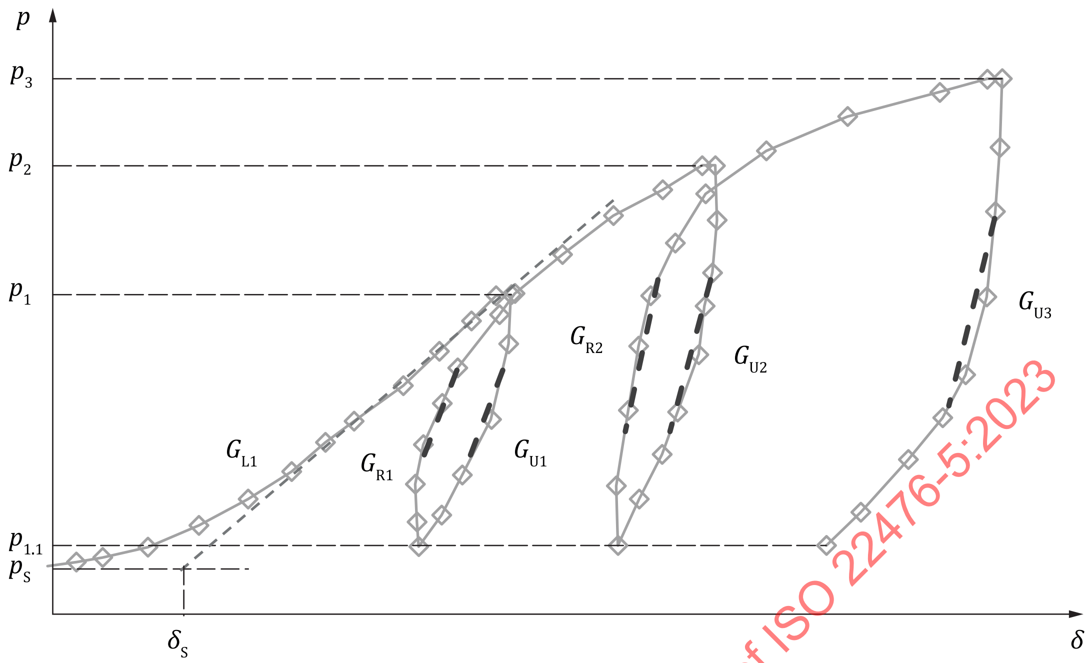
— the first loading modulus G_{L1} are derived from the data after the seating pressure p_s and before the first unloading-reloading loop;

— the unloading moduli G_{Ui} are derived for every unload path between 30 % to 70 % of the pressure range between reversal pressure p_i and minimum pressure $p_{1.1}$;

— the reloading moduli G_{Ri} are derived for every reload path between 30 % to 70 % of the pressure range between minimum pressure $p_{1.1}$ and reversal pressure p_i.

Table 3 — Pressuremeter shear moduli for reference loading programme A

First loading	Unloading	Reloading
G_{L1}	G_{U1}	G_{R1}
-	G_{U2}	G_{R2}
-	G_{U3}	G_{R3}



Key

δ	corrected radial displacement
p	corrected pressure
p_s	seating pressure
$δ_s$	corrected radial displacement corresponding to the seating pressure
$p_{1.1}$	corrected minimum pressure for loops and final unloading
p_i	corrected reversal pressure before loop i or final unloading
G_{L1}	shear modulus in first loading
G_{Ui}	shear modulus in unloading phase i (i = 1 to 3)
G_{Ri}	shear modulus in reloading phase i (i = 1 to 3)

Figure 5 — Prebored pressuremeter shear moduli G_{PBP} in reference procedure A

6.4.3 Reference loading programme B

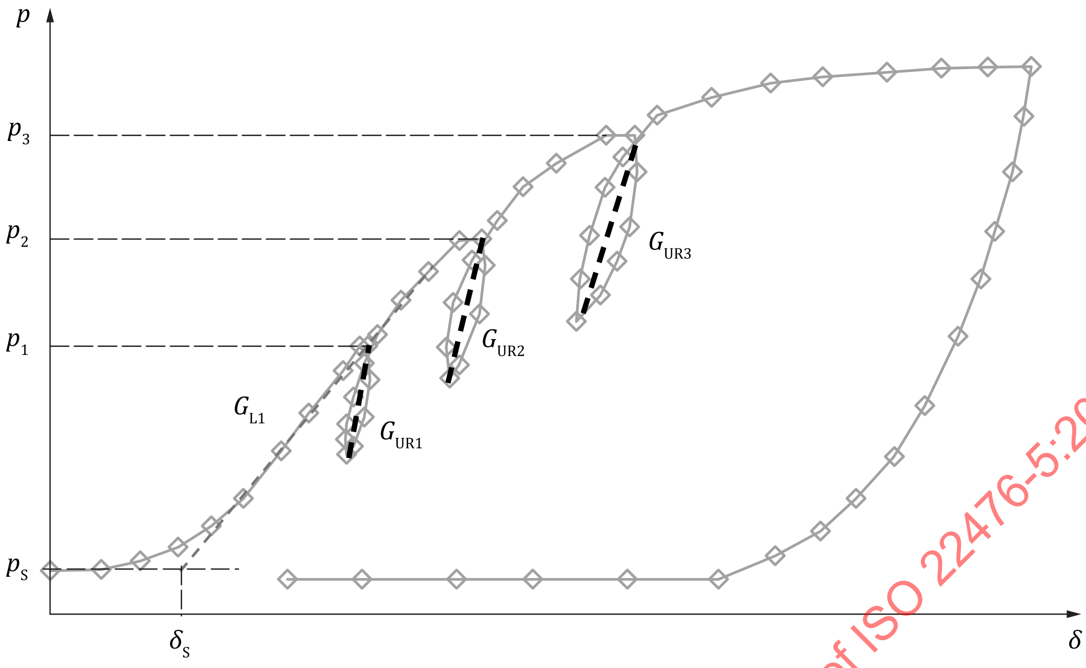
The prebored pressuremeter moduli G_{PBP} should be calculated as follows (see Table 4 and Figure 6):

— the first loading modulus G_{L1} are derived from the data after the seating pressure p_s and before the first unloading-reloading loop;

— a single unloading-reloading modulus value G_{URi} is derived for each unloading-reloading loop, with all data included in the loop.

Table 4 — Pressuremeter shear moduli for reference loading programme B

First loading	Unloading-reloading loop
G_{L1}	G_{UR1}
-	G_{UR2}
-	G_{UR3}



Key

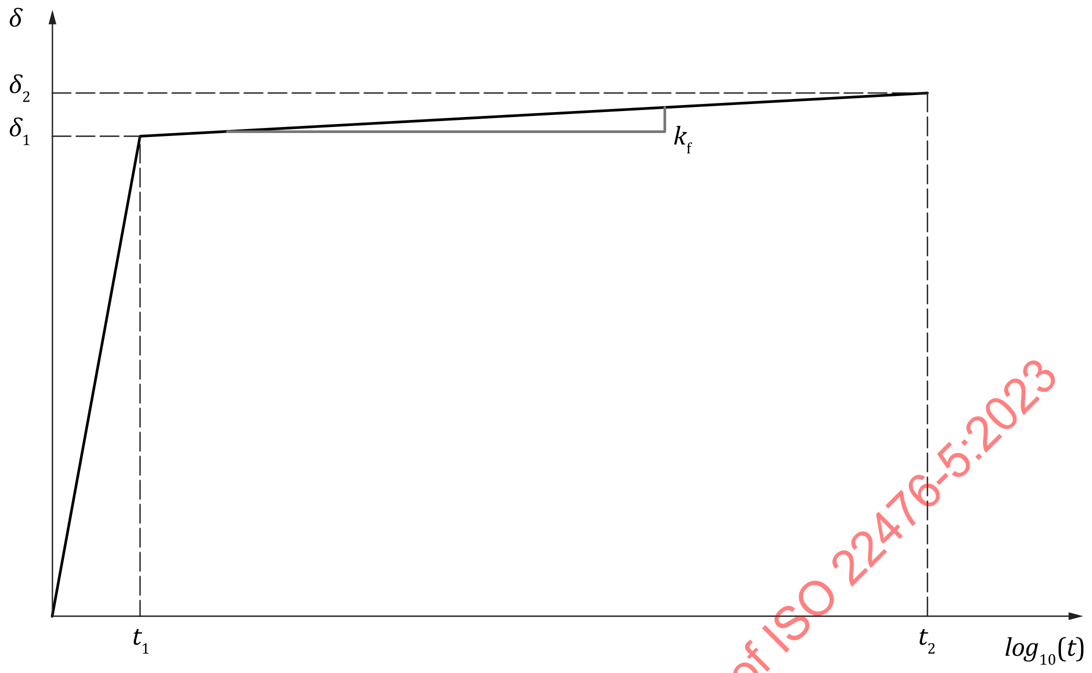
δ corrected radial displacement
p corrected pressure
p_s seating pressure
δ_s radial displacement corresponding to the seating pressure
p_i reversal pressure before loop i or final unloading
G_{L1} shear modulus in first loading
G_{URi} shear modulus in unloading/reloading loop (i = 1 to 3)

Figure 6 — Prebored pressuremeter shear moduli G_{PBP} in reference procedure B

6.4.4 Reference loading programme C

If the controlling parameter is the pressure, the cavity radial displacement should be plotted against the logarithm of time (see Figure 7). The creep parameter k_f, is determined for a given pressure, and shall be derived from Formula (7) (see also Figure 7):

$$k_f = \frac{\delta_2 - \delta_1}{log_{10}(t_2 - t_1)} \quad (7)$$



Key

t time

δ corrected radial displacement

t_1 time at the beginning of the hold period

t_2 time at the end of the hold period

δ_1 corrected radial displacement

δ_2 corrected radial displacement

k_f creep parameter

Figure 7 — Obtention of the creep parameter k_f in the reference loading programme C

7 Reporting

7.1 General

The test results shall be reported to enable a third party to check and understand the results.

7.2 Contents

The reporting shall include the following reports:

— the field report;

— the test report;

— every table and every plot of the test results.

The content of field and test reports is provided in Tables 5 to 10.

Table 5 — General information

Item	Field report	Test report	Every plot
Reference to this document, i.e. ISO 22476-5:2023 and to ISO 22475-1		x	x
Company executing the test	x	x	x
Name and signature of the operator executing the test	x		
Name and signature of the field manager responsible for the project		x	
Details of any deviations from this document		x	

Table 6 — Location of the test

Item	Field report	Test report	Every plot
Borehole ID	x	x	x
Coordinate reference system and tolerances		x	
Elevation of ground surface referred to a stated datum		x	
Borehole features (angle, etc.)	x	x	
Test No.	x	x	x
Depth of test		x	x

Table 7 — Borehole information

Item	Field report	Test report	Every plot
Borehole drilling technique	x		
Drilling tools dimensions and details of the depth of the test pocket	x	x	
Temporary casings dimensions or drilling and supporting fluid description, if applicable	x		
Description of ground cuttings according to ISO 14688-1 and ISO 14689	x	x	
Depth to the groundwater table (if recorded) and date and time of recording	x	x	
Additional observations during drilling	x		
Base of the borehole	x		
Fluid (water or drilling mud) level in the borehole	x	x	
Borehole backfilling according to ISO 22475-1	x		

Table 8 — Test equipment

Item	Field report	Test report	Every plot
Pressuremeter type	x	x	
Geometry and dimensions	x	x	
A description of the drilling and sampling works according to ISO 22475-1	x		
Identification of pressuremeter probe and control unit	x	x	
Measuring ranges of the sensors		x	
Copies of the latest certificates of calibration and if applicable the calibration register		x	
If applicable, calibration cylinder features: material, inside diameter, thickness, etc.	x	x	

Table 9 — Test procedure

Item	Field report	Test report	Every plot
Test specifications	x	x	
Reference loading programme, if applicable	x	x	x
Date of the test	x	x	
Starting and end times of the test	x	x	
Change to the test specifications, and associated reasons	x	x	
Additional observations during the test, and corresponding time	x	x	

Table 10 — Measured and derived parameters

Measured and derived parameters	Field report	Test report	Every plot
Complete set of readings of pressures and radial displacements or volume with time, as read at the control unit	x	x	
Zero and/or reference readings of pressure, and radius or volume before and after the test	x	x	
Zero drift (in engineering units)		x	
Calibration method and data for membrane stiffness and displacement or volume correction	x	x	
Additional corrections applied during data processing (drifts, etc.)	x	x	
Complete set of corrected pressures and radial displacements or volume data points with time	x	x	
Derived parameters and procedures used to obtain them		x	

7.3 Presentation of test results

Presentation of the results of a prebored pressuremeter test shall include data according to 7.2.

The following data shall be provided:

— calibration results (according to Annex A), both in tables and graphs;

— readings as a function of time, for both controlling and measured parameters, in tables;

— corrected values as a function of time, for both controlling and measured parameters, both in tables and graphs;

— corrected pressure versus expansion, both in tables and graphs, with enlarged plots for particular sections of the pressuremeter curve (e.g. for unload-reload loops): expansion may be represented by one of the following:

  — corrected radius or diameter;

  — corrected volume;

  — cavity strain ε_c.

For pressure-expansion curves, the X-axis should be chosen for the controlling parameter. Alternatively, another choice may be made, as long as the controlling and measured parameters are clearly indicated.

Presentation in digital form is permissible for easier data-exchange.

NOTE The tabulated data can be submitted electronically in an agreed format such as the AGS data format [1].

Annex A
(normative)

Calibration and corrections

A.1 Measuring devices

All the control and the measuring devices, including the data logger, shall be periodically checked and calibrated to show that they provide reliable and accurate measurements. The following devices shall be calibrated, if applicable:

— displacement measuring system;

— volume measuring system;

— pressure measuring system;

— pore pressure measuring system;

— geophones or accelerometers.

If any part of the system is repaired or exchanged, the calibration of all devices shall be verified. Calibration shall ensure that the uncertainty required is maintained within the limits of Annex C. Calibration should be performed at least once a year.

A.2 Pressure correction

The pressure loss p_e due to the membrane stiffness, shall be obtained from an appropriate calibration, according to the procedures described in A.2.1 and A.2.2.

The calibration described below shall be carried out as follows:

— at each change of pressuremeter membrane;

— otherwise at intervals appropriate to the use the probe has received but at least once a year.

A.2.1 Preparation of pressuremeter for membrane pressure loss calibration

The pressuremeter probe shall be connected by a short connecting line (less than 2 m) to a pressure source. The membrane shall then be inflated at least three times by injecting fluid up to the maximum deformation.

For this operation, the pressure control unit shall be fitted with a pressure measuring device with accuracy better than 10 kPa.

A.2.2 Membrane pressure loss calibration

The probe is placed upright in the open air. The probe shall be inflated as if it was in the ground, using pressure increments small enough to define the complete range of displacement of the membrane.

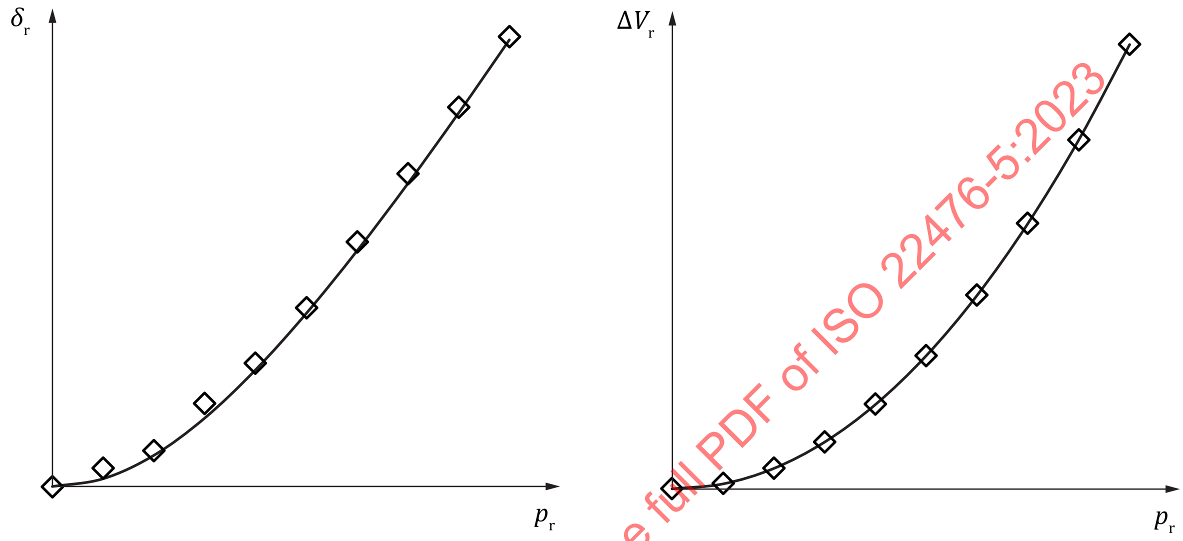
If liquid is used to pressurise the pressuremeter, the difference in elevation between the probe and the measuring unit shall be taken into account.

The pressure versus radial displacement or injected volume curve shall be plotted as shown in Figure A.1. The resulting pressuremeter curve is described by:

— either a relation between the pressure correction and measured radial displacement, $p_e(\delta_r)$;

— or a relation between the pressure correction and measured injected volume, $p_e(\Delta V_r)$.

If the loading programme includes unloading reloading phases, the membrane pressure loss calibration test shall also include unloading phases.



a) With radial displacement measurement   b) With injected volume measurement

Key

p_r pressure, as read at the control unit

δ_r radial displacement, as read at the control unit

ΔV_r injected volume, as read at the control unit

Figure A.1 — Membrane stiffness calibration

A.3 Displacement or volume correction

A.3.1 General

Except for equipment with an outside insert such as described in Figure 3 c), a correction of the measured cavity radial displacement or cavity volume is needed to account for the following parasitic effects:

— membrane compression and other effects (e.g. change in shape of the probe), if the probe expansion is followed either through radial displacement transducers inside the membrane or through its volume;

— overall dilatation of the connecting lines, compressibility of the fluid and volumetric changes in the control unit, if the probe expansion is followed through its volume;

— accommodation of the radial displacement measuring system if the probe expansion is followed through radial displacement transducers inside the membrane.

Corrections shall be based on the results of appropriated calibration tests, described below. Calibrations shall be performed:

- at each change of pressuremeter membrane;
- at each change of connecting lines, control unit or fluid if the probe expansion is followed through its volume;
- at each 50 tests;
- at least once a year.

These calibrations are performed using one or several calibration cylinders, as described in A.3.2.

Corrections obtained through the calibrations test are expressed as:

- either a relation between the radial displacement correction and measured pressure $\delta_e(p_r)$ [or $r_e(p_r,\delta_r)$];
- or a relation between the injected volume correction and measured pressure $\Delta V_e(p_r)$ [or $V_e(p_r,V_r)$].

The displacement or volume loss calibration method includes two distinct steps:

- a first general case mandatory for all test types (A.3.3);
- a second case that becomes mandatory to validate the interpretation of unloading-reloading loops resulting on high values of apparent shear moduli G_{app} (A.3.4).

NOTE Apparent shear moduli G_{PBP} (derived either from initial loading or unloading-reloading loops) greater than 200 MPa are considered high.

A.3.2 Calibration cylinder(s)

The thickness of the calibration cylinder(s) shall be chosen so that its deformability when submitted to inside radial pressure remains low compared to that of the pressuremeter probe, as shown in Figure A.3. When relevant, its deformability shall be considered during the calibration process.

NOTE For an apparent modulus G_{PBP} equal to 1 000 MPa, the use of a calibration cylinder of 100 mm inside diameter and 8 mm thickness leads to a 7 % underestimation.

Additional elements related to the diameter of the calibration cylinder(s) are provided below.

A.3.3 Calibration in the general case

In the general case, two different approaches are proposed:

- a first approach using a single calibration cylinder, that enables to derive the cavity expansion, by applying an expansion correction as a simple function of the probe pressure p_r;
- a second approach using several calibration cylinders, that enables to derive the cavity expansion, based on an expansion correction as a function of both the probe pressure p_r and the probe expansion.

The second approach should be used to enable the derivation of parameters for strain levels corresponding to a cavity diameter significantly different from the single calibration cylinder diameter.

NOTE For a single calibration cylinder of inner diameter d_{cc}, corrections cover a range of diameters reached through the tests comprised between d_{cc} ±10 %.

A.3.3.1 Calibration including one single cylinder

The probe should be pressurized by regular small increments Δp until it comes into contact with the calibration cylinder. After this point, equal increments shall be applied up to the expected maximum pressure of the tests to be performed. The duration of the steps can be adapted to take into account any additional time-dependent effects (creep in the probe membrane).

The resulting calibration curve shall be used to:

— verify that the calibration cylinder is sufficiently rigid in comparison of the expect apparent modulus G_{PBP} expected:

  — if the slope a_{cc} is higher than $a_r/3$, a thicker calibration cylinder shall be used (a_r and a_{cc}, corresponding to the apparent slope of the calibration curve, as shown in Figure A.2),

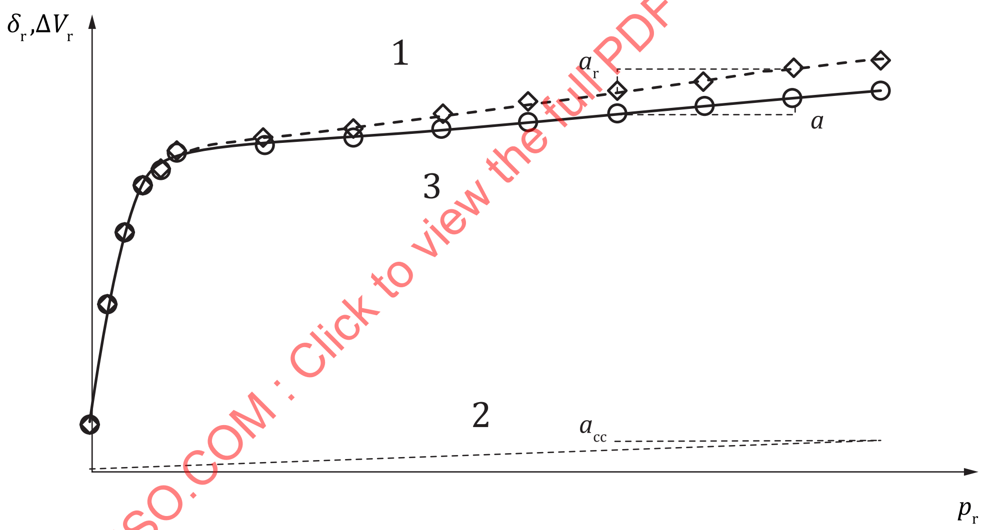
  — if the slope a_{cc} is higher than $a_r/10$, the rigidity of the calibration cylinder shall be considered to determine the displacement or volume correction;

— correct the raw measurements and assess the cavity radial displacement of cavity volume. One of the following procedures may be chosen:

  — derivation of a unique correction factor a (equal to and a_r-a_{cc}), supposing that the calibration curve yields a linear part over the pressure range reached during the pressuremeter test,

  — fitting of the calibration experimental points by any appropriate method,

  — linear interpolation between calibration experimental points.



Key

1 measured behaviour during the displacement or volume calibration associated to the slope a_r

2 self-deformability of the calibration cylinder, associated to the slope a_{cc} to be considered if relevant. It can be measured or be derived theoretically.

3 effective correction to apply to the raw radial displacement or volume, associated to the slope a, if relevant

Figure A.2 — Determination of the combined correction for membrane compression and connecting lines dilatation (if relevant)

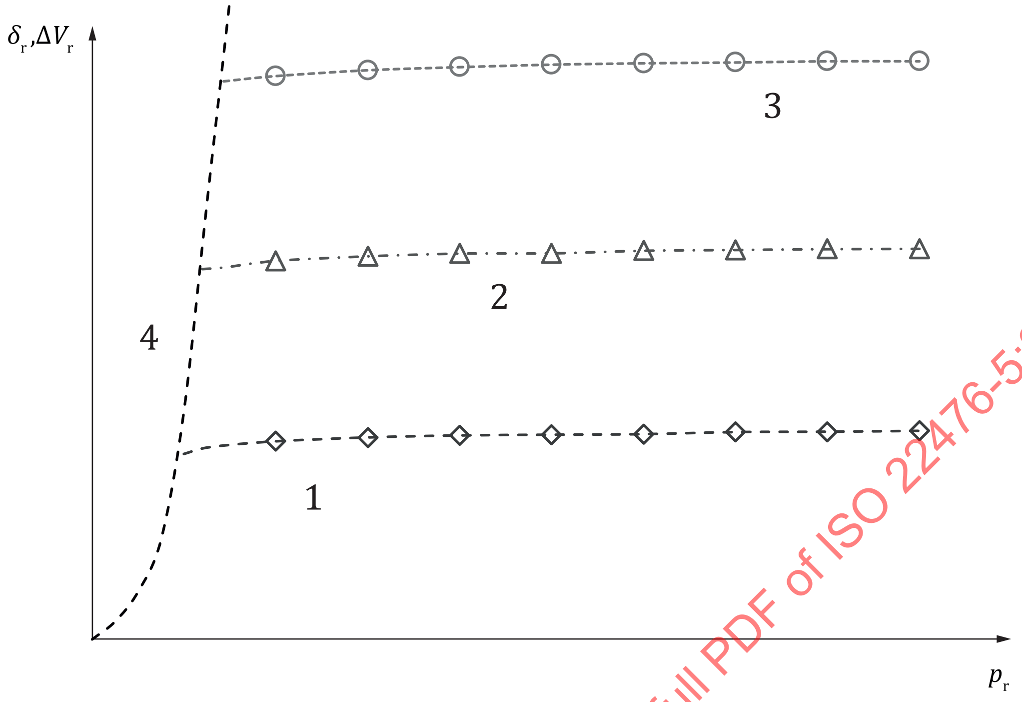
A.3.3.2 Calibration including several cylinders

This approach includes the use of at least three calibration cylinders. The diameters of the calibration cylinders d_{cc} shall be chosen to cover the range of diameters reached during the tests.

Note Correction evolves with the pressuremeter probe expansion.

The deformability of each calibration cylinder shall be considered as in A.3.3.1.

In each calibration cylinder, the probe should be pressurised as in A.3.3, to obtain a set of calibration curves, as given in Figure A.3.



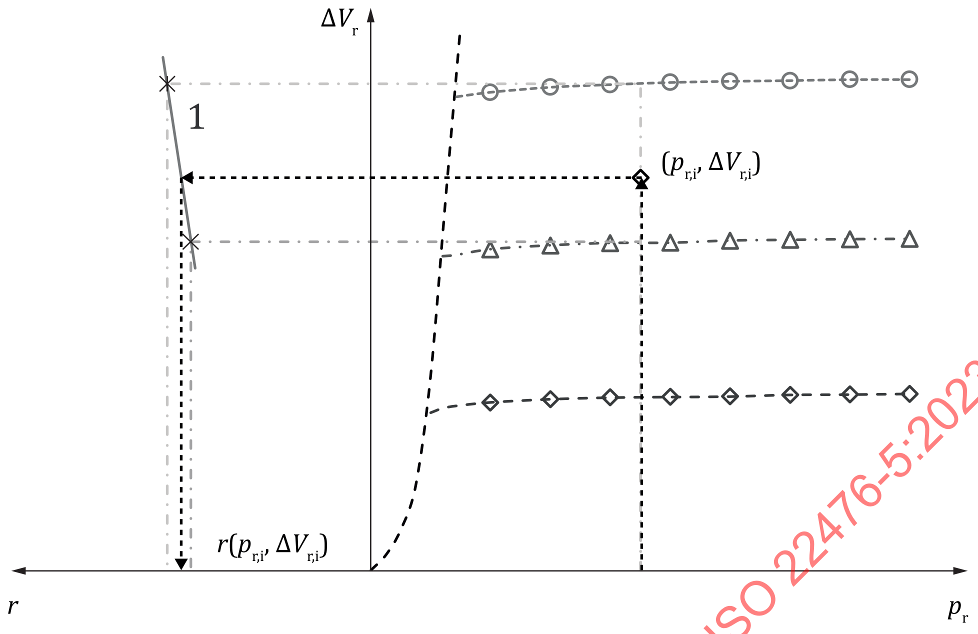
Key

1, 2 and 3 calibration curves associated to calibration cylinders with diameters $d_{cc,1}$ to $d_{cc,3}$

4 pressure loss calibration curve (see Clause A.2)

Figure A.3 — Set of expansion calibration curves

This curve can then be used to derive the cavity radius (or the equivalent cavity volume) as a function of the pressure p_r and of the probe expansion. An example is provided in Figure A.4.



Key

1 external radius of the probe r function of ΔV_r curve, for a given value of $p_r = p_{r,i}$, that already includes the first correction due to the hydraulic head

Figure A.4 — Determination of cavity radial displacement when using several calibration cylinders (example when probe expansion is followed through its volume)

A.3.4 Additional calibration in case of unloading-reloading loops

The method proposed below should be used to directly correct the apparent moduli obtained from each loop, using the apparent equipment (or system) stiffness G_{sys}.

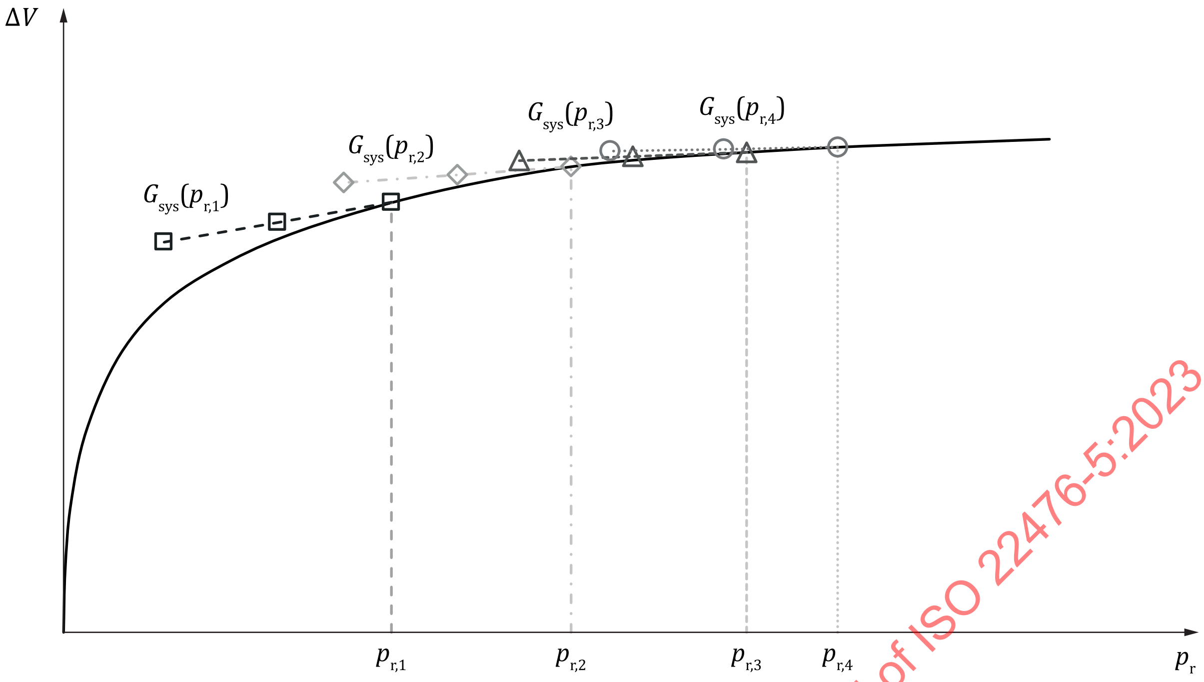
NOTE "Directly" means that a corrected cavity pressure - cavity radius p - r curve is not explicitly determined.

A single calibration cylinder with an inside diameter similar to the cavity diameter during the test should be used.

The probe shall be initially inflated to reach the tube. After this first contact, the probe shall be furtherly inflated, including additional unloading-reloading loops (see Figure A.5):

— either corresponding approximately to the unloading-reloading loops that will be performed during the pressuremeter test;

— or sufficiently numerous to cover the non-linear evolution of the system stiffness G_{sys} within the whole range of pressures associated to the unloading-reloading loops in the pressuremeter test.



Key

$p_{r,i}$ initial pressure for unloading-reloading loop i (i = 1 to 3)

$G_{sys}(p_{r,i})$ apparent system stiffness for unloading-reloading loop i (i = 1 to 3)

Figure A.5 — Determination of the apparent system stiffness G_{sys}

G_{sys} is the apparent system stiffness that can be obtained using Formulae (5) and (6) given in 6.3.

This calibration results can be used to determine the apparent equipment stiffness G_{sys} as a function of the pressure at the beginning of each unloading-reloading loop $p_{r,i}$, according to Figure A.6. Fitting of the calibration experimental points by any appropriate method or linear interpolation between calibration experimental points can be implemented to obtain G_{sys} as a function of $p_{r,i}$.

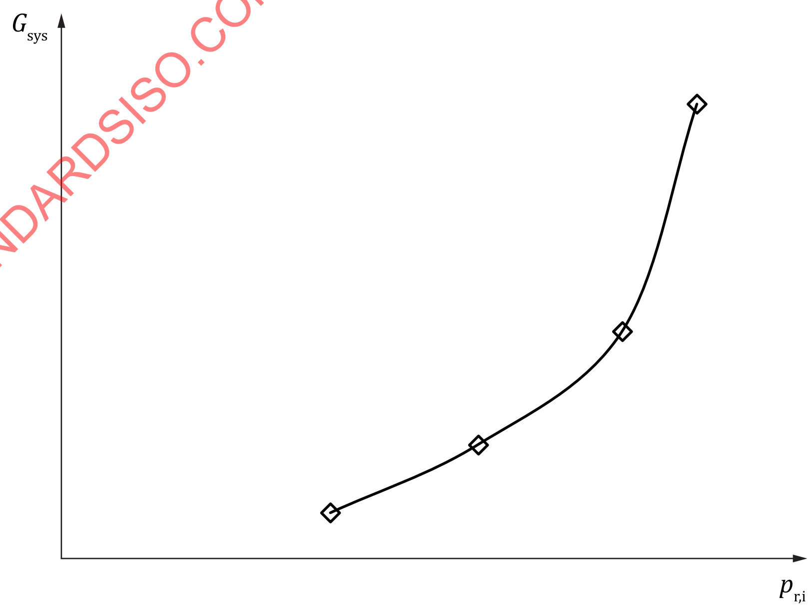


Figure A.6 — Determination of the apparent system stiffness G_{sys} as a function of the pressure at the beginning of the unloading-reloading loops

The corrected apparent shear modulus G_{PBP} is obtained using Formula (A.1), taking into account the pressure in the probe $p_{r,i}+p_h$.

$$\frac{1}{G_{PBP}(p_i)}=\frac{1}{G_{app}(p_i)}+\frac{1}{G_{sys}(p_{r,i}+p_h)} \tag{A.1}$$

Where G_{app} is the uncorrected apparent modulus obtained from corrected values of the cavity pressure described in Clause A.2 and values of radial displacements (or volumes) already including the corrections described in A.3.3.2.