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Geotechnical investigation and testing — Field testing —

Part 8: Full displacement pressuremeter test

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Foreword

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

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

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Geotechnical investigation and testing — Field testing —

Part 8:
Full displacement pressuremeter test

1 Scope

This document specifies the equipment requirements, execution of and reporting on full displacement pressuremeter (FDP) tests.

NOTE This document fulfils the requirements for full displacement pressurementer test as part of the geotechnical investigation services according to EN 1997-1 and EN 1997-2.

Tests with the full displacement pressuremeter cover the measurement in situ of the deformation of soils and weak rocks by the expansion/contraction of a cylindrical flexible membrane under pressure.

2 Normative references

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

ISO 22476-1, *Geotechnical investigation and testing — Field testing — Part 1: Electrical cone and piezocone penetration test*

ISO 22476-4:2012, *Geotechnical investigation and testing — Field testing — Part 4: Ménard pressuremeter test*

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

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.

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

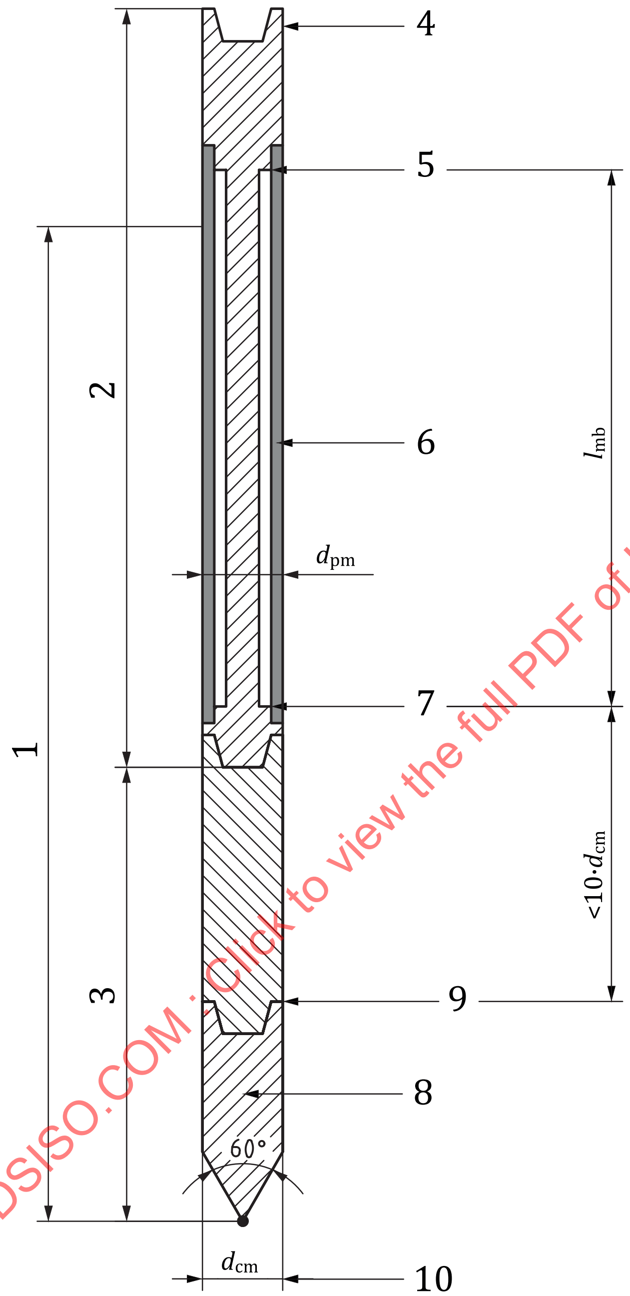
— ISO Online browsing platform: available at https://www.iso.org/obp

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

3.1.1
full displacement pressuremeter
FDP
assembly containing a *pressuremeter module* (3.1.2) and a *cone module* (3.1.3)

Note 1 to entry: The FDP is jacked or driven directly into undisturbed ground with an integral cone at its lower end thereby creating its own test hole. No preparation of the cavity is permitted either by pre-boring, pre-pushing or any other means.

Note 2 to entry: The applied pressure and associated expansion of the probe are measured and recorded so as to obtain the stress-displacement relationship for the soil as tested (see Figure 1).



Key

1 full displacement pressuremeter
2 pressuremeter module
3 cone module
4 push rod connector
5 upper fixed membrane point
6 membrane
7 lower fixed membrane point
8 cone
9 cone tip
10 25 mm to 50 mm (according to ISO 22476-1)

NOTE The example is not to scale.

Figure 1 — Cross section of a full displacement pressuremeter

3.1.2
pressuremeter module
cylindrical device designed to apply a uniform pressure to the walls of a cavity by means of an expandable flexible single-cell membrane

3.1.3
cone module
cylindrical device with a conical shaped lower end and a connection to which the *pressuremeter module* (3.1.2) can be attached

Note 1 to entry: The cone module can be instrumented with cone, friction sleeve and pore pressure sensors according to ISO 22476-1.

3.1.4
membrane
part of the *pressuremeter module* (3.1.2) that is expanded and thereby transmits pressure to the cavity wall

Note 1 to entry: The membrane is fitted on a mandrel. It may be externally or internally reinforced or protected. The reinforcement or protection is deemed to be part of the membrane.

3.1.5
membrane length
l_{mb}
distance between the upper and lower fixed points of the *membrane* (3.1.4)

Note 1 to entry: See Figure 1.

3.1.6
pressuremeter system
pressuremeter module (3.1.2), *cone module* (3.1.3), controlling devices and measuring system in combination with any lines connecting them together

3.1.7
volume-displacement type pressuremeter
pressuremeter module (3.1.2) fitted with a sensor to measure the change in the volume of the expanding cavity

3.1.8
radial-displacement type pressuremeter
pressuremeter module (3.1.2) fitted with sensors to measure the change in the radius or diameter of the expanding cavity

3.1.9
membrane pressure loss
pressure in the *pressuremeter module* (3.1.2) required to expand the *membrane* (3.1.4) in air, expressed as a funtion of the expansion

3.1.10
membrane compressibility
change in thickness of the *membrane* (3.1.4) as related to the change in internal pressure in the *pressuremeter module* (3.1.2)

3.1.11
system compliance
volume change in a *pressuremeter system* (3.1.6) in response to the internal pressure variation in a situation where the expansion of the *membrane* (3.1.4) is restricted

Note 1 to entry: The system compliance takes into account both the deformation of the *pressuremeter system* (3.1.6) and the *membrane compressibility* (3.1.10) and includes time effects.

3.1.12
applied pressure
pressure applied by the external surface of the *membrane* (3.1.4) to the walls of the cavity in the soil or weak rock

3.1.13
calibration cylinder
cylindrical tube of known elastic properties used for the restriction of the membrane expansion and hence for the determination of system compliance

3.1.14
reference reading
reading of a sensor just before the *membrane* (3.1.4) touches the wall of the *calibration cylinder* (3.1.13) when expanding

3.1.15
cavity volume
V
volume of the cavity in the ground between the upper and lower fixed points of the *membrane* (3.1.4)

3.1.16
initial cavity volume
V_0
theoretical *cavity volume* (3.1.15), calculated as:

$$V_0 = l_{mb} \cdot \tfrac{1}{4} \pi (d_{cm})^2$$

where

l_{mb} is the membrane length;

d_{cm} is the maximum diameter of the cone module

3.1.17
volumetric strain
ε_v
change in the volume of the cavity with respect to the *initial cavity volume* (3.1.16)

$$\varepsilon_v = \frac{V - V_0}{V_0}$$

where

V is the cavity volume;

V_0 is the initial cavity volume

Note 1 to entry: Conversions between the volumetric strain and the radial strain are given in Annex E.

3.1.18
initial cavity radius
r_0
theoretical radius of the cavity, calculated as follows:

$$r_0 = 0{,}5\ d_{cm}$$

where d_{cm} is the maximum cone module diameter

3.1.19
radial strain
ε_r
change in the radius of the cavity with respect to the *initial cavity radius* (3.1.18):

$$\varepsilon_r = \frac{r - r_0}{r_0}$$

where

r is the cavity radius;

r_0 is the initial cavity radius

3.1.20
rate of volumetric strain change
$\dot{\varepsilon}_V$
change of the *volumetric strain* (3.1.17) with time:

$$\dot{\varepsilon}_V = \frac{\Delta V}{V_0} \cdot \frac{1}{\Delta t}$$

where

ΔV is the volume change over a selected period Δt;

V_0 is the initial cavity volume;

Δt is the time increment over which the volume change took place

3.1.21
rate of radial strain change
$\dot{\varepsilon}_r$
change of the *radial strain* (3.1.19) with time:

$$\dot{\varepsilon}_r = \frac{\Delta r}{r_0} \cdot \frac{1}{\Delta t}$$

where

Δr is the radius change over a selected period Δt;

r_0 is the initial cavity radius;

Δt is the time increment over which the radial displacement took place

3.1.22
rate of pressure application
$\dot{p}$
rate of change of the applied pressure with time.

$$\dot{p} = \frac{\Delta p}{\Delta t}$$

where

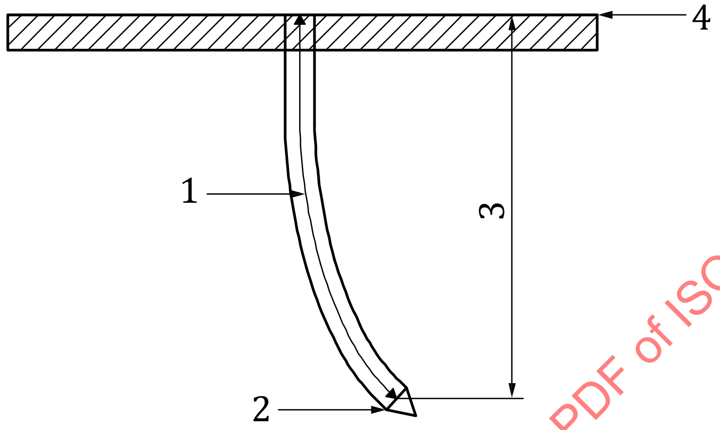
Δp is the pressure change over a selected period Δt;

Δt time increment over which the pressure took place

3.1.23
thrust machine
equipment that pushes the *FDP* (3.1.1) and *rods* (3.1.24) into the ground at a constant rate of penetration

3.1.24
push rods
string of rods for the transfer of forces to the *FDP* (3.1.1)

Note 1 to entry: The fixed horizontal plane (Figure 2) usually corresponds to the level of the ground surface (on shore or off shore). This may be different from the starting point of the test.



Key

1 penetration length
2 base of the conical part of the cone module
3 penetration depth
4 fixed horizontal plane

Figure 2 — Penetration length and penetration depth

3.1.25
penetration depth
z
depth to the base of the cone, relative to the fixed horizontal plane

3.1.26
penetration length
sum of the length of the *push rods* (3.1.24) and of the *FDP* (3.1.1), reduced by the height of the conical part, relative to the fixed horizontal plane

Note 1 to entry: See Figure 2.

3.1.27
test depth
depth where a pressuremeter test is performed, measured at membrane mid-height and relative to the fixed horizontal plane

3.1.28
measuring system
all sensors, ancillary parts and software used to transfer and to store the measurements made during the full displacement pressuremeter test

3.1.29
unload-reload cycle
controlled decrease in the pressure and volume or radius, after which the expansion is resumed

3.1.30
reload-unload cycle
controlled increase in the pressure and volume or radius during the final contraction phase of the test after which the contraction is resumed

3.1.31
zero load reading
stable output of a measuring system if there is zero load on the sensors, i.e. the parameter to be measured has a value of zero while any auxiliary power supply required to operate the measuring system is switched on

3.1.32
drift
absolute difference of the zero load readings or reference readings of the measuring system before and after the execution of the full displacement pressuremeter test

3.1.33
uncertainty
expanded uncertainty with a coverage factor 2

Note 1 to entry: Coverage factors are defined in ENV 13005.

3.2 Symbols

Symbol	Description	Unit
A_c	cross-sectional projected area of the cone	mm^2
d_{cm}	maximum diameter of the cone module	mm
d_{pm}	maximum diameter of the pressuremeter module	mm
d_t	internal diameter of the calibration cylinder	mm
h_c	height of the conical part of the cone module	mm
l_{mb}	membrane length	mm
M_s	system stiffness	kPa/mm^3
P	pressure	kPa
p_h	pressure difference between the pressure sensor and the pressure at the midheight of the membrane	kPa
p_r	pressure reading in the pressuremeter module	kPa
p_m	pressure loss pressure to overcome the membrane resistance	kPa
p_{offset}	offset of the pressure	kPa
p_{rm}	pressure reading corrected for the membrane resistance	kPa
p_{ref}	pressure at reference volume V_{ref}	kPa
p_0	pressure at initial cavity volume V_0	kPa
$\dot{p}$	rate of pressure change	kPa/s
r	cavity radius	mm
r_{offset}	offset of the real radius with the sensor reading of the radius	mm
r_0	initial cavity radius	mm
t	time	s
V	cavity volume	mm^3
V_{offset}	offset of the real volume with the sensor reading of the volume	mm^3
V_{ref}	reference volume	mm^3
V_0	initial cavity volume	mm^3
z	penetration depth	m

Symbol	Description	Unit
ε_r	radial strain	—
ε_v	volumetric strain	—
$\dot{\varepsilon}_r$	rate of strain change	s^{-1}
$\dot{\varepsilon}_V$	rate of volumetric strain change	s^{-1}

4 Equipment

4.1 General

The distance between the cone module and the lower fixed membrane point shall be less than 10 times the maximum cone module diameter.

The probe placement and the tools shall be according to ISO 22476-1 when the FDP is jacked into the ground and according to ISO 22476-4:2012, Annex C when driven into the ground.

4.2 Cone module

The cone modules shall be according to type T or TC, as shown in Table 1.

Table 1 — Types of cone modules

Cone module	Description
T	60-degree cone-shaped lower end without sensors
TC	Cone penetrometer according to EN ISO 22476-1

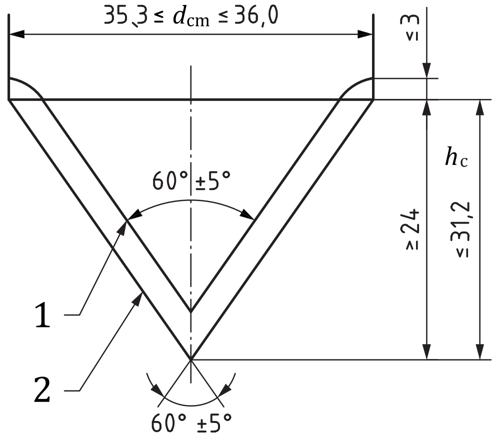
The cone module type T consists of a plain conical part without sensors and a cylindrical extension. No specification on the diameter is suggested.

When a TC cone module is used, the module shall have a diameter (d_{cm}) between 25 mm (A_c = 500 mm^2) and 50 mm (A_c = 2 000 mm^2) and a geometry according to the example presented in Figure 3. The geometry and tolerances shall be adjusted proportionately to the diameter. The surface of the cone module shall be smooth.

NOTE Is is common practice to select a cone module diameter at least ten times greater than the average soil grain size.

The cone module shall not be used if a visual check indicates that it is asymmetrically worn, even if it otherwise fulfils the tolerance requirements.

Dimensions in millimetres unless otherwise indicated



Key

1 minimum acceptable shape of the conical part after wear

2 maximum shape of the conical part

Figure 3 — Tolerance requirements for the cone module

4.3 Pressuremeter module

The external diameter of the pressuremeter module shall initially be equal to or smaller than the maximum diameter of the cone module.

The membrane shall be capable of fully reversible expansion by 30 % radial strain or 75 % volumetric strain.

The ratio of the membrane length to the cone module diameter shall be greater than six.

Both volume-displacement type pressuremeters and radial-displacement type pressuremeters can be used.

NOTE When a volume-displacement type pressuremeter is used, a volume change sensor is usually positioned in the pressuremeter module.

If a radial-displacement type pressuremeter module is used, displacements shall, as a minimum, be measured at three equidistant points or a single diameter in the plane perpendicular to the axis of the pressuremeter module and at the midheight of the membrane.

The surface of the pressuremeter module shall be smooth and free from sudden changes in diameter.

4.4 Measuring system

The measuring system shall be such that the requirements of the specific Accuracy Class (Table 2) can be fulfilled.

The range of the measuring system shall be compatible with the membrane expansion requirements.

5 Test procedure

5.1 Selection of equipment and procedures

Requirements for measurement processes and measuring equipment shall be according to ISO 10012.

Selection of the cone module shall be according to Table 1 and the pressuremeter accuracy class shall be according to Table 2.

If all possible sources of errors are added, the uncertainty of each measurement shall be according to Table 2. The required uncertainty analyses shall include factors such as internal friction, membrane compressibility, pressure loss, system compliance, uncertainties in data acquisition, ambient temperature effects and dimensional errors.

The resolution of the measuring system shall be better than one third of the required uncertainty applicable to the Accuracy Class given in Table 2.

Table 2 — Accuracy Classes

Accuracy Class	Measured parameter	Allowable minimum uncertainty[a]	Minimum test logging frequency
1	Applied pressure Volumetric strain[b] Radial strain[b]	10 kPa or 10 % 0,01 or 4 % 0,01 or 2 %	0,5 Hz
2	Applied pressure Volumetric strain[b] Radial strain[b]	50 kPa or 20 % 0,05 or 10 % 0,1 or 5 %	0,2 Hz

NOTE For extremely soft soils even higher demands on the uncertainty can be needed.

[a] The allowable minimum uncertainty of the measured parameter is the larger value of the two quoted. The relative uncertainty applies to the measured value and not the measured range

[b] For volume-displacement type pressuremeters the requirement on volumetric strain shall be fulfilled, for radial-displacement type pressuremeters the requirement on radial strain shall be fulfilled.

5.2 Preparation

Preparation for using a cone module type TC as in Table 1 shall comply with ISO 22476-1 where applicable. Annex B contains calibration procedures.

Zero load readings of the measuring system shall be determined before the start of the test or sequence of tests within a single penetration.

5.3 Installation

Installation when using a cone module type TC in Table 1 shall comply with ISO 22476-1 where applicable.

The FDP shall be pushed either from the base of a borehole or from the surface to the first test depth continuously. Pre-boring or pre-pushing (regardless of undersize) is not permitted.

The rate of penetration shall be between 10 mm/s and 50 mm/s.

The distance between the upper fixed point of the membrane and the ground surface or the base of the borehole shall be greater than 10 times the maximum diameter of the cone module.

Measurements may be made periodically during probe insertion.

A pressuremeter test shall be started within 2 min following the completion of jacking. The vertical distance between the level where the cone has rested during the upper test and the upper fixed point of the membrane of the lower test shall be greater than 10 times the maximum diameter of the cone module.

The distance between the test location and the location of any previous investigation points shall be according to ISO 22476-1.

The pushing force shall be coaxial with the pushing rods within 2°.

5.4 Pressuremeter test

5.4.1 General

A pressuremeter test is either stress-controlled or strain-controlled or a combination of the two. The method of control shall be specified.

Strain-controlled pressuremeter tests shall have a defined rate of constant volumetric strain or constant radial strain, as applicable.

Stress controlled tests shall be performed at a continuous rate of pressure application.

NOTE Typical rates of strain would be 5 % per minute for radial strain or about 10 % for volumetric strain.

Unloading shall be logged for tests that are according to Accuracy Class 1 (Table 2).

Corrections as described in Annexes C and D shall be performed taking into consideration the maximum pressure and displacement expected during the test.

5.4.2 Optional test stages

Tests may contain unload-reload and reload-unload cycles. These cycles shall be performed according to agreed specifications.

The change in stress or in strain during any such cycle shall be specified. Prior to unloading there may be a period during which the pressure or displacement is held constant.

5.4.3 Frequency of logging parameters

The minimum logging frequency of parameters shall be in accordance with Table 2. Logging shall include clock time.

5.5 Test completion

A test is terminated when the membrane has been deflated after loading to the membrane expansion requirements, or when the maximum pressure capacity according to agreed specifications is reached, whichever is earlier. The membrane expansion requirements are:

— 75 % volumetric strain;

— 30 % radial strain.

NOTE It is common practice to specify the following before the tests: the maximum pressure capacity of the pressuremeter system, the maximum thrust capacity and the possibility of termination of a test when a damage to the equipment is likely to happen.

Zero load readings of the measuring system shall be determined after the completion of the test or sequence of tests within a single penetration.

6 Test results

The measured pressure and the corresponding volume or radius shall each be converted to the applied pressure and volumetric or radial strain.

Drift shall be determined.

The calculation of the corrected values of volume or radius from the readings shall be in accordance with Annex C.

The calculation of the applied pressure from the measured pressure shall be in accordance with Annex D.

7 Report

In the presentation of test results the information shall be easily accessible, preferably in tables or as a standard archive scheme. Presentation in a digital form makes data exchange easier.

When a pressuremeter test incorporates a cone penetrometer, cone module type TC in Table 1, all aspects in relation to the reporting shall be according to ISO 22476-1, where they are not otherwise specified in this clause.

1 General information	**Field report**	**Test report**
1.a. Reference to this document (ISO 22476-8)		x
1.b. Company executing the test	x	x
1.c. Equipment operator executing the test	x	
1.d. Field manager executing the test		x
1.e. Depth to the groundwater table (if recorded) and date and time of recording	x	x
1.f. Depth and possible causes of any interruptions in the pressuremeter tests	x	x
1.g. End criteria applied, i.e. target pressure, maximum pressure, maximum radius, etc.	x	x
1.h. Observations during the test, for example drops of pressure, radius or volume, incidents, buckled rods, abnormal wear or changes in zero load readings	x	x

2 Location of the test	**Field report**	**Test report**
2.a. Identification of the test	x	x
2.b. Elevation of the pressuremeter test related to a known datum		x
2.c. Local or general coordinates		x
2.d. Geodetic reference system and tolerances		x

3 Test equipment	Field report	Test report
3.a. Pressuremeter type	x	x
3.b. Geometry and dimensions of the FDP	x	x
3.c. Type of thrust machine used, pushing capacity, associated jacking and anchoring systems	x	x
3.d. Identification number of the FDP	x	x
3.e. Measuring ranges of the sensors (recommended)		x
3.f. Date of last calibration of the sensors (recommended)		x
3.g. If applicable, calibration cylinder inner diameter	x	

4 Test procedure	Field report	Test report
4.a. Cone Module type (Table 1) and Accuracy Class (Table 2)	x	x
4.b. Test specifications of additional test stages	x	x
4.c. Method of test control (stress controlled or strain controlled)	x	x
4.d. Date of the test	x	x
4.e. Starting time of the test	x	x
4.f. Clock time during the test	x	x
4.g. Depth of the pressuremeter test	x	x

5 Measured parameters	Field report	Test report
5.a. Time in seconds, applied pressure in MPa and volumetric or radial strain measurements in %	x	x
5.b. Zero load readings of pressure, and volume or radius before and after the test and drift (in engineering units)	x	x
5.c. Corrections applied during data processing (e.g. drifts, system stiffness, etc.)		x
5.d. If applicable, calibration data of system compliance, membrane pressure loss and compressibility	x	

Annex A
(informative)

Uncertainties in pressuremeter testing

For both Accuracy Classes an uncertainty statement should be presented.

Uncertainty estimates should be presented in accordance with ISO 10012 and ENV 13005:1999.

Uncertainties in FDP testing can have various sources, amongst which are:

— temperature effects;

— water pressure effects;

— calibrations; e.g. loss of calibration due to damage;

— leakage of system fluid or gas;

— compressibility of fluid, due to among others dissolved air;

— data acquisition limitations;

— wear of the cone module;

— deviation from the original direction of penetration;

— operator effects.

The pressuremeter module should be compensated for ambient temperature effects.

Annex B
(normative)

Calibrations

The following calibrations are recommended:

a) volume-displacement type pressuremeters:

1) pressure sensors;

2) volume-displacement sensors;

3) membrane resistance;

4) system stiffness (membrane compressibility and system expansion);

b) radial-displacement type pressuremeters:

1) pressure sensors;

2) displacement sensors;

3) membrane resistance;

4) membrane compressibility.

NOTE 1 For low-pressure pressuremeter tests the membrane compressibility calibration can be omitted.

NOTE 2 Following any repair of the sensors, readout/control unit and connecting cables/tubes, the displacement and pressure sensors are re-calibrated.

NOTE 3 The material of the membrane can be subjected to exercising prior to field use, to promote the validity of the calibrations.

Annex C
(normative)

Corrections on the volume

For FDP's with volume sensors not directly inside the pressuremeter module, the test results can be corrected for system volume increase in the part of the system between the pressuremeter module and the volume sensor. The system volume increase (V_S) depends on the pressure and can be approximated by a system stiffness calibration in which a pressuremeter module is inflated in a calibration cylinder with an inner diameter (d_t) just larger than the pressuremeter module diameter (d_{pm}).

The volume reading at the point where the external membrane diameter just equals the inner tube diameter is defined as the reference volume reading $\left(V_{ref}^{r,u}\right)$ (readings are denoted with a superscript r, values not corrected for system volume increase are denoted with a superscript u).

$$V_{ref} = l_{mb} \cdot ¼ \pi (d_t)^2$$

where

l_{mb} is the membrane length;

d_t is the internal diameter of calibration cylinder.

This reference volume reading is uncorrected for the system volume increase. The reference volume reading can be corrected for the system volume increase according to (see Figure C.1):

$$V_{ref}^{r} = V_{ref}^{r,u} - V_s\left(p_{ref}\right) = V_{ref}^{r,u} - p_{ref} \cdot \frac{\Delta V_s}{\Delta p} = V_{ref}^{r,u} - \frac{p_{ref}}{M_s}$$

where

p_{ref} is the pressure at reference volume, $V_{ref}^{r,u}$;

$M_s = \frac{\Delta p}{\Delta v_s}$ is the system stiffness (linear approximation).

