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Geotechnical investigation and testing — Field testing —

Part 1: Electrical cone and piezocone penetration test

Reconnaissance et essais géotechniques — Essais en place —

Partie 1: Essais de pénétration au cône électrique et au piézocône

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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).

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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 22476-1:2012), which has been technically revised. It also incorporates the Technical Corrigendum ISO 22476-1:2012/Cor 1:2013.

The main changes are as follows:

— dimensional tolerances of cone penetrometer have been updated;

— application class scheme has been replaced by cone penetrometer class and test category classification scheme;

— introduction of temperature influence on measurements monitoring and requirements of internal temperature sensor for cone penetrometer class 0;

— requirements for the calibration of cone penetrometers have been added;

— minor updates to figures and text have been made.

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

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

Introduction

This document establishes general principles equipment requirements, the execution of and reporting on cone and piezocone penetration tests.

The cone penetration test (CPT) consists of pushing a cone penetrometer using a series of pushrods into the soil at a constant rate of penetration. During penetration, measurements of cone resistance and sleeve friction are recorded. The piezocone penetration test (CPTU) also includes the measurement of pore pressures around the cone. Two International Standards define cone penetration tests: this document defines CPT and CPTU practice using electronic transducers; ISO 22476-12 defines CPT practice using mechanical measuring systems.

"Cone resistance" is the term used in practice and also in this document, although "cone penetration resistance" is a more correct description of the process.

The test results of this document are especially suited for the qualitative and/or quantitative determination of a soil profile together with other investigations (e.g. sampling according to ISO 22475-1 and identification ISO 14688-1) or as a relative comparison with in situ tests.

The results from a cone penetration test are typically used to evaluate:

— stratification;

— soil behaviour type;

— geotechnical parameters such as:

  — soil density;

  — shear strength parameters;

  — deformation and consolidation characteristics;

  — hydraulic conductivity and ground water pressure.

The results from a cone penetration test may also be used directly in geotechnical design calculations.

Geotechnical investigation and testing — Field testing —

Part 1: Electrical cone and piezocone penetration test

1 Scope

This document establishes equipment, procedural and reporting requirements and recommendations on cone and piezocone penetration tests.

NOTE This document fulfils the requirements for cone and piezocone penetration tests as part of geotechnical investigation and testing according to the EN 1997 series.

This document specifies the following features:

a) type of cone penetration test;

b) cone penetrometer class according to Table 2;

c) test categories according to Table 3;

d) penetration length or penetration depth;

e) elevation of the ground surface or the underwater ground surface at the location of the cone penetration test with reference to a datum;

f) location of the cone penetration test relative to a reproducible fixed location reference point;

g) pore pressure dissipation tests.

This document covers onshore and nearshore cone penetration test (CPT). For requirements for offshore CPT, see ISO 19901-8.

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/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

3 Terms, definitions and symbols

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 Terms and definitions

3.1.1
average surface roughness
R_a
average deviation between the real surface of the *cone penetrometer* (3.1.6) and a medium reference plane placed along the surface of the cone penetrometer

3.1.2
base of the cone
cylindrical part of the *cone* (3.1.4) directly behind the conical part of the cone tip

3.1.3
calibration drift
difference between *reference reading* (3.1.34) before commencement of test and first *reference reading* (3.1.34) after calibration

3.1.4
cone
conical shaped bottom part of the *cone penetrometer* (3.1.6) and the cylindrical extension

Note 1 to entry: When pushing the penetrometer into the ground, the *cone resistance* (3.1.7) is transferred through the cone to the load sensor.

Note 2 to entry: This document assumes that the cone is rigid, so when loaded its deformation is very small relative to the deformation of other parts of the cone penetrometer.

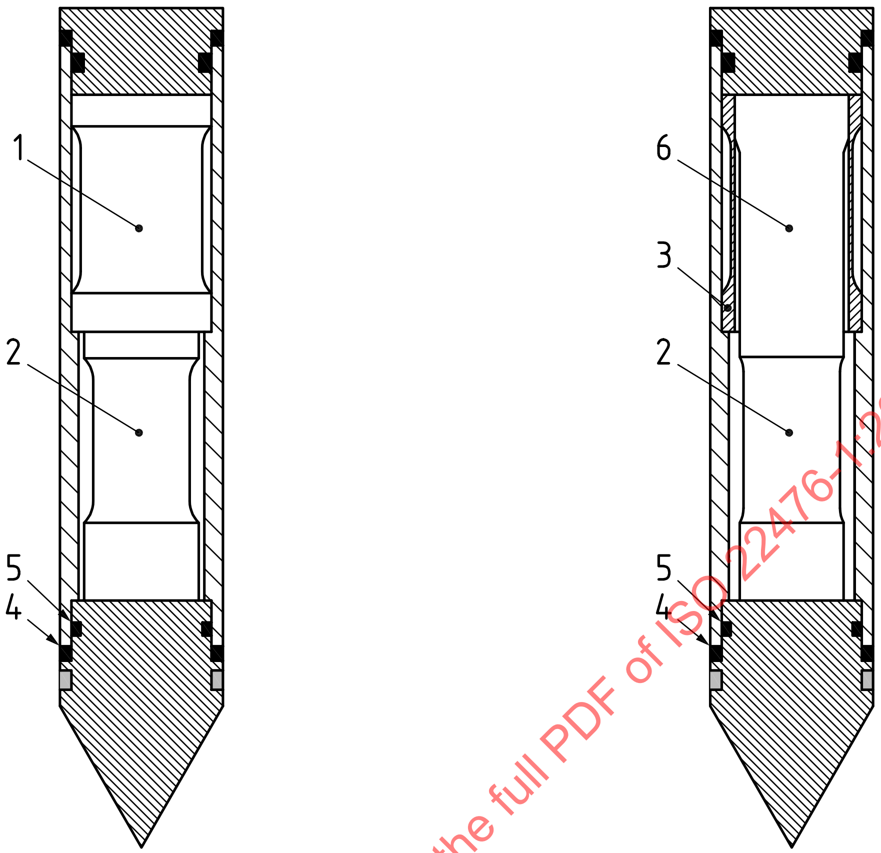
3.1.5
cone penetration test
CPT
test in which a *cone penetrometer* (3.1.6) at the end of a series of *pushrods* (3.1.33) is pushed into the ground at a constant rate of penetration and forces are measured electrically in the cone penetrometer

3.1.6
cone penetrometer
assembly containing the *cone* (3.1.4), *friction sleeve* (3.1.16), any other sensors and *measuring system* (3.1.23) as well as the connection to the *pushrods* (3.1.33)

Note 1 to entry: An example of a cone penetrometer is shown in Figure 1; for other filter locations, see Figure 2.

3.1.7
cone resistance
cone penetration resistance

3.1.8
corrected cone resistance
total cone resistance
q_t
measured cone resistance (3.1.20), q_c, corrected for pore pressure effects



a) Cone resistance and sleeve friction load cells in compression **b) Subtraction type cone penetrometer**

Key

1 sleeve load cell
2 cone load cell
3 thread
4 soil seal
5 water seal
6 load cell for combined axial forces acting on the cone and the friction sleeve

Figure 1 — Cross-sections of example cone penetrometers

3.1.9
corrected friction ratio
R_{ft}
ratio of the *measured sleeve friction* (3.1.22) or *corrected sleeve friction* (3.1.10) to the *corrected cone resistance* (3.1.8) measured at the same depth

Note 1 to entry: Usually, the measured sleeve friction is used; however, if available, the corrected sleeve friction is used.

3.1.10
corrected sleeve friction
f_t
measured sleeve friction (3.1.22), f_s, corrected for pore pressure effects

3.1.11
dissipation test
measurement of the pore pressure change with time, during a pause in pushing while holding the *cone penetrometer* (3.1.6) stationary

3.1.12
excess pore pressure
Δu_1, Δu_2, Δu_3
pore pressure in excess of the original *in situ pore pressure* (3.1.17) at the level of the filter caused by the penetration of the *cone penetrometer* (3.1.6) into the ground, see Formulae (1), (2) and (3):

$$\Delta u_1 = u_1 - u_0 \quad (1)$$

$$\Delta u_2 = u_2 - u_0 \quad (2)$$

$$\Delta u_3 = u_3 - u_0 \quad (3)$$

3.1.13
filter element
porous element in the *cone penetrometer* (3.1.6) that transmits the pore pressure to the pore pressure sensor, maintaining the geometry of the cone penetrometer

Note 1 to entry: Slotted filter may be used as the filter element for measurements of u_2, in certain soil conditions.

3.1.14
friction ratio
R_f
ratio of the *measured sleeve friction* (3.1.22) to the *measured cone resistance* (3.1.20) at the same depth

3.1.15
friction reducer
device used to reduce friction along the *pushrod* (3.1.33)

3.1.16
friction sleeve
section of the *cone penetrometer* (3.1.6) where friction between the soil and the sleeve is developed and the load is transferred to the sleeve load cell

3.1.17
in situ pore pressure
u_0
original pressure of groundwater held within the soil

3.1.18
inclination
angular deviation of the *cone penetrometer* (3.1.6) from the vertical

3.1.19
initial pore pressure
u_i
measured pore pressure (3.1.21) at the start of the *dissipation test* (3.1.11)

3.1.20
measured cone resistance
q_c

quotient of the measured force on the cone, Q_c, and cross-sectional projected area of the cone A_c, see Formula (4):

$$q_c = Q_c / A_c \quad (4)$$

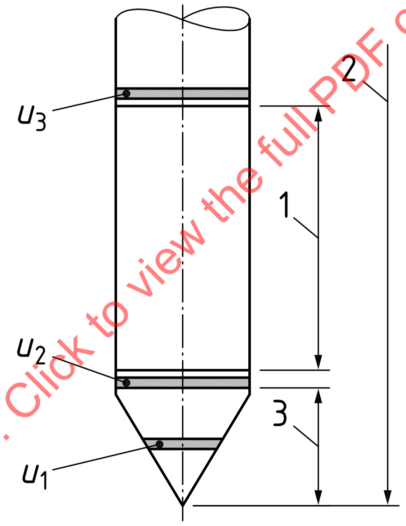
3.1.21
measured pore pressure
u_1, u_2, u_3
pressure measured in *filter element* (3.1.13) during penetration, *dissipation test* (3.1.11) and pore pressure observation test

Note 1 to entry: The pore pressure can be measured at several locations as follows (see Figure 2):

u_1 on the face of the cone;

u_2 on the cylindrical section of the cone (in the gap between the cone and the sleeve);

u_3 just behind the *friction sleeve* (3.1.16).



Key

1 friction sleeve
2 cone penetrometer
3 cone

Figure 2 — Locations of pore pressure filters

3.1.22
measured sleeve friction
f_s
division of the measured force acting on the *friction sleeve* (3.1.16), F_s, by the area of the sleeve, A_s, see Formula (5):

$$f_s = F_s / A_s \quad (5)$$

3.1.23
measuring system
all sensors and auxiliary parts used to transfer and/or store the electrical signals generated during the *cone penetration test* (3.1.6)

Note 1 to entry: The measuring system normally includes components for measuring force (*cone resistance* and sleeve friction), pressure (pore pressure), *inclination* (3.1.18), clock time and *penetration length* (3.1.30).

3.1.24
net area ratio of the cone
a
ratio of the cross-sectional area of shaft, A_n, of the *cone penetrometer* (3.1.6) above the cone at the location of the gap where fluid pressure can act, to the nominal cross-sectional area of the *base of the cone* (3.1.2), A_c

Note 1 to entry: See Figure 6.

3.1.25
net area ratio of the friction sleeve
b
ratio of the difference between cross-sectional area of the bottom of the sleeve friction, A_{sb}, and the top of the sleeve friction, A_{st}, to the area of *friction sleeve* (3.1.16), A_s

3.1.26
net cone resistance
q_n
measured cone resistance (3.1.20) corrected for the total overburden soil pressure and pore pressure

3.1.27
net friction ratio
R_{fn}
ratio of the sleeve friction to the *net cone resistance* (3.1.26) measured at the same depth

3.1.28
normalized excess pore pressure
U
excess pore pressure (3.1.12) during a *dissipation test* (3.1.11) compared to the initial excess pore pressure

Note 1 to entry: See 7.3.

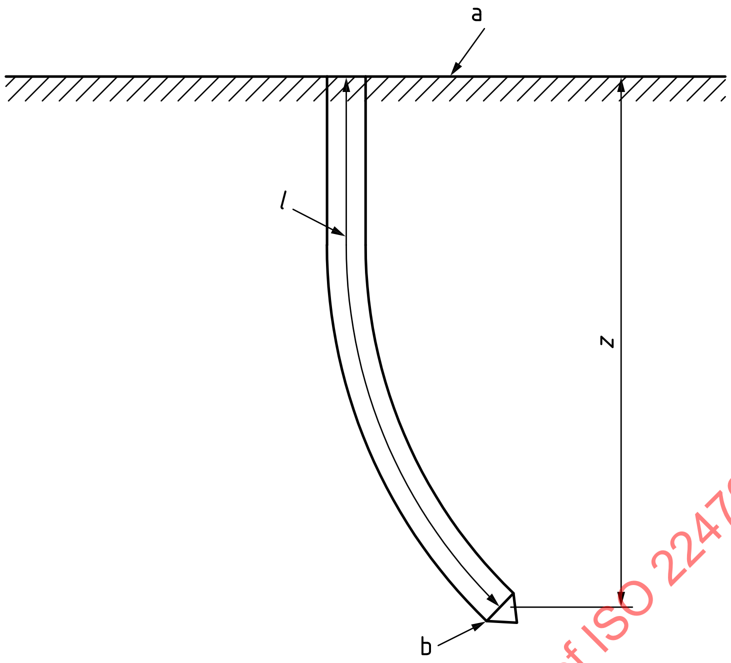
3.1.29
penetration depth
z
vertical depth of the *base of the cone* (3.1.2), relative to a fixed point

Note 1 to entry: See Figure 3.

3.1.30
penetration length
l
sum of the lengths of the *pushrods* (3.1.33) and the *cone penetrometer* (3.1.6), reduced by the height of the conical part, relative to a fixed horizontal plane

Note 1 to entry: See Figure 3.

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



Key

a Fixed horizontal plane.

b Base of conical part of cone.

l penetration length

z penetration depth

Figure 3 — Penetration length and penetration depth (schematic only)

3.1.31
piezocone penetration test
CPTU
cone penetration test (3.1.5) with measurement of the pore pressures around the cone

3.1.32
pore pressure ratio
B_q
ratio of the *excess pore pressure* (3.1.12) at the u_2 filter position to the *net cone resistance* (3.1.26)

3.1.33
pushrod
part of a string of rods for the transfer of forces to the *cone penetrometer* (3.1.6)

3.1.34
reference reading
stable output of a *measuring system* (3.1.23) reading of a sensor just before the penetrometer penetrates the ground or just after the penetrometer leaves the ground

Note 1 to entry: With tests starting onshore from the ground surface, the reference reading equals the zero reading.

3.1.35
thrust machine
equipment that pushes the *cone penetrometer* (3.1.6) and *pushrods* (3.1.33) into the ground at a constant rate of penetration

3.1.36
total overburden stress
σ_{vo}
stress due to the total weight of the soil layers at the depth of the *base of the cone* (3.1.2)

3.1.37
zero drift
absolute difference between the *reference readings* (3.1.34) of a *measuring system* (3.1.23) at the start and after completion of the *cone penetration test* (3.1.5)

3.2 Symbols

Symbol	Name	Unit
A_c	cross-sectional projected area of the cone	mm^2
A_n	cross-sectional area of the load cell or shaft	mm^2
A_s	surface area of the friction sleeve	mm^2
A_{sb}	cross-sectional area of the bottom of the friction sleeve	mm^2
A_{st}	cross-sectional area of the top of the friction sleeve	mm^2
a	net area ratio of cone	
b	net area ratio of sleeve	
b'	repeatability error without rotation	
B_q	pore pressure ratio	
C_{inc}	correction factor for the effect of the inclination of the cone penetrometer relative to the vertical axis	
d_{cone}	diameter of the cone at a specified height	mm
d_c	diameter of the cylindrical part of the cone	mm
d_{fil}	diameter of the filter	mm
d_2	diameter of the friction sleeve	mm
$d_{2l;\theta}$	diameter of the lower one fifth of the friction sleeve at rotational position θ	mm
$d_{2m;\theta}$	diameter of the middle one fifth of the friction sleeve at rotational position θ	mm
$d_{2u;\theta}$	diameter of the upper one fifth of the friction sleeve at rotational position θ	mm
$d_{c;\theta}$	diameter of the cylindrical at rotational position θ	mm
$d_{fil;\theta}$	diameter of the filter element at rotational position θ	mm
$\Delta u_{1,2,3}$	excess pore pressure at filter locations 1, 2 and 3	MPa
F_{fs}	sleeve friction force output	kN
F_N	the range between maximum and the minimum value of calibration range	kN
F_{qc}	cone resistance force output	kN
F_{qc+fs}	force measured by the sensor for combined cone resistance and sleeve friction	kN
F_r	reference axial force applied during calibration (can be F_{rqc} or F_{rfs})	kN
F_{rfs}	reference sleeve friction force	kN
F_{rqc}	reference cone resistance force	kN
F_s	axially measured force on the friction sleeve	kN
f_s	measured sleeve friction	MPa
$f_{s;a}$	apparent sleeve friction	kN
$f_{s;ac}$	temperature-corrected apparent sleeve friction	kPa
$f_{s;r}$	reference sleeve friction	kN
f_t	corrected sleeve friction	MPa
h_c	height of the conical section of the cone	mm
$h_{c;\theta}$	height of the conical section at rotational position θ	mm

Symbol	Name	Unit
h_e	height of the cylindrical extension of the cone	mm
$h_{\mathrm{e};\theta}$	length of the cylindrical extension of the cone at rotational position θ°	mm
i_a	apparent inclination	°
$i_{\mathrm{f}i}$	X_i corresponding to F_r = 0 after applying a series i	kN
i_r	reference inclination	°
i_{0i}	X_i corresponding to F_r = 0 before applying a series i	kN
k	coverage factor	
l	penetration length	m
$l_{\mathrm{gl};\theta}$	length of the gap between the cylindrical part of the cone and the lower end of the friction sleeve at rotational position θ	mm
$l_{\mathrm{gu};\theta}$	length of the gap above the upper end of the friction sleeve at rotational position θ	mm
l_s	length of the friction sleeve	m
$l_{\mathrm{s};\theta}$	length of the friction sleeve at rotational position θ	mm
Q_c	axially measured force on the cone	kN
q_c	measured cone resistance	MPa
$q_{\mathrm{c;a}}$	apparent cone resistance	MPa
$q_{\mathrm{c;ac}}$	temperature-corrected apparent cone resistance	MPa
$q_{\mathrm{c;amax}}$	maximum value of $q_{\mathrm{c;a}}$ for a predefined time period	MPa
$q_{\mathrm{c;amin}}$	minimum value of $q_{\mathrm{c;a}}$ for a predefined time period	MPa
$q_{\mathrm{c;r}}$	reference cone resistance	MPa
q_n	net cone resistance	MPa
$q_{\mathrm{c;max}}$	is the maximum value of cone resistance measured during the penetration phase of the test	MPa
q_t	corrected cone resistance	MPa
r	resolution of the sensor	
R_a	average surface roughness	µm
R_f	friction ratio	%
R_ft	corrected friction ratio	%
R_fn	net friction ratio	%
S	equal to A_c for q_c, and equal to A_f for f_s	mm^2
t	time	s
t_{50}	time needed for 50 % excess pore pressure dissipation	s
U	normalized excess pore pressure	
u	pore pressure	MPa
u_a	apparent pore pressure	MPa
U_Ac	expanded measurement uncertainty for the cross-sectional area of the cone	mm^2
u_Ac	combined standard uncertainty for the cross-sectional area of the cone	mm^2
u_ac	temperature-corrected apparent pore pressure	MPa
U_As	expanded measurement uncertainty for the area of the friction sleeve	mm^2
u_As	combined standard uncertainty for the area of the friction sleeve	mm^2
U_c	expanded measurement uncertainty for calibration of cone resistance and sleeve friction	kPa
u_c	combined standard uncertainty for calibration	kN
$u_{\mathrm{c,dim}}$	combined standard uncertainty of u_c and u_dim	kPa
U_{cfs}	expanded measurement uncertainty for calibration of sleeve friction	kPa
U_class	measurement uncertainty for the determination of cone penetrometer class	kPa

Symbol	Name	Unit
U_{cqc}	expanded measurement uncertainty for calibration of cone resistance	kPa
u_{d2}	combined standard uncertainty for diameter of the friction sleeve	mm^2
u_{dc}	combined standard uncertainty for cone diameter	mm^2
u_{dim}	combined standard uncertainty equal to u_{Ac} for q_c, and equal to u_{As} for f_s	mm^2
$U_{fs\mathrm{:class}}$	measurement uncertainty for sleeve friction for the determination of cone penetrometer class	kPa
u_{i}	initial excess in pore pressure (t=0) during a dissipation test	kPa
u_i	each of the uncertainty contributions consider for the calculation of the combined standard uncertainty	
U_{inc}	expanded measurement uncertainty for cone penetrometer inclination	°
u_{inc}	combined standard uncertainty for cone penetrometer inclination	°
u_{ls}	combined standard uncertainty for length of the friction sleeve	mm
$U_{qc\mathrm{:class}}$	measurement uncertainty for cone resistance for the determination of cone penetrometer class	kPa
u_{r}	reference pressure applied during calibration	MPa
u_{ref}	standard uncertainty of the reference measuring device	
u_t	pore pressure at time t during a dissipation test	MPa
U_u	expanded measurement uncertainty for pore pressure	kPa
$U_{u\mathrm{:class}}$	measurement uncertainty for pore pressure for the determination of cone penetrometer class	kPa
u_{o}	in situ pore pressure	MPa
u_1	pore pressure measured at location 1	MPa
u_2	pore pressure measured at location 2	MPa
u_3	pore pressure measured at location 3	MPa
v	relative reversibility error of the sensor	
X_{a}	computed value of deflection calculated from the interpolation formula	
X_i	deflection output value for a calibration step from series i	
X_{N}	value of F_{qc} (or F_{fs}) corresponding to F_{N}	kN
$\overline{X_{\mathrm{r}}}$	average of the values of X_i	kN
$\overline{X_{\mathrm{wr}}}$	average of the values of X_i without rotation	kN
z	penetration depth	m
α	measured total angle between the vertical axis and the axis of the cone penetrometer	°
β_1	measured angle between the vertical axis and the projection of the axis of the cone penetrometer on a fixed vertical plane	°
β_2	measured angle between the vertical axis and the projection of the axis of the cone penetrometer on a vertical plane that is perpendicular to the plane of angle β_1	°
Δb_{fs}	bending influence on sleeve friction	kPa/N
Δb_{qc}	bending influence on cone resistance	kPa/N
Δb_{u}	bending influence on pore pressure	kPa/N
Δa_{fs}	ambient temperature stability for sleeve friction	kPa/°C
Δa_{fsc}	ambient temperature stability for corrected sleeve friction	kPa/°C
Δa_{qc}	ambient temperature stability for cone resistance	kPa/°C
Δa_{qcc}	ambient temperature stability for corrected cone resistance	kPa/°C
Δa_u	ambient temperature stability for pore pressure	kPa/°C
Δa_{uc}	ambient temperature stability for corrected pore pressure	kPa/°C
Δt_{fs}	transient temperature stability for sleeve friction	kPa/°C

Symbol	Name	Unit
Δt_{fsc}	transient temperature stability for corrected sleeve friction	kPa/°C
Δt_{qc}	transient temperature stability for cone resistance	kPa/°C
Δt_{qcc}	transient temperature stability for corrected cone resistance	kPa/°C
Δt_{u}	transient temperature stability for pore pressure	kPa/°C
Δt_{uc}	transient temperature stability for corrected pore pressure	kPa/°C

4 Equipment

4.1 General

4.1.1 Tolerances

The dimensional tolerances are operational tolerances.

The tolerance on surface roughness is a manufacturing tolerance.

4.1.2 Gaps and soil seals

Gaps between the different parts of the cone penetrometer shall not exceed 5 mm in height. A soil seal shall protect the gap to prevent soil particles from affecting the measurement.

The soil seal shall deform easily relative to the load cell and other elements in the penetrometer, to prevent the transfer of significant forces through the gap.

4.2 Cone penetrometer

The cone penetrometer shall have internal load sensors for the measurement of force on the cone (cone resistance), side friction on the friction sleeve (sleeve friction) and, if applicable, pore pressure at one or several locations on the surface of the cone penetrometer.

NOTE 1 Other sensors can be included in the cone penetrometer.

The axis of all parts of the cone penetrometer shall be coincident.

Cone penetrometers should ideally have a net area ratio of the cone approaching 1 and a net area ratio of the sleeve approaching 0, taking into account the robustness of the cone penetrometer.

NOTE 2 Net area ratio, a, varies between 0,5 and 0,9 for commonly used cone penetrometers.

4.3 Surface roughness and hardness

The cone and friction sleeve of the cone penetrometer shall be manufactured to a minimum hardness of 45 HRc. Hardness Rockwell scale C is defined in ISO 6508-1:2016.

The surface roughness, as mentioned in 4.4 and 4.5, refers to the average roughness, R_a, determined by a surface profile comparator according to ISO 8503, or equivalent.

NOTE The surface roughness requirement intends to prevent the use of an “unusually smooth” or “unusually rough” cone or friction sleeve. Steel, including hardened steel, is subject to wear in soil (in particular sands); and the friction sleeve develops its own roughness with use. It is therefore important that the roughness at manufacture approaches the roughness acquired upon use.

4.4 Cone

The cone consists of a conical part and a cylindrical extension. The cone shall have a nominal apex angle of 60°. The cross-sectional area of the cone shall be 1 000 mm^2, which corresponds to a diameter of 35,7 mm.

Depending on ground conditions, cones with a diameter between 25 mm (A_c = 500 mm^2) and 50 mm (A_c = 2 000 mm^2) may be used for special purposes, without the application of correction factors. In this case, the geometry of the cone shall be adjusted proportionally to the diameter. The geometry of the friction sleeve should be adjusted to obtain comparable results. Use of a cone with $A_c \neq$ 1 000 mm^2 shall be reported.

The diameter of the cylindrical part shall be within the tolerance requirement, as shown in Figure 4:

35,3 mm $\leq d_c \leq$ 36,0 mm

The height of the cylindrical extension shall be within the following tolerance requirement:

7,0 mm $\leq h_e \leq$ 10,0 mm

The height of the conical section shall be within the following tolerance requirement:

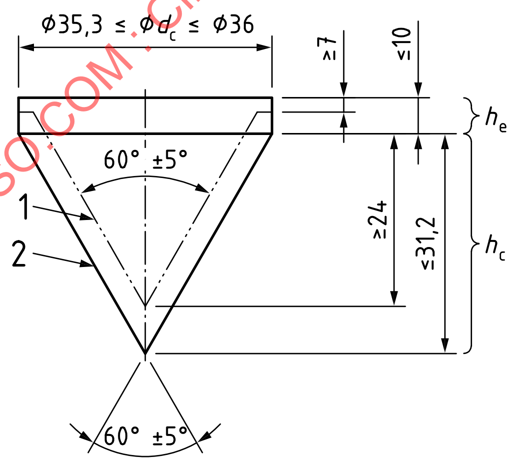
24,0 mm $\leq h_c \leq$ 31,2 mm

If a filter is put at position u_2, the diameter of the filter element itself shall be equal to the diameter of the cone, d_c, with a tolerance of -0,1 mm to 0 mm (see also 4.5 and 4.6).

The cone shall be manufactured to a surface roughness of R_a < 5 µm.

The cone shall not be used if an additional visual check indicates that it is asymmetrically worn or unusually rough, even if it otherwise fulfils the tolerance requirements.

Dimensions in millimetres



Key

1 minimum shape of the cone after wear

2 maximum shape of the cone

Figure 4 — Tolerance requirements for the use of 1 000 mm^2 cone penetrometer

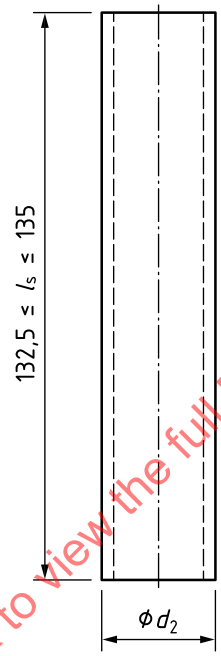
4.5 Friction sleeve

The friction sleeve shall be placed just above the cone. The distance due to gaps and soil seals shall not be more than 5,0 mm.

The surface area, A_s, shall be 15 000 mm^2. Tolerance requirements are shown in Figure 5.

Friction sleeves with an external diameter between 25 mm and 50 mm may be used for special purposes, if used with cones of the corresponding diameter without the application of correction factors. The nominal ratio of the length and the diameter should preferably be 3,75. Ratios of 3 to 5 are allowable.

Dimensions in millimetres



Key

l_s length of the friction sleeve

d_2 diameter of the friction sleeve

Figure 5 — Geometry and tolerances of the friction sleeve

The geometry and tolerances of the friction sleeve shall be within the tolerance requirement, as shown in Figure 5.

The diameter of the friction sleeve, d_2, shall be equal within the following tolerance requirement:

$$d_c \leq d_2 < (d_c + 0{,}25)\ \text{mm}$$

and

$$d_2 < 36{,}1\ \text{mm}$$

The length of the cylindrical part shall be within the following tolerance requirement:

$$132{,}5\ \text{mm} < l_s \leq 135{,}0\ \text{mm}$$

The friction sleeve shall be manufactured to a surface roughness of R_a = 0,4 µm ± 0,25 µm, measured in the longitudinal direction.

The friction sleeve shall not be used if a visual check indicates that it is scratched, asymmetrically worn or unusually rough, even if it otherwise fulfils the tolerance requirements.

The cross-sectional area of the top end of the friction sleeve shall not be smaller than the cross-sectional area of the lower end.

4.6 Filter element

4.6.1 General filter location

A filter position in or just behind the cylindrical extension of the cone is recommended, see Figure 2.

NOTE 1 Measurements at different filter locations in addition to the recommended ones can give valuable information about the ground conditions.

NOTE 2 The measured pore pressure is influenced by soil type, in situ pore pressure and filter location on the surface of the cone penetrometer. The pore pressure consists of two components: the original in situ pore pressure and the additional or excess pore pressure caused by the penetration of the cone penetrometer into the ground.

The filter shall not influence the measured cone resistance or sleeve friction.

Tolerances on filter dimensions are tolerances at the start of a test.

The pore pressure measuring system shall be saturated at the start of the test.

The filter should remain saturated, even when the cone penetrometer is penetrating an unsaturated layer. This is not always possible; in these circumstances, other methods like pre pushing, pre boring or changing saturating fluid can be necessary.

Porous filters should have a pore size between 2 µm and 20 µm, matching a hydraulic conductivity between 10^{-4} m/s and 10^{-5} m/s. Filter materials that get clogged should be avoided.

NOTE 3 The following types of material have been used with good experience in soft normally consolidated clay: sintered stainless steel, carborundum, ceramics, porous PVC (Poly vinyl Chloride), HDPE (High Density Poly Ethyleen) and porous brass filter.

The use of slotted filter shall fulfil the same purpose and general requirements as a porous filter.

The cone penetrometer shall be designed in such a way that it is easy to replace the filter and that the liquid chamber is easy to saturate (see 5.3).

NOTE 4 With regard to the choice of saturating liquid, saturation of pore pressure measurement system, and use of slot filters, see Annex F.

4.6.2 Pore pressure u_1

The surface of the filter shall fit the shape of the cone: it shall not protrude and shall not recess more than 0,1 mm.

The deviation from the surface of the filter to the surface of the cone should be assessed visually.

The filter element should be positioned in the middle third of the conical part.

4.6.3 Pore pressure u_2

The filter element shall be placed in or just behind the cylindrical part of the cone. The diameter of the filter at the start of the test shall equal to the diameter of the cylindrical part of the cone and the friction sleeve, with a tolerance limit of −0,1 mm to 0 mm.

$$(d_2 - 0{,}1) \leq d_{\text{fil}} \leq d_c$$

For correction of pore pressure effects on cone resistance, the filter element should be located in the gap between the cone and the friction sleeve. Since this is not possible in practice, the filter should be located in the cylindrical part of the cone as close as possible to the gap.

4.6.4 Pore pressure u_3

The diameter of the filter shall correspond to the diameter of the friction sleeve with a tolerance limit of −0,1 mm to 0 mm, i.e. the diameter of the filter shall be smaller or equal to the diameter of the friction sleeve:

$$(d_2 - 0{,}1) \leq d_{\text{fil}} \leq d_2$$

The filter element should be placed immediately above and as close as possible to the gap between the friction sleeve and the shaft of the cone penetrometer.

4.7 Pushrods

The pushrods shall have the same diameter as the cone for at least 400 mm measured from the base of the cone for cones with a base area of 1 000 mm^2. For other size cones, this distance shall be scaled linearly in proportion to the diameter.

Prior to each use, the straightness shall be checked visually. The straightness of the pushrods shall be determined as specified in B.1.1, at the intervals given in Table B.1.

Friction along the pushrods can be reduced by a local increase in the rod diameter (friction reducer). The friction can also be reduced by lubrication of the pushrods, for instance by mud injection during the test. The injection point should be at least 400 mm above the base of the cone for cones with a base area of 1 000 mm^2. For other size cones, this distance shall be scaled linearly in proportion to the diameter of the cone.

Above the ground level, the pushrods should be guided by rollers, a casing or similar device to reduce the risk of buckling. The pushrods may also be guided by a casing in water or soft strata to avoid buckling.

The pushrods shall be chosen with respect to the data signal transmission system chosen.

NOTE The pushrods can also be used to support and/or protect parts of the measuring system. With the acoustic transfer of CPT results, the rods are also used for transmission of data.

4.8 Measuring system

4.8.1 Accuracy

The resolution of the measuring system shall be better than one-third of the maximum allowable uncertainty applicable to the cone penetrometer class given in Table 2.

Uncertainties in the measuring system are listed in 5.1.2, and the required calculations are described in Clause B.2.

4.8.2 Sensors for cone resistance and sleeve friction

The load sensor shall be compensated for possible eccentricity of axial forces. The sensor for recording the side friction force shall be constructed so that it measures the friction along the sleeve, and not the earth pressure against it.

Pre-compression devices to overcome the internal resistance generated by seals and o-rings can be used to improve the operational performance of the sensors.

NOTE Normally strain gauged load cells are used for recording cone resistance and sleeve friction.

4.8.3 Sensor for pore pressure

The sensor should not show significant deformation during loading. The sensor communicates with the porous filter on the surface of the cone penetrometer via a liquid-filled chamber. The measuring system should be as rigid as possible (see 5.3) to obtain a good response.

NOTE The pore pressure sensor is usually a pressure transducer of the membrane type.

4.8.4 Sensor for inclination

The inclinometer shall have a measuring range of at least 15° relative to the vertical axis.

An inclination sensor may be omitted where the target penetration is less than 5 m and for test category D.

4.8.5 Sensor for temperature

For a cone penetrometer class 0, a temperature sensor shall be integrated into the cone penetrometer and have a temperature range of −10 °C to +50 °C with a maximum allowable uncertainty of 0,5 °C.

Temperature sensors can be integrated into any cone class. The main purpose of the temperature sensor is to monitor the temperature changes that affects the load cells and pressure transducers. When verification tests are conducted to study the influence of temperature changes on cone penetrometer measurements, the results from the verification and CPT/CPTU temperature records, can be used to apply corrections to the measurements of q_c, f_s and u_2.

4.8.6 Measuring of penetration length

The measuring system shall measure the penetration length during operation.

The measurement system for depth shall also include a procedure for correction of measurements if upward movements of the pushrods occur relative to the depth sensor, caused by a decrease in force on the pushrods.

Maximum allowable uncertainty for measuring of penetration length are defined per test category, see 5.10. For test category A and B, the maximum allowable uncertainty is the largest of 0,1 m and 1 % of current length. For test category C and D, the maximum allowable uncertainty is the largest of 0,2 m and 2 % of current length.

4.8.7 Raw data

The test data shall be recorded as raw data.

Raw data is the output of the measuring system, after converting into units of force for q_c and f_s and pressure u_2 (u_1, u_3 if applicable), temperature (if applicable) and penetration length, without the application of filtering or other corrections performed manually, electronic or by microprocessors.

4.9 Thrust machine

The equipment shall be loaded or anchored to minimize movements of the thrust machine relative to ground level while the penetration occurs.

Required reaction (counterweight) for the thrust machine may be supplied by dead weight and/or soil anchors.

Hammering on the cone penetrometer/rods or rotation of the cone penetrometer is not allowed during the test.

The pushing equipment shall give a stroke of at least 1 m. Other stroke lengths may be used in special circumstances.

5 Test procedures

5.1 Selection of equipment, procedures and evaluation of results

5.1.1 General

Equipment and procedures to be used should be selected considering the expected ground conditions and the project requirements.

Cone penetration tests are classified considering the penetrometer uncertainty characteristics and diagnostic checks of the sensors during the fieldwork (see 5.1.2 and 5.10):

a) Cone penetrometer class

Based on documented calibration results and uncertainty analyses as described in 5.1.2 and Clause B.2, the cone penetrometer class shall be determined.

b) Test category

Recorded observations and measurements during test preparation and execution shall be used, together with the cone penetrometer class, to evaluate the test category of the CPT/CPTU performed. Description of the documentation required is given in 5.10.

Subclause 5.10 and Annex A provide guidance for selection of cone penetrometer type and an indication of test category that can be achieved, based upon required confidence level.

5.1.2 Calibration and verification requirements

The calibration and verification of cone penetrometer sensors shall be performed in a calibration laboratory that meets the requirements of ISO/IEC 17025. The cone penetrometer shall be calibrated in accordance with Annex B for the following measurands, where applicable:

a) cone resistance;

b) sleeve friction;

c) pore pressure;

d) area ratios of the cone (a) and of the friction sleeve (b);

e) inclination.

Annex C provides an example of a calibration report.

Calibration shall be carried out at least every twelve months or when sensors are overloaded or show signs of malfunction or if reference readings before the start of the test shows a drift larger than 2 % of the full scale compared to the calibration zero load readings.

The calibration test report shall include:

- description and identification of the cone penetrometer and measurement system;
- identification of the calibration laboratory (or calibration laboratories);
- description of the calibration laboratory environment during calibration, average temperature and range of variation;
- identification and uncertainty characteristics of reference instruments used for calibration and verification;
- date of calibration, measuring intervals for calibration, calibration and verification results including the interpolation formulae in accordance with Clause B.2;
- results before and after any adjustments or repair;
- the calibration results of the net area ratios of the cone (a) and of the friction sleeve (b) in accordance with Clause B.2; these values are unique to each cone penetrometer and shall be documented in the field report;
- analysis of the uncertainty of the calibration for each of the cone penetrometer sensors; calculations of uncertainty for each of the listed contributions shall conform to Clause B.2;
- statement of conformity with ISO/IEC 17025 and this document;
- statement identifying how the measurements are metrologically traceable;
- statement of conformity with at least one of the cone penetrometer classes (see 5.1.3).

The calibration report shall include the uncertainty contributions defined in Table 1 for the calculation of the expanded measurement uncertainty for each measurand (see Clause B.2).

Table 1 — Uncertainty contributions for each of the measurands

Uncertainty contributions	Measurand		
	Cone resistance	Sleeve friction	Pore water pressure
Dimensions	√	√	√
Reference	√	√	√
Reproducibility	√	√	
Repeatability	√	√	√
Resolution	√	√	√
Zero drift	√	√	√
Interpolation	√	√	√
Reversibility	√	√	√
Apparent load transfer	√	√	

5.1.3 Cone penetrometer class conformity assessment

Cone penetrometers shall be classified following the scheme presented in Table 2. For the fulfilment of class 0 and 1, the cone shall have cone resistance, sleeve friction and pore pressure sensors. A temperature sensor located inside the cone housing and in close proximity to the load sensors shall be used for the fulfilment of class 0 and should be used for class 1. Class 2 and 3 cones shall have cone resistance and sleeve friction sensors and may have pore pressure sensors. The cone penetrometer shall meet all the requirements for each of the sensors for a given class to be achieved.

Each cone penetrometer shall have a statement of conformity for at least one of the cone penetrometer classes of Table 2. Conformity to a cone penetrometer class shall be determined after each calibration of the cone penetrometer. The acceptance criteria for the statement of conformity are defined in Table 2 and the entry values shall be calculated according to the formulae provided in Clause B.2

Table 2 — Classification of cone penetrometers under laboratory conditions

Cone penetrometer class	Measurand	Allowable maximum measurement uncertainty[a]	Ambient temperature stability[b]	Transient temperature stability[c]	Bending influence[d]
		$U_{qc:class}$ $U_{fs:class}$ $U_{u:class}$	Δa_{qc} or Δa_{qcc} $\Delta a_{fs,}$ or Δa_{fsc} Δa_{u} or Δa_{uc}	Δt_{qc} or Δt_{qcc} Δt_{fs} or Δt_{fsc} Δt or Δt_{uc}	Δb_{qc} Δb_{fs} Δb_{u}
0	Cone resistance	15 kPa or 0,5 %	0,5 kPa/°C	2 kPa/°C	0,3 kPa/N
	Sleeve friction	5 kPa or 1 %	0,1 kPa/°C	0,5 kPa/°C	0,1 kPa/N
	Pore pressure	3 kPa or 0,5 %	0,1 kPa/°C	0,5 kPa/°C	0,05 kPa/N
1	Cone resistance	35 kPa or 1 %	2 kPa/°C	10 kPa/°C	0,3 kPa/N
	Sleeve friction	5 kPa or 1 %	0,1 kPa/°C	0,5 kPa/°C	0,1 kPa/N
	Pore pressure	10 kPa or 0,5 %	0,1 kPa/°C	0,5 kPa/°C	0,05 kPa/N
2	Cone resistance	100 kPa or 2 %	10 kPa/°C	50 kPa/°C	1 kPa/N
	Sleeve friction	15 kPa or 2 %	0,5 kPa/°C	2,5 kPa/°C	0,5 kPa/N
	Pore pressure[e]	25 kPa or 1 %	1 kPa/°C	2,5 kPa/°C	0,1 kPa/N
3	Cone resistance	200 kPa or 5 %	10 kPa/°C	100 kPa/°C	2 kPa/N
	Sleeve friction	25 kPa or 10 %	1 kPa/°C	5 kPa/°C	1 kPa/N
	Pore pressure[e]	50 kPa or 5 %	1 kPa/°C	5 kPa/°C	0,2 kPa/N

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

[b] The values of ambient temperature stability represents the maximum allowable for each class.

[c] The values of transient temperature stability represents the maximum allowable for each class.

[d] The values of bending influence represents the maximum allowable for each class.

[e] Pore pressure applies only to CPTU.

Conformity to a cone penetrometer class shall apply when all the following requirements are met.

— Each of the uncertainty values ($U_{qc:class}$, $U_{fs:class}$, $U_{u:class}$), calculated in accordance with Annex B, meets the requirements of Table 2 for each of the measurands for a given cone penetrometer class.

— Resolution and output stability are better than one-third of the allowable maximum uncertainty values of Table 2, for a given cone penetrometer class.

— The values of ambient temperature stability (Δa_{qc}, Δa_{fs}, and Δa_{u}), transient temperature stability (Δt_{qc}, Δt_{fs} and Δt_{u}) and bending influence (Δb_{qc}, Δb_{fs} and Δb_{u}), calculated in accordance to Annex B, meet the requirements of Table 2 for a given cone penetrometer class.

— Each of the expanded measurement uncertainty values for cone penetrometer inclination is better than 1°, for any of the cone penetrometer classes.

The determination of cone penetrometer class is based on a smaller set of uncertainty contributions, U_{class}, as defined in Annex B than those required for expanded measurement uncertainty for the calibration, U, as defined in Annex B. A cone penetrometer can thus conform to a cone penetrometer class, where uncertainties presented in a calibration test report are higher than values of Table 2.

A cone penetrometer can conform to more than one cone penetrometer class, for the case of multiple intervals for calibration.

For cone penetrometers that rely on real-time or post-processing correction for temperature influence on CPT results, the corrected values of ambient temperature stability (Δa_{qcc}, Δa_{fsc} and Δa_{uc}) and the corrected values of transient temperature stability (Δt_{qcc}, Δt_{fsc}, Δt_{uc}), as defined in Annex B, can be used for the assessment of cone penetrometer class in addition to the assessment without applying corrections. The equations applied for correction shall be reported.

5.2 Position and verticality of thrust machine

The distance between the test location and the location of previous investigation points should be sufficient to prevent interaction effects.

Between cone penetration tests, a horizontal distance of 2 m usually is sufficient. The distance to a previous borehole should be at least 20 times the borehole diameter. Some borehole techniques, such as air or water drilling, can require larger distances. Nearby excavations should be avoided.

The thrust machine shall push the pushrods so that the axis of the pushing force is as close to vertical as possible. The deviation from the intended axis should be less than 2° at ground level. The axis of the penetrometer shall correspond to the loading axis at the start of the penetration.

5.3 Preparation of the test

If the cone penetrometer is disassembled as part of routine operational maintenance and servicing, it should be reassembled following the cone manufacturers maintenance and instruction manual.

For cone penetrometers with measurement of pore pressure, the filter element and other parts of the pore pressure system shall be saturated with a non-compressible, de-aired liquid before field use. Appropriate measures should be taken to preserve saturation during the test.

De-aired distilled water, glycerine or silicone oil may be used when testing is carried out in saturated soils. If performing penetration tests in unsaturated soils, over-consolidated clays, dilative soils (e.g. dense sands and silts) or above the groundwater table, the filter should be saturated with glycerine, silicone oil or similar or consider use of slotted filters.

Saturation of the cone penetrometer before penetration starts or during operation in a predrilled hole can be maintained by applying a thin rubber membrane around the filter. During saturation and mounting of the rubber membrane, the penetrometer is subjected to small stresses, so that the sensors can show values different from zero.

The wear of the cone and the friction sleeve shall be checked before the start of the test. When using class 0 cone penetrometers, the diameter of the cone and sleeve shall be measured and recorded before the start of the test. The results shall be used to report cone resistance and sleeve friction values in units of pressure. Annex B provides further details regarding the required dimensional measurements.

NOTE 1 See Annex F in case a slot filter is used.

When penetrating coarse materials, predrilling may be used in parts of the profile if the penetration stops in dense, coarse or stone-rich layers. Predrilling can be used in coarse top layers, sometimes in combination with casings to avoid a collapse of the borehole. In soft or loose soils, predrilling can be used to penetrate the crust to reach the groundwater table. Predrilling can be done by ramming a dummy-rod of 45 mm to 50 mm diameter through the dense layer to provide an open hole and reduce the penetration resistance.

The reference readings of the cone resistance, the sleeve friction and, if applicable, the pore pressure and inclination of the cone penetrometer relative to the vertical axis shall be recorded before and after the test. Reference readings shall be taken with the cone penetrometer in a vertical position, under no load and under similar temperature conditions as close to the ground temperature as possible. The output of cone resistance, sleeve friction and, if applicable, the pore pressure of the cone penetrometer shall be recorded for a period of 1 min at a frequency of at least 1 Hz before and after testing. Reference readings for each sensor shall be calculated as a mean of the recorded values. Output stability for each sensor shall be computed by subtracting the maximum and the minimum values recorded for 1 min and documented.

Annex B contains maintenance, checks and calibration procedures.

NOTE 2 When the cone penetrometer is lowered into the ground or in the water, temperature gradients occur if the temperature of the cone is different from the ground temperature, which will influence the sensors. Therefore, it is essential that the penetrometer is left to come to equilibrium so that the temperature gradients can be reduced to zero before the reference reading and the penetration starts. Usually, the largest gradients occur after 2 min to 3 min. The cone penetrometer is usually temperature-stabilized after 10 min to 15 min.

5.4 Pushing of the cone penetrometer

The penetration length and clock time shall be recorded during the penetration phase of the test. During the penetration test, the cone penetrometer shall be pushed into the ground at a constant rate of penetration of (20 ± 5) mm/s. For the category A test, the rate of penetration shall be (20 ± 2) mm/s.

In dense sands and gravels, penetration rates less than the “standard” can be acceptable, to prevent damage to the cone and cone rods or to achieve larger depths. This variation in the rate of penetration shall be recorded and reported.

NOTE 1 The penetration is regarded as continuous even if the penetration is stopped regularly for a new stroke or mounting of a new pushrod. Some thrust machines can carry out true continuous penetration without any stops which can be an advantage, particularly in layered silt and clay deposits. Stops also give valuable information about pore pressure behaviour and response after continuing penetration; they also help to consider how well saturation has been succeeded.

NOTE 2 The penetration is regarded as discontinuous if larger stops are introduced, such as dissipation tests (see 5.8) or due to unforeseen malfunctions of the equipment.

5.5 Use of friction-reducing techniques

Friction-reducing techniques by increasing the diameter or by injection of water or drilling fluids may be used. The cone penetrometer and, if relevant, the pushrod shall have the same diameter for at least 400 mm measured from the base of the cone before the introduction of any friction reducing technique.

NOTE Further information is provided in Annex G.

5.6 Frequency of test data recording

Test data for the following parameters shall be recorded: penetration length, cone resistance, sleeve friction and, where applicable, inclination, pore pressure and temperature. Recording of the test data shall start immediately above the fixed horizontal plane of Figure 3 and then be recorded at least once for every 20 mm increase in penetration length, except for test category A where a maximum 10 mm increment shall apply. If the values are measured more frequently than the required reporting intervals, then the average value calculated can be reported. Other methods, however, can also be applicable. The method used shall be reported.

NOTE The logging interval for the various measured values can also be increased depending on the detail required in the profile, e.g. detection of thin layers. Usually, the same reading interval is used for registration of cone resistance, sleeve friction and pore pressure.

5.7 Registration of penetration length

The resolution of the penetration length measurement shall be at least 10 mm.

The penetration length shall also be checked and recorded at least every 5 m for tests category A of Table 3. For other categories, the penetration length shall be checked and recorded at the end of the test. Penetration length shall be checked without using the depth sensor.

NOTE The measured parameters for a cone penetrometer with a large inclination can deviate from the values that would have been measured if the cone penetrometer is vertical.

The penetration depth shall be calculated from penetration length and inclination measurements as specified in Annex D.

5.8 Pore pressure dissipation test (PPDT)

If the drainage and/or consolidation characteristics of the soil are to be evaluated, dissipation tests may be carried out at pre-selected depths in the deposit. In a dissipation test, the pore pressure decay is obtained by recording the values of pore pressure with time.

A dissipation test may be used to estimate the in situ geo-hydraulic properties. In fine, low hydraulic conductivity soils, the pore pressure record may be used to evaluate the coefficient of consolidation.

Pore pressure and cone resistance shall be measured with time. The recording frequency should be at least 1 Hz for the first minute of the dissipation test but may be halved for every log (time) cycle after that.

Dissipation test shall be performed without delay after the cone has reached the designated depth. The cone shall stay in the same depth while performing the test without moving down- or upwards.

NOTE 1 The required depth and minimum duration of a dissipation test depend on the soil conditions and the purpose of the measurement. The maximum duration is also a common reference condition for avoiding inappropriately long interruptions.

The dissipation test may be performed with the rods unclamped or clamped. The cone resistance and sleeve friction shall be recorded at the same time intervals as the pore pressure during the test. The execution method (e.g. clamped/unclamped) shall be recorded and reported. If the weight of the equipment is greater than the total resistance of the soil, the dissipation test should be carried out clamped to prevent penetration of the equipment during the test.

NOTE 2 Variation in cone resistance is unavoidable in practice and depends on factors such as type of equipment and soil conditions.

The duration of the dissipation test should typically correspond to at least t_{50}, the time needed for 50 % pore pressure dissipation ($u_t \leq u_o + 0{,}5 \times \Delta u_i$), since t_{50} is the time used in most interpretation methods. If u_o is not known, a cautious estimate of the value should be made.

5.9 Test completion

The penetration with the cone penetrometer and the pushrods should be terminated when one of the following events occurs.

— The desired penetration length or penetration depth has been reached.

— The inclination of the cone penetrometer relative to the vertical axis exceeds the measuring range or 15°.

— The agreed maximum thrust or the maximum capacity of the cone penetrometer or measuring systems is reached.

— Possible damage to the equipment.

— Sudden change in inclination over a short penetration length.

Pore pressure observation test at the end of a CPTU can be carried out when the soils encountered at this depth are predominantly coarse. In a pore pressure observation test, the pore pressure is obtained by monitoring or recording the values of pore pressure with time. In coarse, high permeability soils, the pore pressure observation test is used to evaluate the pore pressure at measured depth. The duration of the pore pressure observation test should exceed 1 min. Pore pressure at the end of observation can be reported, together with monitored time, test depth and cone penetrometer class.

The reference readings of the measured parameters and output stability shall be recorded after extraction of the cone penetrometer from the soil and, if necessary, after cleaning of the cone penetrometer. Reference readings should be taken with the cone penetrometer unloaded under similar temperature conditions as close to the ground temperature as possible.

The observed differences in reference readings before and after test completion shall be used as one of the inputs to determine the test category according to the classification set out in Table 3.

After completion of the test, inspect the cone penetrometer and note any excessive wear or damage.

NOTE The zero-drift determined from reference readings before the test and after cleaning is a measure of the correct functioning of the equipment and is used to evaluate if the requirements of Table 3 can be fulfilled. The reference readings from the uncleaned cone are also important for the interpretation of test results.

5.10 Evaluation of CPT/CPTU in relation to test category

Cone penetrometer class, differences observed in reference readings and the larger value of output stability obtained before and after the test shall be used to determine the test category according to Table 3. Tests shall meet all the requirements for each of the sensors for a given test category to be accomplished. The requirements regarding penetration length are presented in 4.8.6. Further recommendations regarding the selection of equipment and confidence level of test results are provided in Annex A.

Temperature changes cause significant sensor drifts, so it is essential to ensure that similar cone temperature while taking reference readings before and after the test.

During cone retraction, soils can adhere to the cone penetrometer or get trapped in the penetrometer's gaps. This can have an influence in the reference readings taken after the test. It is important to carefully have cleaned or rinsed the cone penetrometer after test completion and before taking reference readings, but not dismantled if the cone sensors are pre-stressed.

Table 3 — Test categories of CPT/CPTU

Test category	Cone penetrometer class	Reference reading checks		
		Parameter	Maximum allowable difference of reference values before and after test	Maximum variation in output stability
A	0	Cone resistance	15 kPa	1 kPa
		Sleeve friction	5 kPa	0,5 kPa
		Pore pressure	3 kPa	0,5 kPa
B	0, 1	Cone resistance	35 kPa	5 kPa
		Sleeve friction	5 kPa	1,5 kPa
		Pore pressure	10 kPa	3 kPa
C	0, 1, 2	Cone resistance	100 kPa	11 kPa
		Sleeve friction	15 kPa	3 kPa
		Pore pressure[a]	25 kPa	8 kPa

[a] Pore pressure applies only to CPTU.

Table 3 *(continued)*

Test category	Cone penetrometer class	Reference reading checks		
		Parameter	Maximum allowable difference of reference values before and after test	Maximum variation in output stability
D	0, 1, 2, 3	Cone resistance	200 kPa	33 kPa
		Sleeve friction	25 kPa	5 kPa
		Pore pressure[a]	50 kPa	16 kPa

[a] Pore pressure applies only to CPTU.

Qualitative observations of test performance are valuable and relevant information to the users and interpreters of the CPT/CPTU datasets and should be reported. Data anomalies like sluggish response of pore pressure, data spikes, unresponsiveness of sensors, soil disturbance are examples of qualitative observations.

5.11 Equipment checks and calibrations

The overall equipment shall undergo regular maintenance, checking and calibration procedures as specified in Annex B.

5.12 Safety requirements

It is presupposed that national safety regulations are followed, for instance, for:

— personal health and safety equipment;

— clean air if working in confined spaces;

— ensuring the safety of the equipment.

6 Test results

6.1 Measured parameters

The following parameters shall be determined where applicable:

l penetration length;

q_c measured cone resistance; q_c shall be expressed in units of pressure determined as the ratio between the measured resistance force and cross-sectional area of the cone; the cross-section area of the cone shall be measured before the start of the test when using class 0 cone penetrometers;

f_s measured sleeve friction; f_s shall be expressed in units of pressure determined as the ratio between the measured resistance force and surface area of the friction sleeve; the surface area of the friction sleeve shall be measured before the start of the test when using class 0 cone penetrometers;

u pore pressure, one or more of the following:

u_1 pore pressure in the face of the cone;

u_2 pore pressure at the cylindrical extension of the cone;

u_3 pore pressure measured above the friction sleeve;

α measured total angle between the vertical axis and the axis of the cone penetrometer;

T temperature.

6.2 Correction of parameters

Recorded values that are not representative due to penetration interruption shall be ignored.

NOTE 1 The surrounding water pressure influences the measured cone resistance and sleeve friction. This is explained by the effect of the water pressure in the gaps between the cone and the friction sleeve, and in the gap above the friction sleeve.

When water pressure is measured using a filter element at the cylindrical extension of the cone (u_2), measured cone resistance shall be corrected by using Formula (6):

$$q_t = q_c + u_2 \times (1 - a) \tag{6}$$

where

q_t is the corrected cone resistance, in MPa;

q_c is the measured cone resistance, in MPa;

u_2 is the pore water pressure in the cylindrical part of the extension of the cone (assumed equal to the pore pressure in the gap between the cone and the sleeve), in MPa;

a is the net area ratio:

$a = A_n / A_c$

where

A_c is the cross-sectional projected area of the cone (see Figure 6);

A_n is the cross-sectional area of the load cell or shaft (see Figure 6).

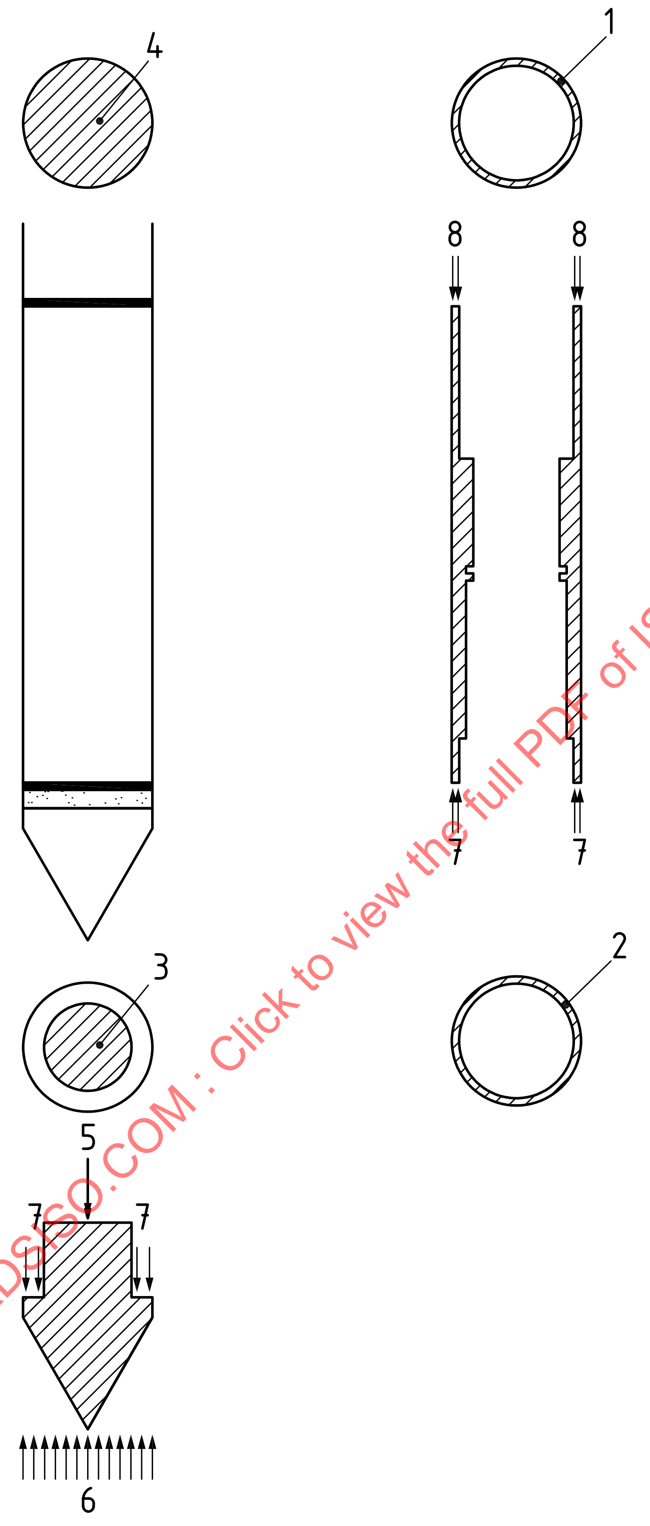
Measurements should only be corrected if u_2 is measured.

u_2 can be estimated from u_1 or u_3 by empirical relations, to obtain an approximately corrected cone resistance. In soft clays and silts, the correction can get substantial, and u_2 should preferably be measured, and corrections carried out if the cone resistance recordings are used for interpretation of mechanical parameters.

The area ratio (a) cannot be determined from geometrical considerations alone but shall be determined during calibration in a pressure chamber or similar. Therefore, the area ratio reported is the area ratio determined during the last calibration.

NOTE 2 The measured sleeve friction is influenced by surrounding water pressure. Since it is not standard practice to measure the pore pressure u_3 above the friction sleeve, the uncorrected sleeve friction f_s is commonly used. A possible correction method for the recorded sleeve friction is given in Annex E.

Various other corrections can be necessary to meet the requirements of the test category, like temperature effects, the cross-sectional area of the cone.



Key

1 cross-sectional area (top), A_{st}
2 cross-sectional area (bottom), A_{sb}
3 cross-sectional shaft area, A_n
4 cross-sectional projected area, A_c
5 axially measured force on the cone, Q_c
6 corrected cone resistance, q_t
7 pore pressure measured at location 2, u_2
8 pore pressure measured at location 3, u_3

Figure 6 — Correction of cone resistance and sleeve friction due to the unequal end area effect

6.3 Calculated parameters

The following parameters shall be calculated, based on the measured parameters:

R_f friction ratio;

z penetration depth.

Correction for inclination, like calculation of penetration depth from penetration length, shall be carried out for test categories A, B and C according to the procedure given in Annex D. Correction for inclination may be omitted if the target penetration depth is less than 5 m.

The following parameter shall be calculated, based on the corrected parameters: R_{ft}, corrected friction ratio.

7 Reporting

7.1 General

In the presentation of test results, the information should be easily accessible, for example, in tables or as a standard archive scheme. The presentation may be in digital form for easier data exchange.

Raw data in accordance with 4.8.7 shall be available in digital format.

All measurements shall be presented relative to the base of the cone in engineering units.

NOTE Methods of peak shaving and other corrections change over time. For this reason, it is important that raw data is stored for future use containing the measured values without corrections.

Subclause 7.2 indicates the information required in:

— the field report of test results;

— the test report.

The field report, completed at the project site, and the test report shall include the information given in 7.2. The test results shall be reported to enable a third party to check and understand the results.

During the cone penetration test, particulars, or deviations from this document, which can affect the results of the measurements and the corresponding penetration length, shall be recorded and reported.

7.2 Reporting of test results

7.2.1 General information

		Field report	Test report
a)	Reference to this document, i.e. ISO 22476-1:2022	x	x
b)	Date of test	x	x
c)	Starting time of the test	x	x
d)	Clock time during the test	x	x
e)	Depth of the start of penetration with reference to the ground surface	–	x
f)	Saturation fluid used in pore pressure system (if piezocone)	x	x
g)	Test type (CPT, CPTU, PPDT, etc.)	x	x
h)	Particulars or deviations from this document	x	x
i)	Company executing the test	x	x

		Field report	Test report
j)	Name and signature of equipment operator executing the test	x	x
k)	Name and signature of field manager responsible for the test results	–	x
l)	Depth to the groundwater table (if recorded)	x	x
m)	Pore pressure information (for instance from piezometers) (if available)	–	x
n)	Depth of predrilling or trenching depth	x	x
o)	Type of materials encountered (if possible)	x	x
p)	Depth of penetration and possible causes of any interruptions (like dissipation tests)	x	x
q)	Stop criteria applied, like target depth, maximum penetration force or inclination	x	x
r)	Method of back filling the hole, if applicable	x	x
s)	Observations done during the test, for example: — presence of gravel; — noise from the pushing rods; — incidents; — buckled rods; — abnormal wear.	x	x
t)	Maximum difference of reference values and maximum variation in output stability (according to Table 3)	x	x
u)	Specific arrangements that deviate from common set up of thrust machine (like a jack-up platform)	x	x

7.2.2 Location of the test

		Field report	Test report
a)	Identification of the test	x	x
b)	Elevation of the cone penetration test	–	x
c)	Local or general coordinates	–	x
d)	Reference system and tolerances	–	x
e)	Reference elevation to a known datum	–	x

7.2.3 Test equipment

		Field report	Test report
a)	Cone penetrometer type	x	
b)	Cone penetrometer class	x	
c)	Geometry and dimensions cone penetrometer	x	
d)	Type of thrust machine used, pushing capacity, associated jacking and anchoring systems	x	x
e)	Manufacturer of cone penetrometer	x	x
f)	Identification number of the penetrometer	x	x
g)	Measuring intervals for calibration of cone	x	
h)	Calibration report	-	x
i)	Filter location	x	x
j)	Filter type and filter material	x	x

		Field report	Test report
k)	Net area ratio (a and b)	x	
l)	Sensor displacements relative to the level of the cone base	x	x

7.2.4 Test results

		Field report	Test report
a)	Test category according to 5.10	x	x
b)	Measured according to 6.1	x	x
c)	Use of pre-stress devices or techniques according to 4.8.2	–	x
d)	Corrected parameters according to 6.2 and 6.3	–	x
e)	Reference readings of measured cone resistance, sleeve friction and, if applicable, pore pressure before and after the test and zero drift (in engineering units)	x	x
f)	Corrections applied during data processing (e.g. zero drifts, cone resistance and sleeve friction corrections)	–	x
g)	In situ pore pressure measurements (if recorded)	x	x
h)	Inclination of the cone penetrometer to the vertical axis, for a maximum penetration depth interval of 1 m, if applicable	–	x

7.3 Presentation of test results

In the graphical presentation of test results, the following axis scaling should be used:

— Penetration depth z 1 scale unit = 1 m;

— Cone resistance q_c, q_t 1 scale unit = 2 MPa or 0,5 MPa;

— Sleeve friction f_s, f_t 1 scale unit = 0,05 MPa;

— Pore pressure u 1 scale unit = 0,2 MPa or 0,02 MPa;

— Friction ratio R_f, R_{ft} 1 scale unit = 2 %;

— Pore pressure ratio B_q 1 scale unit = 0,5.

One scale unit should be 1 cm.

A different scaling may be used in the presentation, if the recommended scaling is used in an additional plot. The recommended scaling can, for example, be used for general presentation, whereas selected parts may be presented for detailed studies, using a different scaling. In clays, and where the test results are to be used for interpretation of soil parameters (categories A and B in Table 3), it is particularly important to use enlarged scaling in the presentation of test results.

For test categories A and B, the cone resistance and sleeve friction shall be determined using the cone cross-section area and sleeve surface area calculated before the start of the test.

The axis scaling for dissipation test results (cone resistance q_c, pore pressure u and time t) shall suit the measured values.

NOTE A common presentation format is to use linear scales for q_c and u and a logarithmic scale for t.

The test results shall be presented as continuous profiles as a function of the penetration depth (for categories A, B and C) or penetration length (for category D) relative to the level of the base of the cone for all sensors.

On reports presenting corrected data, the corrections applied shall be clearly described and it shall specify over which intervals were made.

The test results (according to the test category and test type) that shall be presented are:

— Cone resistance - depth/length q_c (MPa) - z (m);

— Sleeve friction - depth/length f_s (MPa) - z (m);

— Measured pore pressure - depth/length $u_{1,2,3}$ (MPa) - z (m);

— Inclination - depth/length α (°) - z (m) or tabulated, as function of depth.

Penetration depth is the measured length corrected for the measured inclination.

The units used may be kilopascals (kPa), depending on the scale of measured parameters.

Presentation of the results of cone penetration tests according to categories A and B shall, if required, include at least tabular data according to 7.1.

For category A, corrected cone resistance (q_t) shall be plotted in addition; and the corrected sleeve friction (f_t) may be plotted in addition. The corrected parameters should be used in further processing of the data. An exception is made for testing of coarse-grained materials, where the effect of the end area correction is negligible.

In situ pore pressure can be estimated from the location of the groundwater table, or preferably by local pore pressure measurements. It can also be evaluated from the test results by performing dissipation tests in permeable layers. The total overburden stress profile can be determined from density measurements in situ or from undisturbed samples in the laboratory. If adequate information is lacking, an estimate of the density may be obtained by use of a classification chart based on the results from the cone penetration test and local experience.

For further processing of the measured data, the following relationships may be used, if appropriate:

— Excess pore pressure $\Delta u = u - u_o$;

— Net cone resistance $q_n = q_t - \sigma_{vo}$;

— Friction ratio $R_f = (f_s/q_c) \times 100\ \%$;

— Corrected friction ratio $R_{ft} = (f_s/q_t) \times 100\ \%$ (if known, f_t shall be used instead of f_s);

— Pore pressure ratio $B_q = (u_2 - u_o)/(q_t - \sigma_{vo}) = \Delta_{u2}/q_n$;

— Normalized excess pore pressure $U = (u_t - u_o)/(u_i - u_o)$.

Knowledge of the following parameters is required for processing of the test results:

— In situ pore pressure versus depth u_o (MPa) versus z (m);

— Total overburden stress versus depth σ_{vo} (MPa) versus z (m).

These parameters, or additional calculated values, can be used for both identification of strata and classification of soil types, and as basic input values for evaluation in terms of engineering parameters.

The friction ratio shall be presented on the plot. Presentation of the other calculated parameters is optional because they are dependent on interpretation.

Annex A
(informative)

Suitability of test methods

A.1 General

This annex provides supplementary guidance to the selection of test category and related cone penetrometer class, for suitability of test methods.

A.2 Confidence in test results and general test comments

Table A.1 defines the confidence level expected for the geotechnical characterisation of soil proprieties for a given cone class and test category.

The confidence levels in this annex may be improved by statistical analysis on-site and cone-specific data.

Table A.1 — Confidence levels of measurements for the characterisation of geotechnical properties depending on the cone type and test category

<table>
<tr><th rowspan="2">Application</th><th rowspan="2">Confidence level</th><th colspan="4">Cone penetrometer class</th></tr>
<tr><th>0</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td rowspan="3">Characterisations of geotechnical proprieties of soil deposits with
$q_{c;max} \leq 1$ MPa</td><td>High</td><td>A</td><td colspan="3"></td></tr>
<tr><td>Medium</td><td colspan="2">B</td><td colspan="2"></td></tr>
<tr><td>Low</td><td colspan="3">C</td><td></td></tr>
<tr><td rowspan="3">Characterisations of geotechnical proprieties of soil deposits with
1 MPa $< q_{c;max} \leq 3$ MPa</td><td>High</td><td colspan="2">B</td><td colspan="2"></td></tr>
<tr><td>Medium</td><td colspan="3">C</td><td></td></tr>
<tr><td>Low</td><td colspan="4">D</td></tr>
<tr><td rowspan="2">Characterisations of geotechnical proprieties of soil deposits with
$q_{c;max} > 3$ MPa</td><td>High</td><td rowspan="2">Not recommended</td><td colspan="2">B and C</td><td></td></tr>
<tr><td>Medium</td><td colspan="3">D</td></tr>
<tr><td colspan="6">NOTE A, B, C and D are the test categories according to Table 3.</td></tr>
</table>

A.3 Uncertainties in cone penetrometer testing

A.3.1 General

The cone test category is for the assessment of whether a cone penetrometer system is working as expected, but it does not inform on the wider uncertainty of the data gathered. The uncertainty of individual data points of a CPT profile is affected by many factors and should be taken into account when deriving geotechnical parameter values from the recorded data. Some of the factors affecting cone penetration test uncertainty are listed here:

— ambient and transient temperature effects;

— sensor drift caused by overload or bending;

— poor saturation;

— improper transfer of loads due to dirt in gaps and seals;

— deviation of the geometry of the cone.

An uncertainty statement resulting from an uncertainty analysis that considers some of these sources of uncertainty can be presented in the report. The uncertainty analysis can be prepared following the recommendations provided in Reference [11], ISO/IEC 98-3:2008 and ISO 10012.

Some of the factors affecting cone penetration test uncertainty are discussed in A.3.2 to A.3.6. Further discussion on uncertainties associated to CPT/CPTU are provided in Reference [15].

A.3.2 Temperature effects

For a soil profile of dense sand overlying soft clay, there is more uncertainty in the measurements made in the soft clay than there would be in a soft clay only profile, due to thermal effects and hysteresis effects in the cone penetrometer response. For example, friction in dense sand can typically cause a cone penetrometer to heat by about 1 °C/MPa cone resistance; and the resulting heat flux in the cone penetrometer can give an apparent shift in the cone resistance[16]. Ambient temperature compensation systems cannot avoid heat flux effects. Penetration interruption to allow the cone penetrometer to return to stable ambient temperature can mitigate the effect on the cone penetrometer readings. An alternative method is to revisit the investigated location, predrill to known depths to avoid the hard layers and acquire CPT data in the softer layers. It is also possible to measure temperature in the cone penetrometer and partially correct CPT parameters for heat flux effects. In this case all corrections need to be documented and reported.

A.3.3 Sensor overload

In practice, cones can be overloaded outside their maximum design capacity range. This can cause large sensor drift and compromise the accuracy of the test measurements. It is good practice to keep a log that documents some of the cone operational parameters, for instance, number of tests, total meterage of penetration, reference readings, maximum load, max temperature. The latest cones are equipped with data loggers to provide data to confirm users that the instruments have only been used within its calibrated range.

A.3.4 Pore pressure

To improve the accuracy of geotechnical parameter, values derived from cone resistance measurements and the cone resistance are frequently corrected for the effects on the cone resistance of the pore water pressure generated by the cone penetration. However, if the pore water pressure recorded by the pore pressure sensor is not representative of the water pressure around the cone, the correction applied to the cone resistance is incorrect. Such error can be due to the pore pressure filter becoming blocked; or the pore pressure sensor can desaturate due to cavitation due to high negative pore water pressure generated in the test and therefore not respond representatively below this as a result of the soil behaviour. Note that the gap behind the cone over which pore water pressure affects the cone resistance will possibly not be saturated; and pore pressure in the gap can be significantly different from the measured pore pressure. In all these cases, the assumed correction for pore pressure effects on the cone resistance is erroneous and can cause errors in derived geotechnical parameter values.

Pore pressure sensors can lose saturation while the cone penetrates unsaturated or partially saturated soil above the ground water table leading to inaccurate pore pressure measurements. This can be avoided by using slotted filters or by restarting the test with a fully saturated cone after predrilling to the ground water level.

A.3.5 Sleeve friction

Significant variability is reported in the sleeve friction measurements made by different designs of cone penetrometer that all conform to ISO requirements. Therefore, compared with cone resistance measurements, there is larger uncertainty in the sleeve friction measurements undertaken in cone penetration testing.

A.3.6 Variations in testing speed

It is not uncommon that penetration speeds vary and are lower (typical) or higher (uncommon) than desired. Cone penetration speed is dependent on applied thrust which is commonly controlled by the pressure applied in the thrust system.

Cone penetration speed can influence the pore pressure response (drained, partially drained or undrained) of specific soils/soft rocks, e.g. chalks, silt. Pore pressure response in turn affects cone resistance during penetration. For example, a soil responding undrained during a CPT typically has lower resistance to cone penetration. The speed of cone penetration can influence the pore pressure response i.e. at lower speeds partially drained or drained conditions occur, whereas at higher speeds, a soil response can be undrained. Changes in pore pressure response are the dominant mechanics which can result in a significant different penetration resistance of a cone penetrometer.

Effects of varying penetration speed on cone resistance in soils with a constant pore pressure response, i.e. either drained or undrained, are limited. Examples of the effect of variable cone penetration speed are provided in Reference [12]. If the penetration speed deviates from the required (20 ± 5) mm/s, this should be included in the test report.

Annex B
(normative)

Maintenance, checks and calibration

B.1 Maintenance and checks

B.1.1 Linearity of pushrods

Before the test is carried out, the linearity of the pushrods should be checked by one of the following methods:

— holding the rod vertically and rotating it; if the rod appears to wobble, the pushrod should be replaced;

— rolling the rods on a plane surface; if the rod appears to wobble, the pushrod should be replaced;

— sliding a straight hollow tube which is slightly longer than the rod over the rod; the pushrod should pass through the tube without jamming.

If any indications of bending appear, the use of the rods should be suspended.

Other methods of checking the straightness can be used.

NOTE In test category D, there is no inclinometer, so it is more important to control the straightness of the rods.

B.1.2 Wear of the cone penetrometer

The wear of the cone and the friction sleeve shall be checked regularly (see Table B.1) to ensure that the geometry satisfies the tolerances (see 4.4 and 4.5). A standard geometrical pattern similar to a new or unused cone penetrometer may be used in this control.

When using class 0 cone penetrometers, the cross-sectional area of the cone and the area of the sleeve friction shall be determined following the next procedure.

— Measure and record the diameter of the cylindrical (steel) part of the cone perpendicular to the axis of the cone$d_{c;0}$ at rotational position θ_0 = 0° of the cone penetrometer, $d_{c;120}$ at θ_{120} = 120° and $d_{c;240}$ at θ_{240} = 240°. The cross-sectional projected area of the cone (A_c) shall be calculated using Formulae (B.1) and (B.2):

$$A_c = 0{,}25 \times \pi \times d_c^{\,2} \tag{B.1}$$

where

$$d_c = \frac{\left(d_{c;0} + d_{c;120} + d_{c;240}\right)}{3} \tag{B.2}$$

— Measure and record the diameter of the friction sleeve $d_{21;0}$, $d_{21;120}$ and $d_{21;240}$, as for $d_{c;0}$, $d_{c;120}$ and $d_{c;240}$ at 3 positions along the vertical axis of the friction sleeve (lower one fifth of the friction, middle one fifth of the friction sleeve and upper one fifth of the friction sleeve). For calculation of the surface area of the friction sleeve, it is assumed that the length does not change by wear and tear and that the length of the friction sleeve according to the calibration report (l_s) shall be used. The surface area of the friction sleeve (A_s) shall be calculated using Formulae (B.3) and (B.4):

$$A_s = \pi \times d_2 \times l_s \quad \text{(B.3)}$$

where

$$d_c = \frac{\left(d_{2l;0} + d_{2l;120} + d_{2l;240}\right) + \left(d_{2m;0} + d_{2m;120} + d_{2m;240}\right) + \left(d_{2u;0} + d_{2u;120} + d_{2u;240}\right)}{9} \quad \text{(B.4)}$$

B.1.3 Gaps and seals

The seals and gaps between the different parts of the cone penetrometer shall be checked according to Table B.1. In particular, the seals should be checked for intruding soil particles and cleaned. The penetrometer shall be cleaned before storage.

B.1.4 Pore pressure measuring system

If pore pressure measurements are carried out, the filter should have sufficient permeability for a satisfactory response (see 4.6.1). The pore pressure system should be completely saturated before the penetration starts, and this saturation should be maintained until the cone penetrometer reaches the groundwater-surface or saturated soil. For maintenance intervals, see Table B.1.

Before each test, the filter shall be checked visually for damage, wear and clogging. Preferably before each test, the filter should be replaced and the saturation procedure should be carried out.

B.1.5 Maintenance procedures

For maintenance and calibration of the equipment, the check scheme in Table B.1 shall be followed, along with any additional manufacturer's requirements for the particular equipment.

Table B.1 — Control scheme for maintenance routines

Checking routine	Start of test	End of test	Every twelve months
Penetrometer:			
Calibration	–	–	x[a]
Reference readings	x	x	–
Filter element	x	x	–
Wear	x	x	–
Gaps and seals	x	x	–
Thrust machine and rods:			
Depth sensor	–	–	x
Penetration rate sensor	–	–	x
Verticality of thrust machine	x	–	–
Pushrods	x	–	–

[a] At intervals, see 5.1.2.

B.2 Calibration and verification of cone penetrometer

B.2.1 Environment and preparation

The calibration and verification of cone penetrometer sensors shall be performed in a calibration laboratory that meets the requirements of ISO/IEC 17025.

The calibration and measurements of cone penetrometer sensors (cone resistance, sleeve friction, pore pressure and inclination) shall be performed at a stable temperature to within ±1 °C. This temperature shall be within the range 18 °C to 28 °C and shall be recorded to an uncertainty of < 1 °C at ≥ 0,01 Hz.

Enough time shall be allowed for the cone penetrometer to attain a stable temperature at the calibration laboratory.

Calibration and verification shall be conducted on a fully assembled cone penetrometer, including all components, seals and embedded software (systems). The cone penetrometer shall be clean prior to calibration and verification.

B.2.2 Measuring intervals for calibration

The measuring intervals for calibration of the sensors of the cone penetrometer should be selected to cover the measuring intervals of interest. The measuring intervals should include zero load. Considerations for the measuring intervals of interest include expected ground conditions and operational setting.

A measuring interval of interest of 0 °C to 15 °C is typically selected for calibration of inclination.

B.2.3 Cone resistance and sleeve friction calibration

B.2.3.1 General

The calibration of cone resistance and sleeve friction shall be conducted using a frame allowing vertical clamping of a cone penetrometer and the application of axial force, F_r, to the cone and the friction sleeve. The reference can consist of a loadcell or dead weight capable of measuring axial force F_r. The data acquisition unit(s) shall be able to record the output of the force reference and the output of the cone penetrometer.

B.2.3.2 Test method

The test method shall be as follows.

a) Record reference cone resistance force F_{rqc} (or reference sleeve friction force F_{rfs}), cone resistance force output F_{qc} and the sleeve friction force output F_{fs} and, where applicable, apparent pore pressure u_a throughout the test at ≥ 1 Hz. For subtraction cone penetrometers, values for F_{fs} shall be determined as $F_{fs} = F_{qc+fs}$, where F_{qc+fs} is the force output of the combined cone resistance and sleeve friction load cell.

b) Place the cone penetrometer vertically.

c) Commence warm up by connecting the cone penetrometer to a power supply and maintain the cone penetrometer at zero load until variation of F_{qc} is less than 3 kPa per 100 s and the variation of F_{fs} is less than 0,2 kPa per 100 s.

d) Perform pre-loading of the cone penetrometer, consisting of the application of the maximum calibration force F_N at least three times and returning to F_{rqc} = 0 after every application. The duration of the application of each pre-load shall be between 60 s and 90 s.

   For a compression type cone penetrometer [see Figure 1 a)], it is necessary to perform pre-loading separately for the cone and the friction sleeve.

e) Maintain a waiting period of at least 30 s after completion of the pre-loading part of the test method.

f) Commence the calibration of the cone resistance sensor at F_{rqc} = 0 and then apply F_{rqc} by increasing load steps covering the measuring interval for calibration. The values of F_{qc} of the first series (i = 1), taken at a reference angle θ = 0° are denoted deflection X_1 (see Figure B.1).

   NOTE 1 A deflection is defined as the difference between a reading under force and the reading without force taken prior to the commencement of each load step sequence.

g) Reduce F_{rqc} to zero load condition and maintain a waiting period of at least 30 s. Apply an identical loading series and waiting period after returning to zero load at the same reference angle θ = 0°. The values of F_{qc} of this series (i = 2) are denoted X_2 (see Figure B.1).

NOTE 2 Recorded values of F_{rqc} can be negative at zero load condition.

h) Apply at least two further series of consecutive increasing and decreasing load steps at θ = 120° and θ = 240°. The values of F_{qc} are denoted X_3 for the loading series and X'_4 for the unloading series at θ = 120° and denoted X_5 and X'_6 at θ = 240° (see Figure B.1); maintain a waiting period of at least 30 s after each series.

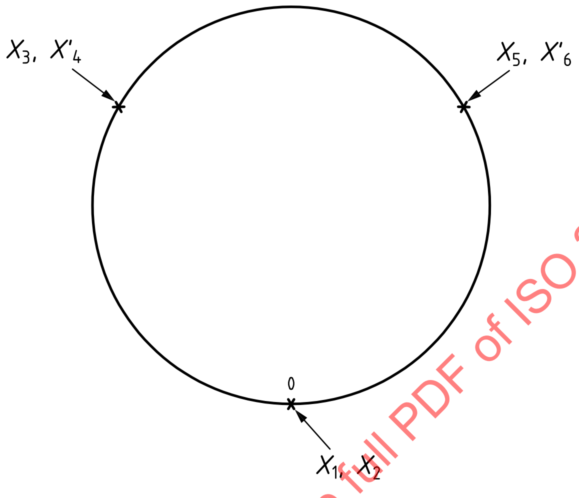


Figure B.1 — Positions of the cone penetrometer

i) Commence the calibration of the sleeve friction sensor at F_{fs} = 0 and then apply F_{rfs} to the friction sleeve, by increasing load steps covering the measuring interval for calibration. The values of F_{fs} of the first series (i = 1), taken at a reference angle θ = 0° are denoted X_1 (see Figure B.1).

j) Reduce F_{rfs} to zero load conditions and maintain a waiting period of at least 30 s. Apply an identical loading series and waiting period after returning to zero at the same reference angle θ = 0°. The values of F_{fs} of this series (i = 2) are denoted X_2 (see Figure B.1).

k) Apply at least two further series of consecutive increasing and decreasing load steps at θ = 120° and θ = 240°. The values of F_{fs} are denoted X_3 for the loading series and X'_4 for the unloading series at θ = 120° and denoted X_5 and X'_6 at θ = 240° (see Figure B.1); maintain a waiting period of at least 30 s after each series.

A waiting period of at least 3 min between subsequent measurement series shall be maintained.

Records shall be made of each $F_{rqc,}$ F_{qc}, F_{rfs}, F_{fs}, where applicable, for each force step.

The number of load steps, F_r, recorded for each increasing series and decreasing series shall not be less than one hundred. These loads shall be distributed uniformly over the measuring interval(s) for calibration. An interpolation for F_{qc} and an interpolation formula for F_{fs} shall be determined by a statistical best-fit of all the deflections X and X' within the respective measuring intervals for calibration.

NOTE 3 For calibration of cone resistance and sleeve friction, a statistical weighting method can be applied to reduce bias for increasing axial forces versus decreasing axial forces applied to the cone penetrometer during calibration.

B.2.3.3 Assessment of calibration uncertainty

The assessment of calibration uncertainty shall be according to Formulae (B.5) to (B.21), except that U_{fs} shall be determined according to a formula similar to Formula (B.5), if all of the following applies:

- calibration of f_s for a subtraction type cone penetrometer;
- F_r is applied to the cone and thus indirectly to the force sensor for combined axial force on the cone and friction sleeve.

The formula similar to Formula (B.5):

- shall be according to the evaluation of measurement uncertainty given in ISO/IEC 17025:2017, particularly subclause 7.6;
- shall incorporate $k=2$ and shall take account of subtraction dependencies for f_s;
- shall be included in the calibration report.

The expanded measurement uncertainty for the calibration U_c (denoted as U_{cqc} for cone resistance and U_{cfs} for sleeve friction) shall be calculated using a coverage factor, k, equal to 2 for each value of F_r according to Formula (B.5):

$$U_c = (u_{c,dim} / S) \times k \tag{B.5}$$

where $u_{c,dim}$ is the combined standard uncertainty of u_c and u_{dim} according to Formula (B.6):

$$u_{c,dim} = \sqrt{(u_c)^2 + ((u_{dim} \times F_r)/S)^2} \tag{B.6}$$

where

u_{dim} is equal to u_{Ac} for q_c, and equal to u_{As} for f_s as defined below;

S is equal to A_c for q_c, and equal to A_s for f_s;

F_r is F_{rqc} corresponding to each load step (or F_{rfs} corresponding to each load step);

u_c is the combined standard uncertainty for calibration.

$$u_c = \sqrt{\sum_{i=1}^{8} u_i^2} \tag{B.7}$$

The parameter U_{class} (denoted as $U_{qc:class}$ for cone resistance and $U_{fs:class}$ for sleeve friction) for the cone class statement of conformity shall be calculated for each value of F_r according to Formula (B.8), except that $U_{fs:class}$ shall be determined according to a formula similar to Formula (B.8), if all of the following applies:

- calibration of f_s for a subtraction type cone penetrometer;
- F_r is applied to the cone and thus indirectly to the force sensor for combined axial force on the cone and friction sleeve.

The formula similar to Formula (B.8):

- shall be according to the evaluation of measurement uncertainty given in ISO/IEC 17025:2017, particularly subclause 7.6;
- shall incorporate $k=2$ and shall take account of subtraction dependencies for f_s;

— may omit u_1;

— shall be included in the calibration report.

$$U_{\text{class}} = \frac{2}{S} \times \sqrt{\sum_{i=2}^{8} u_i^2} \tag{B.8}$$

Uncertainty contributions u_i shall be calculated as follows.

— u_1 is the standard uncertainty associated with the reference force F_r, expressed in units of force;

— u_2 is the standard uncertainty associated with reproducibility of the calibration results.

$$u_2 = \left|\frac{F_N}{X_N}\right| \times \sqrt{\frac{1}{6} \times \sum_{i=1,3,5} \left(X_i - \overline{X_r}\right)^2} \tag{B.9}$$

where

F_N is the range between maximum and the minimum value of F_{rqc} (or F_{rfs}) for the selected measuring interval for calibration;

X_N is the value of F_{qc} (or F_{fs}) corresponding to F_N;

X_i is F_{qc} (or F_{fs}) for a selected value of F_r (each load step) from series i;

$\overline{X_r}$ is the average of the values of X_i:

$$\overline{X_r} = \frac{X_1 + X_3 + X_5}{3} \tag{B.10}$$

NOTE Linear interpolation can be used if averaging requires use of slightly different values for data pairs of X_i and F_r.

— u_3 is the standard uncertainty associated with repeatability.

$$u_3 = \left|\frac{b' \times F_r}{\sqrt{3}}\right| \tag{B.11}$$

where b' is the repeatability error without rotation.

$$b' = \left|\frac{X_2 - X_1}{\overline{X_{wr}}}\right| \tag{B.12}$$

where $\overline{X_{wr}}$ is the average of the values of X_i without rotation.

$$\overline{X_{wr}} = \frac{x_1 + x_2}{2} \tag{B.13}$$

If $\overline{X_{wr}} = 0$, then u_3 may be set to zero.

— u_4 is the standard uncertainty associated with resolution.

$$u_4 = \frac{r}{\sqrt{6}} \tag{B.14}$$

where r is the resolution of the sensor.

— u_5 is the standard uncertainty associated with zero drift.

$$u_5 = \max_{1\le i\le 6}\left|\frac{i_{fi} - i_{0i}}{X_N} \times F_r\right| \tag{B.15}$$

where

i_{fi} is X_i corresponding to $F_r = 0$ after applying a series i;

i_{0i} is X_i corresponding to $F_r = 0$ before applying a series i.

If the lowest value of F_r for the measuring interval for calibration is greater than zero, then values for i_{fi} and i_{0i} may be adjusted accordingly.

— u_6 is the standard uncertainty associated with interpolation.

$$u_6 = \left|\frac{\overline{X_r} - X_a}{\overline{X_r}} \times F_r\right| \tag{B.16}$$

where X_a is the computed value of deflection calculated from the interpolation formula.

If $\overline{X_r} = 0$, then u_6 may be set to zero.

— u_7 is the standard uncertainty associated with reversibility.

$$u_7 = \frac{v \times |F_r|}{\sqrt{3}} \tag{B.17}$$

where v is the relative reversibility error of the sensor.

$$v = \frac{v_1 + v_2}{2} \tag{B.18}$$

$$v_1 = \left|\frac{X_4' - X_3}{X_3}\right| \tag{B.19}$$

$$v_2 = \left|\frac{X_6' - X_5}{X_5}\right| \tag{B.20}$$

— u_8 is the standard uncertainty associated with apparent load transfer from other sensor.

$$u_8 = \max|F_{qc}| \; or \; \max|F_{fs}| \tag{B.21}$$

where

$\max|F_{qc}|$ is the maximum (absolute) value of F_{qc} recorded during any of the series i for calibration of sleeve friction; $\max|F_{qc}|$ applies to u_c of $q_{c;a}$;

$\max|F_{fs}|$ is the maximum (absolute) value of F_{fs} recorded during any of the series i for calibration of cone resistance; $\max|F_{fs}|$applies to u_c of $f_{s;a}$.

B.2.3.4 Calibration results

Test records shall include maximum and minimum air temperature, the interpolation formula, F_r, F_{qc} and F_{fs} and, where applicable, u_a, versus time at the recording frequency of B.2.3.1.

The calibration report shall include:

— information according to 5.1.2;

— values of A_c and A_s selected for calculation of reference cone resistance $q_{c;r}$ ($q_{c;r} = F_{rqc} / A_c$), apparent cone resistance $q_{c;a}$ ($q_{c;a} = F_{qc} / A_c$), reference sleeve friction $f_{s;r}$ ($f_{s;r} = F_{rfs} / A_s$) and apparent sleeve friction $f_{s;a}$ ($f_{s;a} = F_{fs} / A_s$);

Nominal values may be selected for A_c and A_s.

— values of F_r, F_{qc} and F_{fs} and, where applicable, u_a for at least 10 representative points evenly spread to cover the calibration measuring interval for each of the loading series and unloading for q_c;

— values of F_r, F_{fs} and F_{qc} and, where applicable, u_a for at least 10 representative points evenly spread to cover the calibration measuring interval for each of the loading and unloading series for f_s;

— graphical results of F_{qc} and F_{fs} records versus F_r;

— measurement uncertainty results u_i, u_c, u_{dim}, $u_{c,dim}$ and U_{qc} for at least 10 pairs of F_r and F_{qc} for each of the loading and unloading series for q_c; measurement uncertainty results u_i, u_c, u_{dim}, $u_{c,dim}$ and U_{fs} for at least 10 pairs of F_r and F_{fs} for each of the loading and unloading series for f_s.

The parameters F_r, F_{qc} and F_{fs} may be replaced by $q_{c;r}$, $f_{s;r}$, $q_{c;a}$, $f_{s;a}$ expressed in MPa or kPa.

B.2.4 Calibration of pore pressure sensor

B.2.4.1 General

The calibration of the cone pressure sensor shall be conducted in a pressure vessel filled with water or gas. The reference consisting of a pressure sensor shall be capable of measuring pressure u_r. A thermometer for measuring the temperature in the pressure vessel shall be used. The data acquisition unit(s) shall be able to record reference pressure, the output of the cone penetrometer sensors and temperature of the fluid in the pressure vessel.

B.2.4.2 Test method

The test method shall be as follows.

— Record the reference pressure u_r, apparent pore pressure u_a of the cone penetrometer, cone resistance force output F_{qc} and sleeve friction force output F_{fs} throughout the calibration at ≥ 1 Hz.

  The parameters F_{qc} and F_{fs} may be replaced by $q_{c;a}$, $f_{s;a}$ expressed in MPa or kPa, where apparent cone resistance is $q_{c;a} = F_{qc} / A_c$ and apparent sleeve friction is $f_{s;a} = F_{fs} / A_s$.

— Place the cone penetrometer at atmospheric pressure in the pressure vessel ensuring that the cone penetrometer is not in contact with the pressure vessel except above the friction sleeve.

— Apply two pressure cycles. For each cycle, apply u_r in the pressure vessel in a series of increasing pressure steps covering the measuring interval for calibration. One pressure step shall be placed at $u_r = 2$ MPa to allow the determination of net area ratios according to B.2.4.4. Once the maximum pressure has been reached follow with a series of identical pressure steps in decreasing order. Records of u_r, u_a, F_{qc} and F_{fs} shall be taken for each pressure step. A waiting period of at least 3 min shall apply between subsequent cycles.

— After completion of the two cycles, reduce the pressure in the vessel to atmospheric pressure and continue recording of u_a for at least 30 s.

  For the first pressure cycle, the deflections from the pore pressure sensor recorded in the increasing pressure series (i = 1) are denoted X_1. The deflections recorded in decreasing series (i = 2) are denoted X'_2. The deflections for the second pressure cycle are denoted X_3, X'_4 for the increasing and decreasing pressure series respectively.

  NOTE A deflection is defined as the difference between a reading under pressure and a reading without pressure taken prior to the commencement of each cycle.

The number of reference pressure steps, u_r, recorded for each increasing series and decreasing series shall not be less than twenty. An interpolation formula shall be determined by a statistical best-fit of all the deflections X and X' within the measuring interval for calibration.

B.2.4.3 Assessment of calibration uncertainty

The expanded measurement uncertainty (U_u) for each value of u_r shall be calculated using a coverage factor, k, equal to 2 and according to Formula (B.22):

$$U_u = k \times \sqrt{\sum_{i=1}^{6} u_i^2} \tag{B.22}$$

The measurement uncertainty, $U_{u:\text{class}}$ for the cone class statement of conformity shall be calculated for each value of u_r according to Formula (B.23):

$$U_{u:\text{class}} = 2 \times \sqrt{\sum_{i=2}^{6} u_i^2} \tag{B.23}$$

Uncertainty contributions u_i shall be calculated as follows.

— u_1 is the standard uncertainty associated with the reference pressure u_r, expressed in units of pressure;

— u_2 is the standard uncertainty associated with repeatability.

$$u_2 = \left| \frac{b' \times u_r}{\sqrt{3}} \right| \tag{B.24}$$

where b' is the repeatability error.

$$b' = \left| \frac{X_3 - X_1}{\overline{X_{1,3}}} \right| \tag{B.25}$$

X_i is the deflection from series i;

$\overline{X_{1,3}}$ is the mean value if the deflections.

$$\overline{X_{1,3}} = \frac{X_1 + X_3}{2} \tag{B.26}$$

If $\overline{X_{1,3}}$ = 0, then u_2 may be set to zero.

— u_3 is the standard uncertainty associated with resolution.

$$u_3 = \frac{r}{\sqrt{6}} \tag{B.27}$$

where r is the resolution of the sensor.

— u_4 is the standard uncertainty associated with zero drift.

$$u_4 = \max_{i=1,2,3,4} \left| \frac{i_{fi} - i_{0i}}{X_N} \times u_r \right| \tag{B.28}$$

where

i_{fi} is X_i at u_r = 0 after applying a series (i);

i_{0i} is X_i at $u_r = 0$ before applying a series (i);

X_N is the value of u_a corresponding to the maximum calibration pressure.

If the lowest value of u_r for the measuring interval for calibration is greater than zero, then values for i_{fi} and i_{0i} may be adjusted accordingly.

— u_5 is the standard uncertainty associated with interpolation.

$$u_5 = \left| \frac{\overline{X_{1,3}} - X_a}{\overline{X_{1,3}}} \times u_r \right| \tag{B.29}$$

where X_a is the computed value of deflection calculated from the interpolation formula.

If $\overline{X_{1.3}} = 0$, then u_5 may be set to zero.

— u_6 is the standard uncertainty associated with reversibility.

$$u_6 = \frac{v \times |u_r|}{\sqrt{3}} \tag{B.30}$$

where

$$v = \frac{v_1 + v_2}{2} \tag{B.31}$$

$$v_1 = \left| \frac{X'_2 - X_1}{X_1} \right| \tag{B.32}$$

$$v_2 = \left| \frac{X'_4 - X_3}{X_3} \right| \tag{B.33}$$

B.2.4.4 Determination of net area ratios

The net area ratio of the cone a and the net area ratio of the friction sleeve b shall be computed using the formulae $a = q_{c;a} / u_r$ and $b = f_{s;a} / u_r$ at reference pressure $u_r = 2$ MPa. The net area ratios should be computed with the mean values of $q_{c;a}$ and $f_{s;a}$ for the two cycles.

B.2.4.5 Calibration results

Test records shall include maximum and minimum temperature of the fluid in the pressure vessel, the interpolation formula, u_r, u_a, $q_{c;a}$, and $f_{s;a}$ versus time at the recording frequency of B.2.4.2.

The calibration report shall include:

— information according to 5.1.2;

— graphical results of all u_a records versus u_r;

— values of A_c and A_s selected for calculation of $q_{c;a}$ and $f_{s;a}$;

NOTE Nominal values can be selected for A_c and A_s.

— values of u_r, u_a, $q_{c;a}$, and $f_{s;a}$ for at least 10 pressure steps of each pressure series;

— measurement uncertainty results u_i, u_c, and U_u for at least 10 pairs of u_r and u_a for each of the pressure series;

— graphical results of u_a records versus u_r;

— values of net area ratio a for cone resistance and b for sleeve friction.

B.2.5 Determination of cone and friction sleeve dimensions

B.2.5.1 General

The dimensional measurement shall be conducted with a measuring device with an expanded measurement uncertainty lower than 0,05 mm. A thermometer for measuring ambient air temperature shall be used. Air temperature variations throughout the test shall not exceed ±3 °C.

B.2.5.2 Test method

The test method shall be as follows.

— Measure and record the diameter of the cylindrical (steel) part of the cone $d_{c;0}$ at rotational position $\theta = 0^o$ of the cone penetrometer, $d_{c;120}$ at $\theta_{120} = 120^o$ and $d_{c;240}$ at $\theta_{240} = 240^o$.

— Measure and record the diameter of the filter element $d_{fil;0}$, $d_{fil;120}$ and $d_{fil;240}$, as for $d_{c;0}$, $d_{c;120}$ and $d_{c;240}$.

  The radial distance between the outer surface of the filter element and the steel immediately above and below the filter element may be recorded at θ_0, θ_{120} and θ_{240} for a u_1 filter element.

— Measure and record the diameter of the lower one fifth of the friction sleeve $d_{2l;0}$, $d_{2l;120}$ and $d_{2l;240}$, as for $d_{c;0}$, $d_{c;120}$ and $d_{c;240}$.

— Measure and record the diameter of the middle one fifth of the friction sleeve $d_{2m;0}$, $d_{2m;120}$ and $d_{2m;240}$, as for $d_{c;0}$, $d_{c;120}$ and $d_{c;240}$.

— Measure and record the diameter of the upper one fifth of the friction sleeve $d_{2u;0}$, $d_{2u;120}$ and $d_{2u;240}$, as for $d_{c;0}$, $d_{c;120}$ and $d_{c;240}$.

— Measure and record the height of the conical section $h_{c;0}$ at rotational position $\theta_0 = 0^o$ of the cone penetrometer, $h_{c;120}$ at $\theta_{120} = 120^o$ and $h_{c;240}$ at $\theta_{240} = 240^o$.

— Measure and record the length of the cylindrical extension of the cone $h_{e;0}$, $h_{e;120}$ and $h_{e;240}$, as for $h_{c;0}$, $h_{c;120}$ and $h_{c;240}$.

  Values for $h_{e;0}$, $h_{e;120}$ and $h_{e;240}$ may be derived from distance measurements relative to a vertical datum.

— Measure and record the length of the gap between the cylindrical part of the cone and the lower end of the friction sleeve $l_{gl;0}$, $l_{gl;120}$ and $l_{gl;240}$, as for $h_{c;0}$, $h_{c;120}$ and $h_{c;240}$.

— Measure and record the length of the friction sleeve $l_{s;0}$, $l_{s;120}$ and $l_{s;240}$, as for $h_{c;0}$, $h_{c;120}$ and $h_{c;240}$.

— Measure and record the length of the gap above the upper end of the friction sleeve $l_{gu;0}$, $l_{gu;120}$ and $l_{gu;240}$, as for $l_{gl;0}$, $l_{gl;120}$ and $l_{gl;240}$.

B.2.5.3 Assessment of dimensional uncertainty

Expanded measurement uncertainty shall be determined using a coverage factor k equal to 2 and according to Formulae (B.34) and (B.35):

$$U_{Ac} = k \times u_{Ac} \tag{B.34}$$

$$U_{\mathrm{As}} = k \times u_{\mathrm{As}} \quad \text{(B.35)}$$

u_{Ac} is the combined standard uncertainty for the cross-sectional area of the cone:

$$u_{\mathrm{Ac}} = 0{,}5 \times \pi \times u_{\mathrm{dc}} \times d_{\mathrm{c}} \quad \text{(B.36)}$$

where u_{dc} is the combined standard uncertainty for cone diameter:

$$u_{\mathrm{dc}} = \sqrt{\left(\frac{b_{\mathrm{c}} \times d_{\mathrm{c}}}{\sqrt{3}}\right)^2 + u_{ref}^2} \quad \text{(B.37)}$$

where

$$b_{\mathrm{c}} = \frac{\max\limits_{\theta=0,120,240} \left| d_{\mathrm{c},\theta} - d_{\mathrm{c}} \right|}{d_{\mathrm{c}}} \quad \text{(B.38)}$$

$$d_{\mathrm{c}} = (d_{\mathrm{c};0} + d_{\mathrm{c};120} + d_{\mathrm{c};240}) / 3; \quad \text{(B.39)}$$

u_{ref} is the standard uncertainty of the reference measuring device;

u_{As} is the combined standard uncertainty for the area of the friction sleeve:

$$u_{\mathrm{As}} = \pi \times \sqrt{(u_{\mathrm{d2}} \times l_{\mathrm{s}})^2 + (u_{\mathrm{ls}} \times d_2)^2} \quad \text{(B.40)}$$

where u_{ls} is the combined standard uncertainty for length of the friction sleeve:

$$u_{\mathrm{ls}} = \sqrt{\left(\frac{b_{\mathrm{ls}} \times l_s}{\sqrt{3}}\right)^2 + u_{ref}^2} \quad \text{(B.41)}$$

where

$$b_{\mathrm{ls}} = \frac{\max\limits_{\theta=0,120,240} \left| l_{s,\theta} - l_s \right|}{l_{\mathrm{s}}} \quad \text{(B.42)}$$

$$l_{\mathrm{s}} = (l_{\mathrm{s};0} + l_{\mathrm{s};120} + l_{\mathrm{s};240}) / 3; \quad \text{(B.43)}$$

u_{d2} is the combined standard uncertainty for diameter of the friction sleeve:

$$u_{d2} = \sqrt{\left(\frac{b_{c2} \times d_2}{\sqrt{3}}\right)^2 + u_{ref}^2} \quad \text{(B.44)}$$

where

$$b_{\mathrm{c2}} = \frac{\max\limits_{\theta=0,120,240;k=l,m,u} \left| d_{2k,\theta} - d_2 \right|}{d_2} \quad \text{(B.45)}$$

$$d_2 = ((d_{2\mathrm{l};0} + d_{2\mathrm{l};120} + d_{2\mathrm{l};240}) + (d_{2\mathrm{m};0} + d_{2\mathrm{m};120} + d_{2\mathrm{m};240}) + (d_{2\mathrm{u};0} + d_{2\mathrm{u};120} + d_{2\mathrm{u};240})) / 9; \quad \text{(B.46)}$$

B.2.5.4 Test results

Test records shall include tabular results of the measured values of diameter, height, length versus rotational position.

The test report shall include, where applicable:

— information according to 5.1.2;

— cone diameter d_c;

— cross-sectional area of the cone A_c in mm^2, determined by Formula (B.47):

$$A_c = 0{,}25 \times \pi \times d_c^2; \tag{B.47}$$

— cone area uncertainties $u_{Ac,}$ and U_{Ac};

— values for diameter of the filter element d_{fil}, diameter of the lower one fifth of the friction sleeve d_{2l}, diameter of the middle one fifth of the friction sleeve d_{2m} and diameter of the upper one fifth of the friction sleeve d_{2u}, determined as described for d_c;

— diameter of the friction sleeve d_2 in mm;

— vertical height of the cone h_c in mm, determined by Formula (B.48):

$$h_c = (h_{c;0} + h_{c;120} + h_{c;240}) \;/\; 3; \tag{B.48}$$

— length of the cylindrical part of the cone h_e, length of the gap between the cylindrical part of the cone and the lower end of the friction sleeve l_{gl}, length of the friction sleeve l_s, and length of the gap above the upper end of the friction sleeve l_{gu}, determined as described for h_c;

— area of the friction sleeve A_s in mm^2, determined by Formula (B.49):

$$A_s = \pi \times d_2 \times l_s; \tag{B.49}$$

— friction sleeve area uncertainties u_{As} and U_{As}.

B.2.6 Calibration of a cone penetrometer for inclination

B.2.6.1 General

The calibration of the cone penetrometer shall be conducted in a frame capable of clamping the cone penetrometer in a range of spatial reference points with the aid of a reference inclinometer, namely for vertical reference inclination (i_r = 0°), ≤ 5° increments of i_r, 0° rotation (θ_0) and 90° rotation (θ_{90}). The minimum measuring interval for calibration shall be 0° to 15° from vertical. A thermometer for measuring ambient air temperature shall be used. Air temperature variations throughout the test shall not exceed ±3 °C. The data acquisition unit(s) shall be able to record the output of the sensor for the inclination of the cone penetrometer.

B.2.6.2 Test method

The test method shall be as follows.

— Record the reference inclination i_r for each of the spatial reference positions of the clamping frame used for calibration, using the reference inclinometer.

— Place the cone penetrometer in the clamping frame, with i_r at the maximum value of the selected measuring interval for calibration, rotate the cone penetrometer and record θ_0 as the point where i_a reaches the maximum value.

— Record i_r and i_a for θ_0, at vertical position i_r = 0° and then at increasing increments equal or lower than 5° of i_r until the selected measuring interval for calibration range is reached.

— Record i_r and i_a for θ_{90}, as for θ_0.

— Determine an interpolation formula by a statistical best-fit of all values of i_a within the measuring interval for calibration.

B.2.6.3 Assessment of inclination calibration uncertainty

The expanded measurement uncertainty (U_{inc}) for each value of i_r shall be determined using a coverage factor k equal to 2 and according to Formula (B.50):

$$U_{inc} = k \times \sqrt{\sum_{i=1}^{4} u_i^2} \qquad \text{(B.50)}$$

u_1 is the standard uncertainty associated with the reference inclinometer sensor used during the calibration expressed in degrees.

u_2 is the standard uncertainty associated with reproducibility of the calibration results.

$$u_2 = \left| \frac{F_N}{X_N} \right| \times \sqrt{\frac{1}{4} \cdot \sum_{\theta=0,90} \left(X_i - \overline{X_r} \right)^2} \qquad \text{(B.51)}$$

where

F_N is the maximum value of i_r for the selected measuring interval for calibration;

X_N is the value of i_a corresponding to F_N;

X_i is i_a for a selected value of i_r from series θ_i;

$\overline{X_r}$ is the average of the values of X_i:

$$\overline{X_r} = \frac{X_{\theta 0} + X_{\theta 90}}{2} \qquad \text{(B.52)}$$

u_3 is the standard uncertainty associated with resolution.

$$u_3 = \frac{r}{\sqrt{6}} \qquad \text{(B.53)}$$

where r is the resolution of the sensor.

u_4 is the standard uncertainty associated with interpolation.

$$u_4 = \left| \frac{\overline{X_r} - X_a}{\overline{X_r}} \times i_r \right| \qquad \text{(B.54)}$$

where X_a is the computed value of deflection calculated from the interpolation formula.

If $\overline{X_r}$ = 0, then u_4 may be set to zero.

B.2.6.4 Test results

Test records shall include tabular results of air temperature, the interpolation formula, and pairs of i_r and i_a for each of the spatial reference positions of the cone penetrometer. The test report shall include:

— information according to 5.1.2;

— maximum inclination used for calibration of the cone penetrometer;

— measurement uncertainty results U_{inc} and u_{inc} for each increment of i_r including $i_r = 0$.

The maximum value of U_{inc} shall be used for conformity assessment according to 5.1.3.

B.2.7 Verification of a cone penetrometer for temperature influence

B.2.7.1 General

The verification of a cone penetrometer for temperature influence shall be conducted in a frame capable of clamping the cone penetrometer vertically and shall include a thermal disconnection from the cone penetrometer.

The test shall include two thermostat baths. Thermostat bath 1 shall be capable of maintaining a constant temperature of fluid at 30 °C to a standard uncertainty of < 0,5 °C for the duration of the test. Thermostat bath 2 shall be capable of maintaining a constant temperature of fluid at 0 °C to a standard uncertainty of < 0,5 °C for the duration of the test. The fluid in the thermostat baths can consist of tap water or mixture of water and antifreeze; and the temperature of the fluid in each thermostat bath shall be measured by reference thermometer. Output of the cone penetrometer shall be recorded on a data acquisition unit(s). Temperatures of the fluid in the thermostat baths should be recorded on a data acquisition unit(s).

NOTE A bath containing tap water and melting ice made from tap water can serve as thermostat bath 2.

B.2.7.2 Test method

The test method shall be as follows.

— Maintain temperature of the fluid in thermostat bath 1 at 30 °C throughout the test and record actual temperature values at ≥ 0,01 Hz.

— Maintain temperature of the fluid in thermostat bath 2 at 0 °C throughout the test and record actual temperature values at ≥ 0,01 Hz.

— Record apparent cone resistance $q_{c;a}$, apparent sleeve friction $f_{s;a}$ and, where applicable, apparent pore pressure u_a and apparent temperature T_a throughout the test at ≥ 1 Hz.

— Where applicable, determine and record temperature-corrected apparent cone resistance $q_{c;ac}$, temperature-corrected apparent sleeve friction $f_{s;ac}$ and temperature-corrected apparent pore pressure u_{ac} throughout the test at ≥ 1 Hz.

  Both of the following shall apply to cone penetrometers that rely on real-time or post-processing correction for temperature influence on CPT results.

  a) recording of $q_{c;a}$, $f_{s;a}$ and, where applicable, u_a;

  b) where applicable, determining and recording of $q_{c;ac}$, $f_{s;ac}$ and u_{ac}.

  Such correction can, for example, be derived from algorithms that incorporate data acquired by a temperature sensor in the cone penetrometer.

— Place the cone penetrometer in thermostat bath 1, so that the cone penetrometer reaches a uniform temperature of 30 °C throughout, defined as the earlier of:

  a) the end of a period of 500 s when the variation of $q_{c;a}$ during that period is less than 2 kPa;

  b) one hour after the placement of the cone penetrometer in the thermostat bath.

— Thereafter, quickly transfer the cone penetrometer to thermostat bath 2, so that

  a) the apex of the cone is at least 10 mm above the bottom of the thermostat bath;

b) the fluid level of the thermostat bath coincides with the gap immediately above the friction sleeve.

— After 3 min, quickly return the cone penetrometer to thermostat bath 1.

— After 10 min, quickly return the cone penetrometer to thermostat bath 2.

— After 10 min, quickly return the cone penetrometer to thermostat bath 1.

— After 3 min, return the cone penetrometer to thermostat bath 2.

— Determine t_{end}, defined as the earlier of:

a) the start of a period of 500 s when ($q_{c;amax} - q_{c;amin}$) is less than 2 kPa, where $q_{c;amax}$ is the highest value of $q_{c;a}$ during that period and $q_{c;amin}$ is the lowest value of $q_{c;a}$ during that period;

b) one hour after the start of the last transfer.

B.2.7.3 Test results

The test records and test report shall include, where applicable:

— calibration report for the reference thermometer of thermostat bath 1 and the reference thermometer of thermostat bath 2;

— description of the apparatus and if applicable, the test method(s) for temperature correction, for cone penetrometers that rely on real-time or post-processing correction for temperature influence on CPT results;

— temperatures of the thermostat baths, $q_{c;a}$, $q_{c;ac}$, $f_{s;a}$, $f_{s;ac}$, u_a ,u_{ac} and T_a versus time at the recording frequencies of B.2.7.2;

— cross-sectional area of the cone and area of the friction sleeve used for calculation of $q_{c;a}$ and $f_{s;a}$;

— ambient temperature stability for cone resistance (Δa_{qc}) in kPa/°C, determined by $\Delta a_{qc} = |(q_{c;a30} - q_{c;a0})|/(T_{30} - T_0)$, where $q_{c;a30}$ is the value of $q_{c;a}$ at the time t_{30} immediately before the first transfer of the cone penetrometer to thermostat bath 2; $q_{c;a0}$ is the value of $q_{c;a}$ at time t_{end}; T_{30} is the temperature at t_{30}; and T_0 is the temperature at t_{end};

— ambient temperature stability for corrected cone resistance (Δa_{qcc}) in kPa/°C, determined by $\Delta a_{qcc} = |(q_{c;ac30} - q_{c;ac0})|/(T_{30} - T_0)$, where $q_{c;ac30}$ and $q_{c;ac0}$ are the values of $q_{c;ac}$ at t_{30} and t_{end}, as for Δa_q;

— ambient temperature stability for sleeve friction and corrected sleeve friction (Δa_{fs} and Δa_{fsc}) in kPa/°C and ambient temperature stability pore pressure (Δa_u and Δa_{uc}) in kPa/°C determined as described for Δa_{qc} and Δa_{qcc};

— transient temperature stability for cone resistance (Δt_{qc}) in kPa/°C, determined by $\Delta t_{qc} = |(q_{c;amax} - q_{c;amin})|/(T_{30} - T_0)$, where $q_{c;amax}$ is the highest value of $q_{c;a}$ between t_{30} and t_{end} and $q_{c;amin}$ is the lowest value of $q_{c;a}$ between t_{30} and t_{end};

— transient temperature stability for corrected cone resistance (Δt_{qcc}) in kPa/°C, determined by $\Delta t_{qcc} = |(q_{c;acmax} - q_{c;acmin})|/(T_{30} - T_0)$, where $q_{c;acmax}$ is the highest value of $q_{c;ac}$ between t_{30} and t_{end} and $q_{c;acmin}$ is the lowest value of $q_{c;ac}$ between t_{30} and t_{end};

— transient temperature stability for sleeve friction (Δt_{fs} and Δt_{fsc}) in kPa/°C and transient temperature stability for pore pressure (Δt_u and Δt_{uc}) in kPa/°C, determined as described for Δt_{qc} and Δt_{qcc}.

For cone penetrometer classes 2 and 3, the verification for temperature influence may be limited to reporting the results for 20 or more tests if the cone penetrometers are of the same design, the same type and made according to the same manufacturing and assembly process. The results for these penetrometers should all meet the decision rule for temperature influence defined in Table 1.

For cone penetrometer class 0, the test report shall additionally include, where applicable:

— variation in cone resistance (Δf_{gqc}) in kPa/s, determined by $\Delta f_{gqc} = |(q_{c;fgmax} - q_{c;fgmin})|/0,05(t_{i+20} - t_i)$, where ($q_{c;fgmax} - q_{c;fgmin}$) represents the largest difference between values of $q_{c;a}$ for any 20 s period $t_{i+20} - t_i$;

— variation in cone resistance (Δf_{gqcc}) in kPa/s, determined by $\Delta f_{gqcc} = |(q_{cc;fgmax} - q_{cc;fgmin})|/0,05(t_{i+20} - t_i)$, where ($q_{cc;fgmax} - q_{cc;fgmin}$) represents the largest difference between values of $q_{c;ac}$ for any 20 s period $t_{i+20} - t_i$;

— variation in sleeve friction (Δf_{gfs} and Δf_{gfsc}) in kPa/s and variation in pore pressure (Δf_{gu} and Δf_{guc}) in kPa/s, determined as described for Δf_{gqc} and Δf_{gqcc}.

B.2.8 Verification of a cone penetrometer for bending influence

B.2.8.1 General

The verification shall be performed in a frame capable of clamping the cone penetrometer horizontally with an independent loading device or means to apply a dead weight, capable of measuring a radial force F_r, applied at the cylindrical part of the cone, where F_r is a static force between 90 N and 110 N with a standard uncertainty of < 1 N. The data acquisition unit(s) shall record the output of the cone penetrometer. Air temperature variations throughout the test shall not exceed ±3°.

B.2.8.2 Test method

The test method shall be as follows.

— Record the cross-sectional area of the cone A_c selected for calculation of relative cone resistance $q_{c;a}$.

— Record the area of the friction sleeve A_s selected for calculation of relative sleeve friction $f_{s;a}$.

— Record $q_{c;a}$, $f_{s;a}$ and, where applicable, apparent pore pressure u_a and apparent temperature T_a throughout the test at ≥ 1 Hz.

— Place the cone penetrometer horizontally in the clamping frame, so that the horizontal distance between the point of fixity at the clamping frame and the cone is between 400 mm and 600 mm. An extension rod may be connected to the cone penetrometer to achieve the required horizontal distance.

— Apply F_r for a period of between about 5 s and 30 s and record its minimum value.

— Rotate the cone penetrometer axially in 7 increments of 45° and repeat the previous step for each increment.

B.2.8.3 Test results

Test records shall include:

— standard uncertainty for F_r;

— values of A_c and A_s selected for calculation of $q_{c;a}$ and $f_{s;a}$;

— values of $q_{c;a}$, $f_{s;a}$ and, where applicable, u_a, versus time at the recording frequency of B.2.8.2;

— values for F_r for each of the rotational positions of the cone penetrometer.

The test report shall include:

— bending influence on cone resistance (Δb_{qc}) in kPa/N, determined by $\Delta b_{qc} = (q_{c;amax} - q_{c;amin})/F_r$ for the rotational position showing the largest value for ($q_{c;amax} - q_{c;amin}$), where $q_{c;amax}$ is the highest value of $q_{c;a}$ and $q_{c;amin}$ is the lowest value of $q_{c;a}$ for the following measuring sequence: unloaded → F_r → unloaded;

— bending influence on sleeve friction (Δb_{fs}) and bending influence on pore pressure (Δb_u), determined as described for Δb_{qc}.

For cone penetrometer classes 2 and 3, the verification for bending influence may be limited to reporting the results for 20 or more tests if the cone penetrometers are of the same design, the same type and made according to the same manufacturing and assembly process. The results for these penetrometers should all meet the decision rule for bending influence as defined in Table 2.

Annex C
(informative)

Calibration report example

C.1 General

The calibration report aims to provide additional clarity regarding the presentation of calibration results. It should be noted that this example partially fulfils the requirements of Annex B. For example, shortening led to omission of some of the required reporting for calibrations.

Calibration Report

Calibration Laboratory Prof. De Beer Limited; 10, Macallan street. London

Calibration tests were performed at Calibrations Limited calibration laboratory facility in London. (Testing Laboratory No.9999).
This report refers to results of calibration tests performed on a cone penetrometer including dimensions verification, cone resistance calibration, sleeve friction calibration, pore pressure calibration, inclination calibration, verification of temperature influence and verification of bending influence.
The cone penetrometer was calibrated on behalf of Site Investigations Limited (contact: technical.enquires@siteinvestigations.com)
Prof. De Beer Limited laboratory methodologies and management system conforms with ISO17025 and ISO22476-1 requirements for calibration.
The measurements and references are metrologically trazable in accordance with ISO 17025 requirements.

Accredited by XXXX

Calibrated Instrument		Cone Sensors	Calibration Interval	Maximum Rating	Sensor Classification
Description	CPTU probe (4 sensors)	**Cone**	0 to 80 MPa	120	Class 0
Manufacturer	SCJKT	**Sleeve friction**	0 to 0.7 MPa	1.5	Class 0
Type	Compression	**Pore pressure**	0 to 10 MPa	10	Class 1
Serial number	775241	**Inclinometer**	0 to 20°	40°	
Condition	Used and serviced with new	**Temperature**	0 to 70 °C	90 °C	

The calibration report presented here demonstrates that this instrument conforms with the requirements for a cone penetrometer class 1 as set out by ISO 22476-1 if temperature corrections are applied to the measured results. And conforms with cone penetrometer class 2 when no temperature influence corrections are applied. The results relate only to the calibration of the cone penetrometer with serial number 775241.

Calibration test	Performed by	Date	Approved by	Date
Calibration report	JD	19/04/2022	SS	20/04/2022
Calibration certificate	JD	19/04/2022	SS	20/04/2022
Number of pages in report	9			

Reference standard	Manufacturer	Type	Serial No.	Combined Standard Uncertainty	
Force Reference 1 (F_{rqc})	BHM	C120	1001	$0{,}00009F_{rqc} + 0{,}00030$	(kN)
Force reference 2 (F_{rfs})	BHM	C5	1583	$0{,}00025F_{rfs} + 0{,}00055$	(kN)
Pressure reference (u_r)	BHM	P20	3210	$0{,}00004u_r + 7{,}00000$	(kPa)
Calliper reference (u_r)	BHM	C450	58620	0,05	(mm)
Inclinometer (u_i)	BHM	I438	54126	0,00472I + 0,00417	°
Temperature (T_r)	SCJKT	TC	10144	0,01	° C

Calibration Conditions

Ambient temperature	22 ± 1 °C
Environmental Humidity	30 ± 3 rel.
Atmospheric Pressure	100,1 ± 0,2 kPa

Calibration Method

The calibration was performed according to ISO 22476-1 and ISO 17025 requirements for calibration of cone penetrometers. The uncertainty evaluation for each of the calibrated sensors has been carried out in accordance with ISO 22476-1 requirements.

This calibration report documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).

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