International Society for Soil Mechanics
and Geotechnical Engineering (ISSMGE)

International Reference Test Procedure for the Cone Penetration Test (CPT) and the Cone Penetration Test with pore pressure (CPTU)

Report of the ISSMGE
Technical Committee 16
on
Ground Property Characterisation from In-situ Testing

1999 (corrected 2001)

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Soil Characterisation by In Situ Tests:
International Reference Test Procedure for CPT/CPTU

This report contains the International Reference Test Procedure (IRTP) for the Cone Penetration Test (CPT) and the Cone Penetration Test with pore pressure (CPTU). The report was prepared by a working Group of ISSMGE Technical Committee 16, 'Ground Characterisation from In Situ Testing'. The following persons from the working group compiled the document:

Tom Lunne, Norwegian Geotechnical Institute (NGI), Norway
John Powell, Building Research Establishment (BRE), UK
Joek Peuchen, Fugro, Holland
Rolf Sandven, NTNU, Norway
Martin van Staveren, Delft Geotechnics, Holland

Several other members of the working group contributed by commenting on the document.

ABSTRACT: The Cone Penetration Test (CPT) consists of pushing a cone penetrometer using a series of push rods 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 at or close to the cone. The test results may be used for interpretation of stratification, classification of soil type and evaluation of engineering soil parameters. This report presents the recommended guidelines for test equipment, field procedures and presentation of test results. In addition, recommendations for required accuracy, calibration routines and maintenance procedures are outlined. The recommendations are meant to replace international reference test procedures (IRTP) recommended by the International Society for Soil Mechanics and Foundation Engineering (ISSMFE) in 1989 for the electrical CPT/CPTU. This is not a standard but a set of recommendations for good practice. These are meant to form the basis of future efforts for national/international standardisation. For the mechanical CPT the 1989 version will still be valid.

CONTENTS

1 INTRODUCTION

Two categories of the cone penetration test are considered.

1. The electric cone penetration test (CPT) which includes measurement of cone resistance and sleeve friction.
2. The piezocone test (CPTU) which is a cone penetration test with the additional measurement of pore pressure.

Note: This document may also be used for CPT/CPTU without measurement of sleeve friction.

The CPT is performed with a cylindrical penetrometer with a conical tip, or cone, penetrating into the ground at a constant rate of penetration. During penetration, the forces on the cone and the friction sleeve are measured.

The CPTU is performed as the CPT but with the additional measurement of the pore pressure at one or several locations on the penetrometer surface.

Note: Usually, the measurements are carried out using electronic transfer and data logging, with a measurement frequency that can secure detailed information about the soil conditions.

The results from a cone penetration test can in principle be used to evaluate:

- stratification
- soil type
- soil density and in situ stress conditions
- mechanical soil properties
  - shear strength parameters
  - deformation and consolidation characteristics

Note: The results from cone penetration tests may also be used directly in design e.g. pile foundations, liquefaction potential (e.g. Lunne et al. 1997).

Cone penetration testing with pore pressure measurements (CPTU) gives a more reliable determination of stratification and soil type than standard CPT. In addition, CPTU gives a better basis for interpretation of the results in terms of mechanical soil properties.

The purpose of this reference test procedure is to establish definitions and requirements for equipment and test method, which will lead the users to employ the same procedures on an international basis.

The reference test procedure is to a large extent based on testing procedures and guidelines given by the ISSMFE Technical Committee on Penetration Testing (1989) but is updated to include details on measurements of pore pressure i.e. the CPTU. This is not a standard but a set of recommendations for good practice. These are meant to form the basis of future efforts for national/international standardisation. For the mechanical CPT the 1989 version will still be valid.

Note: It is permitted to deviate from the requirements of this document if it can be demonstrated that the deviation(s) in results are not significantly different compared to results of the tests following the IRTP given herein.

2 DEFINITIONS

2.1 *Cone penetration test*

The pushing of a cone penetrometer at the end of a series of cylindrical push rods into the ground at a constant rate of penetration.

2.2 *Cone penetrometer*

The cone penetrometer is the assembly containing the cone, friction sleeve, any other sensors and measuring systems as well as the connection to the push rods. Figure 2.1 shows a section through an example of a cone penetrometer.

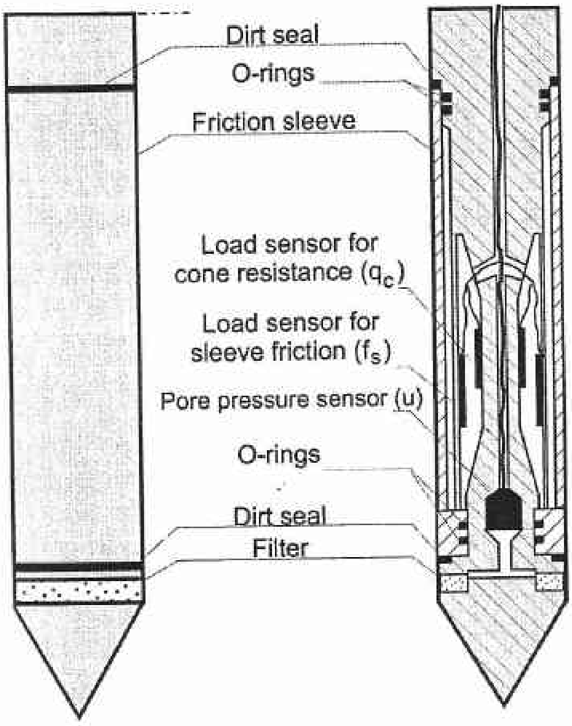

Figure 2.1 Section through an example of a cone penetrometer

The cone penetrometer includes internal load sensors for measurement of force against the cone (cone resistance), side friction against the friction sleeve (sleeve friction) and if applicable pore pressure at one or several locations on the surface of the cone penetrometer. An internal inclinometer is included for measurement of the penetrometer inclination to meet the requirements of the accuracy classes 1, 2 and 3 as given in Table 5.2.

Note: Other sensors can be included in the cone penetrometer.

2.3 *Cone*

The cone has an apex angle of 60° and forms the bottom part of the cone penetrometer. When pushing the penetrometer into the ground, the cone resistance is transferred through the cone to the load sensor.

Note: In this document it is assumed that the cone is rigid, so that its relative deformation when loaded is very small compared to other parts of the cone penetrometer.

2.4 *Friction sleeve*

The friction sleeve is the section of the cone penetrometer upon which the sleeve friction is measured.

2.5 *Filter element*

The filter element is the porous element inserted into the cone penetrometer to allow transmission of the pore pressure to the pore pressure sensor, while maintaining the correct geometry of the cone penetrometer.

2.6 *Measuring system*

The measuring system includes all sensors and ancillary parts which are used to transfer and/or store the electrical signals which are generated during the cone penetration test. The measuring system normally includes components for measuring force (cone resistance, friction), pressure (pore pressure) and depth.

2.7 *Push rods*

The push rods are a string of rods for transfer of compressive and tensile forces to the cone penetrometer.

> Note: The push rods can also be used for supporting and/or protecting parts of the measuring system. With acoustic transfer of sounding results the rods are also used for transmission of data.

2.8 *Thrust machine*

The thrust machine is the equipment which pushes the cone penetrometer and rods into the ground along a vertical axis at a constant rate of penetration.

> Note: Required reaction for the thrust machine may be supplied by dead weights and/or soil anchors.

2.9 *Penetration depth and length*

Penetration depth: Depth of the base of the cone, relative to a fixed horizontal plane (Figure 2.2).
Penetration length: Sum of the length of the push rods and the cone penetrometer, reduced by the height of the conical part, relative to a fixed horizontal plane (Figure 2.2).

> Note: The fixed horizontal plane usually corresponds with a horizontal plane through the (underwater) ground surface at the location of the test.

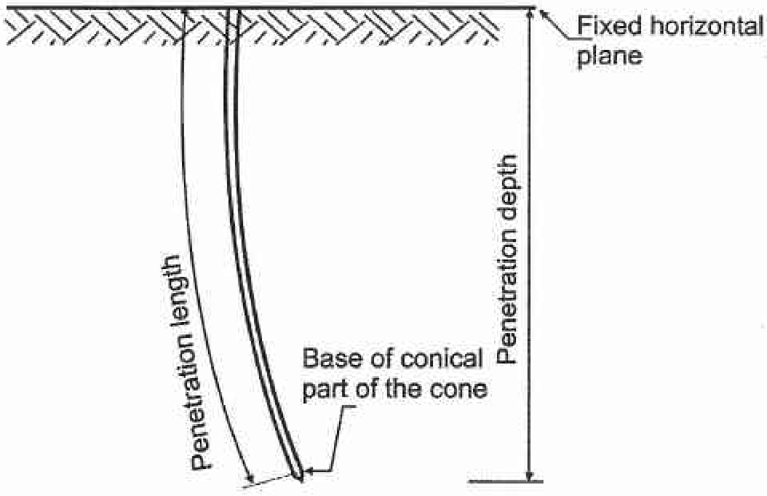

Figure 2.2 Penetration length and penetration depth

2.10 *Friction reducer*

A friction reducer consists of a local and symmetrical enlargement of the diameter of a push rod to obtain a reduction of the friction along the push rods.

2.11 *Cone resistance, q_c*

Measured cone resistance, q_c, is found by dividing the measured force on the cone, Q_c, by the cross-sectional area, A_c:

$$q_c = Q_c/A_c$$

2.12 *Sleeve friction, f_s*

Measured sleeve friction, f_s, is found by dividing the measured force acting on the friction sleeve, F_s, by the area of the sleeve, A_s:

$$f_s = F_s/A_s$$

2.13 *Pore pressure, u*

The pore pressure, u, is the fluid pressure measured during penetration and dissipation testing. The pore pressure can be measured at several locations as shown in Figure 2.3.

The following notation is used:

u_1: Pore pressure measured on the cone face
u_2: Pore pressure measured at the cylindrical extension of the cone
u_3: Pore pressure measured immediately behind the friction sleeve

Note: The measured pore pressure varies with 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.

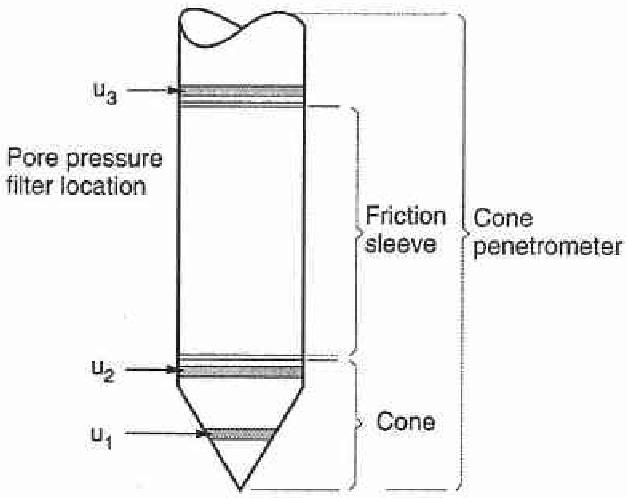

Figure 2.3 Locations of measured pore pressures

2.14 *Excess pore pressure, Δu*

The excess pore pressure is $\Delta u = u - u_o$, where u_o is the in situ pore pressure existing in the ground at the level of the cone before the penetration starts.

Note: Δu_1, Δu_2 or Δu_3 should be used according to the location at which the pore pressure is measured; see Figure 2.3.

2.15 *Net area ratio, a*

The ratio of the cross-sectional area of the load cell or shaft of the cone penetrometer above the cone at the location of the gap or groove where pore pressure can act, to the nominal cross-sectional area of the base of the cone.

Note: See section 5.11 and Figure 5.1 for details.

2.16 *Corrected cone resistance, q_t*

The corrected cone resistance, q_t, is the measured cone resistance, q_c, corrected for pore pressure effects, and is found from:

$$q_t = q_c + (1-a) \cdot u_2$$

Note: Section 5.11 gives more details on this correction.

2.17 *Friction ratio, R_f*

The ratio, expressed as a percentage, of the sleeve friction to the cone resistance both measured at the same depth.

Note: In some cases the inverse of the friction ratio, called the friction index, is used. Whenever possible the corrected cone resistance q_t should be used in calculating R_f.

2.18 *Pore pressure ratio, Bq*

The pore pressure ratio B_q is defined as:

$$B_q = \Delta u_2/(q_t-\sigma_{vo})$$

where σ_{vo} is the total vertical stress existing in the ground at the level of the cone before the penetration starts.

2.19 *Zero reading, reference reading and zero drift*

Zero reading: The output of a measuring system when there is zero load on the sensor, i.e. the measured parameter has a value of zero, any auxiliary power supply required to operate the measuring system being switched on.

Reference reading: the reading of a sensor just before the penetrometer is pushed into the soil e.g. in the offshore case the reading taken at the sea bottom - water pressure acting.

Zero drift: Absolute difference of the zero reading or reference reading of a measuring system between the start and completion of the cone penetration test.

2.20 *Accuracy, precision and resolution*

Accuracy is the closeness of a measurement to the true value of the quantity being measured. It is the accuracy of the measuring system as a whole that is ultimately important not the individual parts.

Precision is the closeness of each set of measurements to each other. It is synonymous with repeatability and can be expressed as a value with say a standard deviation indicating the scatter.

> Note: In terms of calibration then if a measurement system shows, for example, a repeatable but non-linear calibration, then the use of a linear approximation for the calibration would immediately result in a loss of accuracy, however the results may still be repeatable and precise. The loss of accuracy would be related to the difference between the true and assumed calibration lines. The use of any incorrect calibration could result in repeatable (precise) results which would have a systematic error and would be inaccurate. Precision or repeatability is not a guarantee of accuracy.
>
> The most desirable situation is to have an instrument that is accurate and precise. This is a prerequisite to obtaining accurate and precise readings in the field where it is then important to record all information such as temperature, wear etc, during the field testing that could influence the accuracy of the final deduced readings.

The resolution of a measuring system is the minimum size of the change in the value of a quantity that it can detect. It will influence the accuracy and precision of a measurement.

2.21 *Dissipation test*

In a dissipation test the pore pressure change is obtained by recording the values of the pore pressure with time during a pause in pushing and whilst the cone penetrometer is held stationary.

3 METHODOLOGY

The following reference conditions shall be determined:

a) the type of cone penetration test, according to Table 5.1

> Note: Filter element location u_1, u_2 or u_3 should be decided upon.

b) the Accuracy Class, according to Table 5.2
c) the required penetration length or penetration depth

> Note: The required penetration length or penetration depth depends on the soil conditions, the allowable penetration force, the allowable forces on the push rods and push rod connectors and the application of a friction reducer and/or push rod casing and the measuring range of the cone penetrometer.

d) the elevation of the ground surface or the underwater ground surface at the location of the cone penetration test with reference to a Datum
e) the location of the cone penetration test relative to a fixed location reference point
f) if applicable, the method of back filling of the hole in the soil resulting from the cone penetration test
g) if applicable, the depths and duration of the pore pressure dissipation tests.

> Note: The required depth and minimum duration of a dissipation test depends on the soil conditions and the purpose of the measurement. A maximum duration is also a common reference condition for avoiding inappropriately long interruptions.

Note: If the drainage- and/or consolidation characteristics of the soil are to be evaluated, dissipation tests can be carried out at preselected depths in the deposit. In a dissipation test, the pore pressure decay is obtained, by recording the values of pore pressure with time. In fine grained, low permeability soil, the pore pressure record is used to evaluate the coefficient of consolidation, c. In well-draining soils, a dissipation test can additionally be used to evaluate the in situ pore pressure.

The determination of the cone resistance of the soil, the CPT length and, if applicable, the sleeve friction and/or pore pressure of soil and the inclination of the cone penetrometer relative to the vertical axis, shall be according to Section 5, taking into account the Accuracy Class according to Table 5.2, the required depth and the maximum allowable inclination of the cone penetrometer relative to the vertical axis.

The apparatus required to undertake the work shall meet the requirements of Section 4.

4 EQUIPMENT

4.1 *Geometry of the cone penetrometer*

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

Note: Cone penetrometer design should aim for a high net area ratio and also the end area of the top end of the friction sleeve should preferably be equal or slightly greater than the cross sectional area of the lower end.

4.2 *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 nominally be 1000 mm^2, which corresponds to a diameter of 35.7 mm.

Note: Cones with a diameter between 25 mm (A_c = 500 mm^2) and 50 mm (A_c = 2000 mm^2) are permitted for special purposes, without the application of correction factors. The recommended geometry and tolerances should be adjusted proportionately to the diameter.

The diameter of the cylindrical part shall be within the tolerance requirement as shown in Figure 4.1:

$$35.3 \text{ mm} \leq d_c \leq 36.0 \text{ mm}.$$

The length of the cylindrical extension shall be within the tolerance requirement:

$$7.0 \text{ mm} \leq h_e \leq 10.0 \text{ mm}$$

The height of the cone shall be within the following tolerance requirement:

$$24.0 \text{ mm} \leq h_c \leq 31.2 \text{ mm}$$

Note: If a u_2 position filter is included the diameter of the filter element itself may be larger than the steel dimensions given above. See also Sections 4.3 and 4.4.

The face of the cone should be smooth.

Note: The surface roughness, R_a, should typically be less than 5 µm. This is defined as the average deviation between the real surface of the probe and a medium reference plane placed along the surface of the probe. See also note in Section 4.3.

The cone shall not be used if it is asymmetrically worn, even if it otherwise fulfils the tolerance requirements.

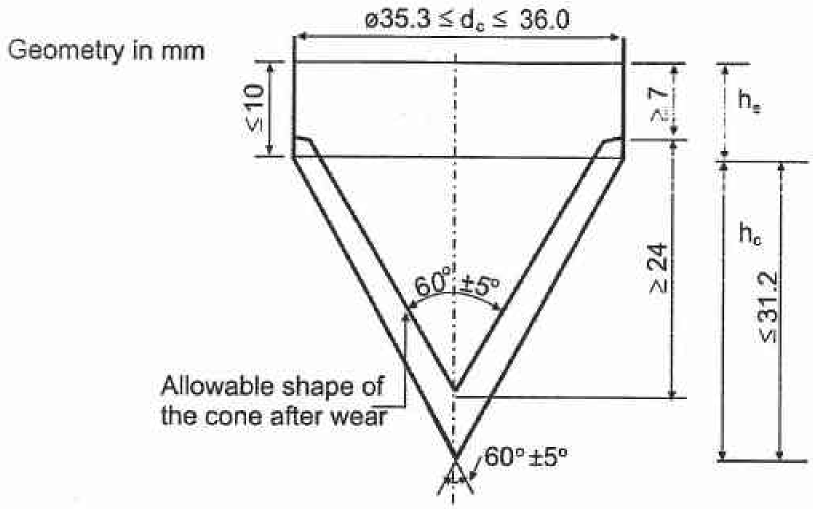

Figure 4.1 Tolerance requirements for use of cone penetrometer

4.3 *Friction sleeve*

The friction sleeve shall be placed just above the cone. The maximum distance due to gaps and soil seals shall be 5.0 mm.

The nominal surface area shall be 15000 mm^2. Tolerance requirements are shown in Figure 4.2.

Note: Friction sleeves with an external diameter between 25 mm and 50 mm are permitted for special purposes when used with cones of the corresponding diameter without the application of correction factors. The recommended geometry and tolerances should be adjusted proportionally to the diameter of the base of the cone. The preferred ratio of the length of the friction sleeve and the diameter of the base of the cone is 3.75, but values between 3.5 and 4.0 are permissible.

Note: Conical wear affects the measurement of sleeve friction. It should be taken into account for accuracy of the sleeve friction measurements.

The diameter of the friction sleeve shall be equal to the maximum diameter of the cone, with a tolerance requirement of 0 to +0.35 mm.

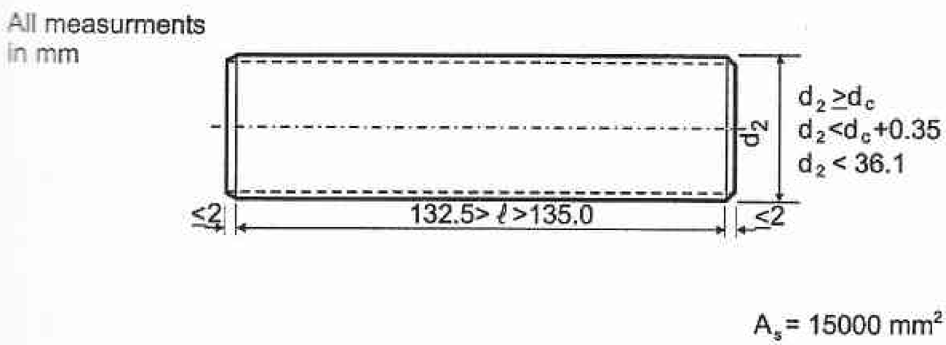

Figure 4.2 Geometry and tolerances of friction sleeve

The friction sleeve shall have a surface roughness of 0.4 µm ± 0.25 µm, measured in the longitudinal direction.

Note: The surface roughness refers to average roughness R_a determined by a surface profile comparator according to ISO 8503 (1988) or equivalent. Average roughness is "the arithmetic average of the absolute distances for the actual profile to the centreline" and applies to a specified test length (typically in the range 2.0 mm to 4.0 mm, depending on the applied standard). The intention of the surface roughness requirement is to prevent the use of an "unusually smooth" and "unusually rough" 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. It is believed that the surface roughness requirement will usually be met in practice for common types of steel used for penetrometer manufacture and for common ground conditions (sand and clay). The effort required for metrological confirmation may thus be limited in practice. The use of the R_a parameter may be reasonable for geotechnical applications, but the use of the parameter R_y is possibly more relevant. The surface roughness R_y is the distance between the highest peak and deepest trough within one cut-off length, taken as the maximum of a series of cut-off lengths within a test length. Further research is necessary to define adequate parameters for the effects of geometry on sleeve friction accuracy.

4.4 *Filter element*

A filter position in or just behind the cylindrical extension of the cone is recommended, but other filter locations can be accepted, see Figure 2.3.

Note: Filter locations in addition to the recommended one can give valuable information about the soil conditions.

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 shall correspond to the diameter of the cone and the friction sleeve, with a tolerance limit 0.0 to +0.2 mm. The filter can be larger, but never smaller than the diameter of the cone. The filter shall not have a larger diameter than the friction sleeve.

Note: The following relation applies:

$$d_{friction\ sleeve} \geq d_{filter} \geq d_{cone}$$

Note: This filter position also gives more consistent results for classification and interpretation purposes.

Note: For correction of cone resistance for pore pressure effects, the best location of the filter element would be in the groove between the cone and the friction sleeve. A location in the cylindrical part of the cone is recommended for obtaining and maintaining saturation of the pore pressure system.

Pore pressure u_1:
The diameter of the filter shall correspond to the diameter of the cone with a tolerance limit 0.0 - 0.2 mm. The shape of the filter should fit to the shape of the cone, i.e. the diameter of the filter shall be equal to but not larger than the diameter of the conical part in the position of the filter.

Note: It is recommended to place the filter element within the middle third of the conical part.

Pore pressure u_3:
The diameter of the filter shall correspond to the diameter of the friction sleeve with a tolerance limit 0.0 - 0.2 mm, i.e. the diameter of the filter can be equal to but not larger than the diameter of the friction sleeve.

Note: It is recommended to place the filter element immediately above the groove between the friction sleeve and the shaft of the cone penetrometer.

The filter shall be saturated at the start of the test.

Note: It is important that the filter remains saturated even when the cone penetrometer is penetrating an upper unsaturated layer.

Note: Porous filters should have a pore size between 2 and 20 μm, corresponding to a permeability between 10^{-4} and 10^{-5} m/sec. Filter materials that get clogged by fine particles should be avoided.

Note: The following types of material have been used with good experience in soft normally consolidated clay: sintered stainless steel or bronze, carborundum, ceramics, porous PVC and HDPE.

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 Section 5.3.).

Note: With regard to the choice of saturating liquid, saturation of pore pressure measurement system, and use of slot filters, see Section 5.4.

4.5 *Gaps and soil seals*

The gap between the different parts of the cone penetrometer shall not exceed 5 mm. The gap shall be protected by a soil seal so that soil particles do not move into it.

Note: The soil seal must be easy to deform relative to the load cell and other elements in the penetrometer, so that no significant forces can be transferred through the gap.

4.6 *Push rods*

Deviation from a straight line through the ends of 1 m long rod shall be within permissible limits. A check of rod straightness shall follow the criteria given below:

- Each of the 5 lower rods shall have a maximum deviation from the centreline of 1 mm.
- Two connected rods (of the lower 5) shall at a maximum have a deviation of 4 mm.

The other rods shall have a maximum deviation of 2 mm. Two connected rods (of the rest) shall have a maximum deviation of 8 mm.

Note: The above requirements are valid for 1m long rods. If other lengths of rod are used for special purposes then the requirements should be adjusted accordingly.

Note: The straightness of the push rods can be checked by holding the rod vertically and rotating it. If the rod appears to wobble, the straightness is not acceptable.

Note: Friction along the push rods can be reduced by a local increase in the rod diameter (friction reducer). The friction could also be reduced by lubrication of the push rods, for instance by mud injection during the test.

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

Note: The push rods should be chosen with respect to the required penetration force and the data signal transmission system chosen.

4.7 *Measuring system*

The resolution of the measuring system shall be better than one-third of the accuracy applicable to the required accuracy class given in Table 5.2.

Note: An electric cable can be used to transfer signals from the sensors to a recording unit at ground level, or alternatively acoustic transmission through the rods, or electronic transmission to a memory unit in the cone penetrometer.

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.

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

Sensor for pore pressure

The sensor shall show insignificant deformation during loading. The sensor communicates with a porous filter on the surface of the cone penetrometer via a liquid chamber.

Note: The pore pressure sensor is normally a pressure transducer of the membrane type.

Note: This system measures the pore pressure in the surrounding soil during penetration.

Sensor for inclination

The inclinometer should have a measuring range of at least 20° relative to the vertical axis.

Measuring system for penetration length.

The measuring system shall include a depth sensor for registration of the penetration length.

Note: If relevant, the measurement system for depth should also include a procedure for correction of measurements if upward movements of the push rods occur relative to the depth sensor, caused by a decrease in force on the push rods.

4.8 *Thrust machine*

The equipment shall be able to penetrate the cone penetrometer at a standard speed of 20 mm/s ±5 mm/s, and it shall be loaded or anchored such that it limits movements relative to ground level while the penetration occurs.

Note: Hammering or rotation of the penetration rods during measurements shall not be used.

Note: The pushing equipment should give a stroke of at least 1000 mm. Other stroke lengths may be acceptable in special circumstances.

5 PROCEDURES

5.1 *Selection of cone penetrometer*

Select a cone penetrometer to fulfil the requirements of the penetration test according to Table 5.1.

Table 5.1 Types of cone penetration tests

Type of cone penetration test	Measured parameter
A	Cone resistance
B	Cone resistance and sleeve friction
C	Cone resistance and pore pressure
D	Cone resistance, sleeve friction and pore pressure

Note: Cone penetration tests with measurements of pore pressures at more than 1 location are variants of types C or D.

5.2 *Selection of equipment and procedures according to required accuracy class*

Equipment and procedures to be used shall be selected according to the required accuracy class given in Table 5.2.

If all possible sources of errors are added, the accuracy of the recordings shall be better than the largest of the values given in Table 5.2.

Note: The errors may include internal friction, errors in the data acquisition, eccentric loading and temperature effects.

Table 5.2 Accuracy classes

Accuracy class	Measured parameter	Allowable minimum accuracy*	Maximum length between measurements
1	Cone resistance Sleeve friction Pore pressure Inclination Penetration depth	50 kPa or 3% 10 kPa or 10% 5 kPa or 2% 2° 0.1 m or 1%	20 mm
2	Cone resistance Sleeve friction Pore pressure Inclination Penetration depth	200 kPa or 3% 25 kPa or 15% 25 kPa or 3% 2° 0.2 m or 2%	20 mm
3	Cone resistance Sleeve friction Pore pressure Inclination Penetration depth	400 kPa or 5% 50 kPa or 15% 50 kPa or 5% 5° 0.2 m or 2%	50 mm
4	Cone resistance Sleeve friction Penetration length	500 kPa or 5% 50 kPa or 20% 0.1 m or 1%	100 mm

* See definitions in Section 2.20

Note: The allowable minimum accuracy of the measured parameter is the larger value of the two quoted. The relative or % accuracy applies to the measurement rather than the measuring range or capacity.

Note: See Appendix B regarding calculation of penetration depth from penetration length and measured inclination.

Note: Class 1 is meant for situations where the results will be used for precise evaluation of stratification and soil type as well as parameter interpretation in profiles including soft or loose soils. For Classes 3 and 4, the results should only be used for stratification and for parameter evaluation in stiff or dense soils. Class 2 may be considered more appropriate for stiff clays and sands.

Note: At extreme air temperatures, the probe should be stored so that its temperature is in the range 0 - 25°C. During the sounding, zero readings should be carried out with the probe temperature as close as possible to the ground temperature, and all sensors and other electronic components in the data acquisition system should be temperature stabilised.

Note: Current thinking is that for Class 1 testing (see Table 5.2) the temperature sensitivity of the probe transducers should be better than:

2.0 kPa/°C	for cone resistance
0.1 kPa/°C	for sleeve friction
0.05-0.1 kPa/°C	for pore pressure (measuring range 1-2 MPa)

These stability requirements are valid for probes with a load capacity of 5 tonnes. For probes with different capacities, the presented requirements can be changed proportionally with due consideration to the effects on the accuracy of the measured value.

Note: For all classes the temperature sensitivity should be an integral part of the CPT Accuracy Classes given in Table 5.2.

Metrological confirmation applicable to a cone penetration test shall be according to ISO 10012-1; 1992 (E).

5.3 *Position and level of thrust machine*

Position the thrust machine at a distance of at least 1 m from a previous cone penetration test, or at a distance of at least 20 times the borehole diameter of a previous borehole.

Note: Smaller distances may affect the measurements.

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

5.4 *Preparation of the cone penetrometer*

The actual cross-sectional area of the base of the cone and, if applicable, the actual external cylindrical surface area of the friction sleeve shall be determined and recorded as required to achieve the Accuracy Class of Table 5.2.

For cone penetrometers with measurement of pore pressure the filter element and other parts of the pore pressure system shall be saturated with a liquid before field use.

Note: Usually, de-aired, distilled water is used when testing is carried out in saturated soils. When performing penetration tests in unsaturated soils, dry crust and dilative soils (e.g. dense sands), the filter should be saturated with glycerine or similar, which makes it easier to maintain saturation throughout the test. When deaired water is used, the filters should be boiled for at least 15 minutes. The filter should be cooled in the water, before being stored in a sealed container. A larger volume of de-aired water should also be prepared. This water is necessary when mounting before use. Boiling of filters may not be acceptable for some types of filters (e.g. HDPE). If glycerine (or silicone oil) is used, the dry filters are placed directly in the liquid and treated with vacuum for approximately 24 hours. A larger volume of liquid should be treated similarly and stored in a sealed container. The transducer chamber is usually saturated with the same fluid as used for the filter. This can be done by direct injection of fluid into the chamber, or by treatment of the dismantled probe in a vacuum chamber. The vacuum should be applied until no air bubbles escape from the probe (approx. 15-30 mins). The final mounting of filter and seals should be carried out with the penetrometer submerged in the saturation fluid. After mounting, the fitting of the filter should be checked. The height of the filter should be sufficient so that the filter is not loose, but small enough so that the filter can be rotated by the finger tips. This prevents excessive stresses in the joint around the filter, and also reduces any influence on the measurements. After mounting the filter, it is good practice to cover the filter element with a rubber membrane, which will burst when the penetrometer comes into contact with the soil. Other alternatives are also possible. If clogging is suspected then a new filter should be mounted for each test.

Note: During saturation and mounting of the rubber membrane, the penetrometer will be subjected to small stresses, so that the sensors can show values different from zero.

Note: *Slot filter*

In this system, the pore pressure is measured by an open system with a 0.3 mm slot immediately behind the conical part (e.g. Larsson, 1995). Hence the porous filter element between the soil and the pressure chamber becomes redundant. The slot communicates with the pressure chamber through several channels. The pressure chamber is saturated by de-aired water, antifreeze liquid or other liquid, whereas the channels are saturated with gelatine, silicone grease or similar. Both gelatine and silicone grease are well-suited for field use. When silicone grease is used, this is injected into the channels directly from a tube. This can cause insufficient saturation of the pore pressure system, since air bubbles may be entrapped in the grease. This is avoided by using gelatine, but some more time is needed for preparation using this saturation medium.

The use of a slot filter may reduce the time required for preparation of the probe. In addition, this pore pressure system also maintains its saturation better when passing through unsaturated zones in the soil. The pressure changes in the saturated system are recorded by a pressure sensor, similar to conventional porous filter piezocones. As for other cone penetrometers, the requirements for sufficient saturation are the same, so that adequate pore pressure response is obtained during penetration.

Note: *Predrilling*

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 may be used in coarse top layers, sometimes in combination with casings to avoid collapse of the borehole. In soft or loose soils, predrilling should be used through the crust down to the groundwater table. The predrilled hole should be filled with water if the pore pressure shall be measured by a water-saturated system. If the ground water table is located at large depths, the pore pressure system should be saturated with glycerine. In some cases, the predrilling can be carried out by ramming a dummy-rod of 45 - 50 mm diameter through the dense layer to provide an opening hole and reduce the penetration resistance.

Note: *Temperature stabilisation*

Before commencing testing, zero readings of all sensors should be taken with the cone penetrometer unloaded and temperature-stabilised ideally at ground temperature.

When the cone penetrometer is lowered into the ground, small temperature gradients will occur if the air temperature is different from the ground temperature. This will influence the sensors, and it is therefore important that the penetrometer is left to come to equilibrium so that the temperature gradients can be reduced to zero before the penetration starts. Usually, the largest gradients will occur after 2 - 3 minutes. The cone penetrometer will usually be completely temperature-stabilised after 10 - 15 minutes.

See Table 5.2 for required accuracies and Appendix A for calibration procedures.

The zero readings of the cone resistance and the penetration length and, if applicable, the sleeve friction and pore pressure and the inclination of the cone penetrometer relative to the vertical axis shall be recorded.

Note: Whenever possible the zero readings should be taken when the cone penetrometer is at or near the temperature of the ground.

Note: The reference readings for underwater cone penetration tests are those applicable immediately above the underwater ground surface.

5.5 *Pushing of the cone penetrometer*

During the penetration test, the probe shall be pushed into the ground at a constant rate of penetration 20 ± 5 mm/s. The rate shall be checked by recording time.

Note: The penetration is regarded as continuous even if the penetration is stopped regularly for a new stroke or mounting of a new push rod. Some thrust machines can carry out true continuous penetration without any stops and this can be an advantage, particularly in layered silt- and clay deposits.

Note: The penetration is regarded as discontinuous if larger stops are introduced, such as dissipation tests (see Section 2.21) or due to unforeseen malfunctions of the equipment.

5.6 *Use of friction reducer*

The use of a friction reducer (see definition Section 2) is permissible. The cone penetrometer and if relevant the push rod shall have the same diameter for at least 400 mm before the introduction of the friction reducer if applicable.

5.7 *Frequency of logging parameters*

The minimum logging frequency of parameters shall be in accordance with Table 5.2. Logging shall include (clock)time for Accuracy Classes 1 & 2 of Table 5.2.

Note: The logging interval for the various measured values can also be chosen from a consideration of the detail required in the profile, i.e. detection of thin layers. Usually the same reading interval is used for registration of cone resistance, sleeve friction and pore pressure.

Note: The average measured value over the 20 mm interval may be used, even if the values are measured more frequently. The maximum logging interval should be according to Table 5.2.

5.8 *Registration of penetration depth*

The level of the cone base shall be determined according to Table 5.2, relative to the ground level or another fixed reference system (not the thrust machine). The resolution of the depth sensor shall be at least 0.01 m.

The penetration length shall also be measured and recorded at least every 5 m for tests according to Accuracy Class 1 of Table 5.2, not using the depth sensor.

The penetration of the cone penetrometer and the push rods shall be terminated when the required penetration length or penetration depth according to Section 3 has been reached, or when the inclination of the cone penetrometer relative to the vertical axis has reached 20°. The penetration length shall be measured and recorded not 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 was vertical. Appendix B gives guidelines on how to calculate penetration depth from penetration length and inclination measurements.

Note: During the cone penetration test, particulars or deviations from this standard should be recorded, which can affect the results of the measurements and the corresponding penetration length.

5.9 *Dissipation test*

Pore pressure and cone resistance shall be measured with time. It is particularly important to take frequent readings at the beginning of the dissipation test.

Note: The logging frequency should be at least 2 Hz for the initial 1st min of the dissipation test, 1 Hz between 1 min and 10 min, 0.5 Hz between 10 min and 100 min and 0.2 Hz thereafter, as applicable.

Note: The duration of the dissipation test should normally correspond to at least the time needed for 50 % pore pressure dissipation (t_{50} -> $u_t = u_o + 0.5\ u_i$), since t_{50} is the time used in most interpretation methods.

Note: The procedure for interruption of penetration should aim for constant cone resistance during the dissipation test. Variation in cone resistance is unavoidable in practice and will depend on factors such as type of equipment and soil conditions.

5.10 *Test completion*

The zero readings of the measured parameters shall be measured and recorded after extraction of the cone penetrometer from the soil and, if necessary after cleaning of the cone penetrometer. The zero drift of the measured parameters shall be within the allowable minimum accuracy according to the required accuracy class of Table 5.2.

The cone penetrometer shall be inspected and any excessive wear or damage noted.

5.11 *Correction of measurements*

Recorded values that are not representative due to penetration interruption shall be corrected for. Correction of measured parameters for zero drift shall be done if appropriate for meeting the requirements of the Accuracy Classes according to Table 5.2.

When the probe is subjected to an all-round water pressure, this will influence the cone resistance and sleeve friction. This is explained by the effect of the water pressure in the grooves between the cone and the friction sleeve, and in the groove above the friction sleeve. This effect shall be accounted for cone penetrometer types C and D of Table 5.1 and where the filter element is at the cylindrical extension of the cone (u_2) by using the following correction formula (e.g. Campanella et al., 1982):

Cone resistance:

$$q_t = q_c + u_2 \cdot (1 - a)$$

where:

q_t = corrected cone resistance
q_c = cone resistance
u_2 = pore water pressure in the cylindrical part of extension of the cone (assumed equal to the pore pressure in the gap between the cone and the sleeve)
a = net area ratio = A_n/A_c (see Figure 5.1)
A_c = projected area of the cone
A_n = area of load cell or shaft

Note: It is recommended to only carry out this correction if u_2 is measured. Approximate calculation procedures are available in some soil types for the determination of q_t for filter element positions other than the u_2 location (Lunne et al. 1997).

Note: The net area ratio 'a' varies between 0.3 and 0.9 for commonly used cone penetrometers. The area ratio cannot be determined from geometrical considerations alone, but should be determined by tests in a pressure chamber or similar.

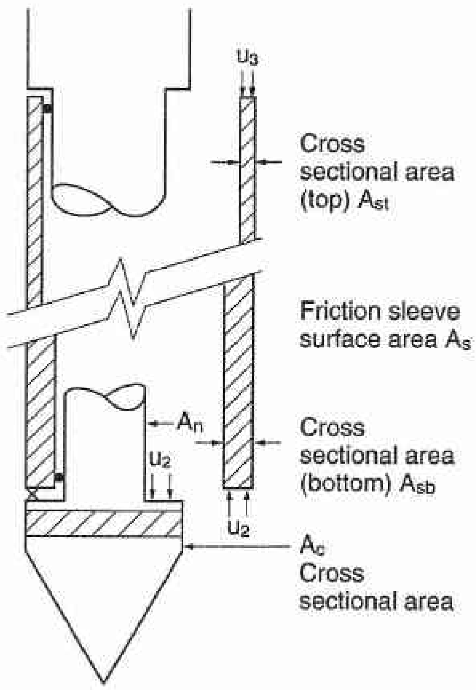

Figure 5.1 Correction of cone resistance and sleeve friction due to the unequal end area effect.

Note: The measured sleeve friction is influenced by a similar effect. However, since it is not usual to measure the pore pressure above the friction sleeve, the uncorrected sleeve friction, f_s, is commonly used. A possible correction method for the recorded sleeve friction is however given below, see Figure 5.1:

Sleeve friction:

$$f_t = f_s - \frac{(u_2.A_{sb} - u_3.A_{st})}{A_s}$$

where:
f_t = corrected sleeve friction
f_s = sleeve friction
A_s = area of friction sleeve
A_{sb}= cross sectional area of the bottom of the friction sleeve
A_{st}= cross sectional area of the top of the friction sleeve
u_2 = pore pressure measured between the friction sleeve and the cone
u_3 = pore pressure measured above the friction sleeve

This correction should only be carried out if both u_2 and u_3 are measured.

Note: These corrections are most important in fine-grained soils where the excess pore pressure during penetration can be significant. It is recommended to use corrected values of the test results for interpretation and classification purposes.

Correction for inclination, i.e. calculation of penetration depth from penetration length, should also be carried out according to the procedure given in Appendix B to meet the requirements of Accuracy Classes 1, 2 and 3 (see Table 5.2).

Note: Various other corrections may be required to meet the requirements of the Accuracy Classes, e.g. temperature effects, cross sectional area of cone, compression of the push rods, rebound of the thrust machine etc.

6 REPORTING OF TEST RESULTS

6.1 *General reporting and presentation of test results*

The following information shall be reported from a (piezo)cone penetration test (selected information marked with * shall be included on every plot from the test):

- Cone penetrometer type, geometry and dimensions, filter location, net area ratio.

  Note: The actual dimensions of the cone and friction sleeve should be used whenever possible.

- Type of thrust machine used, pushing capacity, associated jacking and anchoring systems
- Use of soil anchors (number and type) if applicable
- Date of test *
- Identification of the test *
- Co-ordinates and altitude of the cone penetration test *
- Reference altitude
- Depth to the groundwater table (if recorded)

- In situ pore pressure measurements (if recorded)
- Depth of predrilling
  - Note: when possible also the type of materials encountered
- If trenching is carried out: trenching depth
  - Note: when possible also type of materials encountered
- Depth of the start of penetration
- Saturation fluid used in pore pressure system (if piezocone)
- Depth and possible causes of any stops in the penetration (e.g. dissipation tests)
- Zero readings of cone resistance and, if applicable sleeve friction and pore pressure before and after the test and zero drift (in engineering units)
- Stop criteria applied, i.e. target depth, maximum penetration force, etc
- Corrections applied during data processing (e.g. zero drifts)
- Reference to this IRTP or other standard
- Test type (Table 5.1) and Accuracy Class (Table 5.2)
- If applicable, the inclination of the cone penetrometer to the vertical axis, for a maximum penetration depth spacing of 1m

Note: In the presentation of test results, the information should be easily accessible, for example in tables or as a standard archive scheme.

Note: In addition to the above it is desirable that the following information is given:
- Manufacturer of cone penetrometer
- Observations done in the test, for example the presence of stones, noise from the pushing rods, incidents, buckled rods, abnormal wear or changes in zero / reference readings
- Identification number of the penetrometer, and measuring ranges of the transducers
- Date of last calibration of sensors

6.2 *Choice of axis scaling*

In the graphical presentation of test results the following axis scaling shall be used when required:

- Penetration depth z:	1 cm = 1 m
- Cone resistance q_c, q_t:	1 cm = 2 MPa
- Sleeve friction f_s, f_t:	1 cm = 0.05 MPa = 50 kPa
- Pore pressure u:	1 cm = 0.2 MPa = 200 kPa
- Friction ratio R_f:	1 cm = 2 %
- Pore pressure ratio B_q:	1 cm = 0.5

Note: 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 (Accuracy Classes 1 and 2, see Table 5.2), it is particularly important to use enlarged scaling in the presentation of test results.

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.

6.3 *Presentation of test results*

The test results shall be presented as continuous profiles of:

- Cone resistance - depth	q_c (MPa) - z (m)
- Sleeve friction - depth	f_s, (MPa) - z (m)
- Pore pressure - depth	u_2 (MPa) - z (m)
- Other pore pressures - depth	u (MPa) - z (m)

(location of pore pressure measurement should be given)

The depth here shall be according to Table 5.2 corrected when necessary for the measured inclination.

Presentation of the results of cone penetration tests according to Accuracy Classes 1 and 2 shall, if required, include tabular data according to Section 6.1. Tabular data per penetration length spacing according to Table 5.2 shall include the time t in s, penetration depth z in 0.01 m, cone resistance q_c in 0.01 MPa and, if applicable, sleeve friction in 1 kPa, pore pressure in 1 kPa, friction ratio R_f in 0.1%, corrected cone resistance q_t in 0.01 MPa, inclination of the cone penetrometer in °.

If relevant corrected values of cone resistance (q_t) and sleeve friction (f_t) should be plotted in addition, and should preferably 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.

Note: 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.

Note: Further processing of the measured data can be carried out based on the following relationships:

- Excess pore pressure	$\Delta u = u - u_o$
- Net cone resistance	$q_n = q_t - \sigma_{vo}$
- Friction ratio	$R_f = (f_s/q_c) \times 100$ %
- Pore pressure ratio	$B_q = (u_2 - u_o)/(q_t - \sigma_{vo}) = \Delta u_2/q_n$
- Normalised excess pore pressure	$U = (u_t - u_o)/(u_i - u_o)$ where u_t is the pore pressure at time t in a dissipation test and u_i is the pore pressure at the start of the dissipation test

Note: In addition the following parameters can be computed for effective stress interpretation:

- Cone resistance number $N_m = q_n/(\sigma_{vo}' + a)$ (a = attraction)

Note: Information of the following parameters is needed in the processing of the test results:

- In situ, initial pore pressure - depth	u_o (MPa) - z (m)
- Total overburden stress - depth	σ_{vo} (MPa) - z (m)
- Effective overburden stress - depth	$\sigma_{vo}' = \sigma_{vo} - u_o$

Note: These parameters, or additional derived and normalised values, can be used for both identification of strata and classification of soil types, and as basic input values for interpretation of engineering parameters.

7 REFERENCES

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Larsson, R. 1995. Use of a thin slot as filter in piezocone test. *Proc CPT'95*, 2: 35-40.

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APPENDICES:

APPENDIX A- MAINTENANCE, CHECKS AND CALIBRATION

A1 MAINTENANCE AND CHECKS

A1.1 *General*

This Appendix contains informative guidance on maintenance, checks and calibrations. The guidance notes are meant to represent good practice.

A1.2 *Linearity of push rods*

Before the test is carried out, the linearity of the push rods shall be checked. A rough impression of the linearity may be obtained by rolling the rods on a plane surface. If any indications of bending appear, the linearity should be checked according to the procedures outlined in Section 4.6.

A1.3 *Wear of the cone*

The wear of the cone and the friction sleeve shall be checked regularly to ensure that the geometry satisfied the tolerances. A standard geometrical pattern similar to a new or unused probe may be used in this control.

A1.4 *Gaps and seals*

The seals and gaps between the different parts of the probe shall be checked regularly. In particular, the seals should be checked for intruding soil particles and cleaned.

A1.5 *Pore pressure measuring system*

If pore pressure measurements are carried out, the filter should have sufficient permeability for satisfactory response. The filter should be kept saturated between the tests. 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.

A1.6 *Maintenance procedures*

When maintenance and calibration of the equipment is carried out, the check scheme in Table A1.1 may be used, along with the producer's manual for the particular equipment.

Table A1.1 Control scheme for recommended maintenance routines

Checking Routine	Start of project	Start of test	End of test	Every 3.rd month
Verticality of thrust machine		x		
Penetration rate		x		
Depth sensor				x
Safety functions	x			x
Push rods	x	x		
Wear	x	x	x	
Gaps and seals	x	x	x	
Filter	x	x	x	
Zero drift		x	x	
Calibration	x			x*
Function control	x			x

* and at intervals during long term testing

A2 CALIBRATIONS

A2.1 *General procedures*

A new cone penetrometer has to be calibrated with respect to:

- the net area ratios, used for correction of measured cone resistance and sleeve friction
- influence of internal friction – restriction to movement of the individual parts.
- possible interference effects (electrical cross talk etc).
- transient temperature effects

The calibrations and checks are specific to each cone penetrometer. They will show variations during a penetrometer's life caused by small changes in the function and geometry of the cone penetrometer. In such cases, a re-calibration of the probe should be carried out. Calibration of the data acquisition system should be carried out regularly, according to the criteria listed below:

- at least every 3 months with the cone penetrometer in continuous use, or after approximately 100 soundings (approximately 3000 m)
- a new calibration should be carried out after soundings under difficult conditions, where the probe has been loaded close to its maximum capacity.

The calibrations should be carried out using the same data acquisition system, including cables, as in the field test, representing a check of possible inherent errors of the system. During the fieldwork, regular function controls of the equipment shall be carried out. These should be carried out at least once per location and/or once per day. Furthermore, a function control and possibly also a re-calibration should be carried out if the operator suspects overloading of the load sensors (loss of calibration).

In general the requirements presented in ISO 10012-1:1992(E) should be followed.

A2.2 *Calibration of cone resistance and sleeve friction*

The calibration of cone resistance and sleeve friction are performed by incrementally loading and unloading axially the cone and the friction sleeve. When loading the friction sleeve alone, the cone is substituted by a specially adapted calibration unit. This unit is designed so that the axial forces are transferred to the lower end area of the friction sleeve. The calibrations of cone resistance and sleeve friction are carried out separately, but the other sensors are checked to ensure that they are not influenced by the applied load. The calibration is carried out for various measuring ranges, with special emphasis on those ranges relevant for the forthcoming tests. When a new probe is calibrated, the sensors should be subjected to 15-20 repeated loading cycles up to the maximum load, before the actual calibration is carried out. The requirement for separate calibration procedures for cone and friction sleeve is not usually required for subtractive cone penetrometers.

The influence of non axial loading on the cone penetrometer and its effect on the measured parameters should be checked.

A2.3 *Calibration of pore pressure and net area ratio*

The calibration of the pore pressure measuring system shall be done in a pressure chamber. For pore pressure effects on the cone resistance and sleeve friction, the calibration of the net area ratio a shall be carried out in a specially designed pressure chamber (e.g. Figure A1), constructed so that the lower part of the penetrometer can be mounted in the chamber and be sealed above the friction sleeve. The enclosed part of the probe is then subjected to an incrementally increasing chamber pressure, and cone resistance, sleeve friction and pore pressure are recorded. In this way a calibration curve for the pore pressure transducer is obtained and the net area ratio can be determined from the response curves for cone resistance and sleeve friction. The pressure chamber is also well suited to check the response of the pore pressure sensor to cyclic pressure variations.

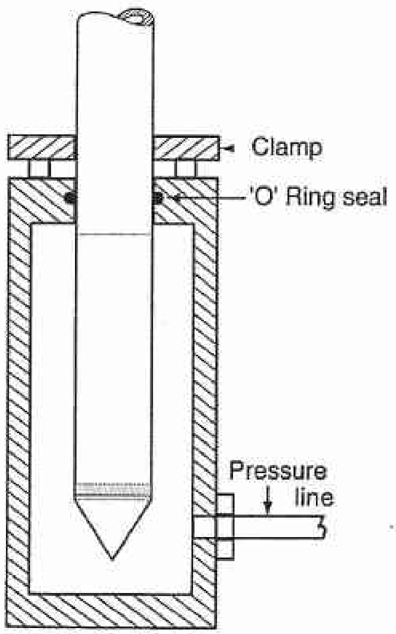

Figure A1 Pressure chamber for determination of the end area ratios a and b (from Lunne et al., 1997)

A2.4 *Calibration of temperature effects*

The cone penetrometer shall also be calibrated for temperature effects at various temperature levels, for example by lowering the cone penetrometer into water reservoirs at different temperatures. The sensor signals are recorded until the values stabilise. From these results a measure for changes in zero readings per °C is obtained and an impression is gained of the time needed for temperature stabilisation in the field performance. This is important information for a proper preparation of the test equipment before the penetration test starts.

The above applies to ambient temperatures only and not to transient temperatures.

A2.5 *Calibration of depth sensor*

The depth sensor calibration should be calibrated at least every 3rd month or after repair.

APPENDIX B - CALCULATION OF PENETRATION DEPTH

CORRECTION FOR PENETRATION DEPTH DUE TO INCLINATION

The depth of cone penetration tests according to Accuracy Classes 1, 2 and 3 of Table 5.2 can be corrected for inclination by the equation:

$$z = \int_{o}^{l} C_h \cdot dl$$

where:

z is the penetration depth, in m;
l is the penetration length, in m;
C_h is a correction factor for the effect of the inclination of the cone penetrometer relative to the vertical axis

Equations for the calculation of the correction factor C_h for the influence of the inclination of the cone penetrometer relative to the vertical axis, on the penetration depth:

a) for an now-directional inclinometer:

$$C_h = \cos\alpha$$

where:

α is the measured angle between the vertical axis and the axis of the cone penetrometer, in °

b) for a bi-axial inclinometer:

$$C_h = (1 + \tan^2 \alpha + \tan^2 \beta)^{-\frac{1}{2}}$$

where:

α is the angle between the vertical axis and the axis and the projection of the cone penetrometer on a fixed vertical plane, in°;
β is the angle between the vertical axis and the axis and the projection of the cone penetrometer on a vertical plane that is perpendicular to the plane of angle α, in°.

Note: It may be necessary to apply additional corrections to the CPT depth.

Note: The determination of the correction factor for the penetration depth should take account of a complex loading sequence. Additional factors include: bending and compression of the push rods and push rods connectors, vertical movements of the ground surface or the underwater ground surface and vertical movements of the depth sensor relative to the ground surface or the underwater ground surface. For some situations, such as penetration interruptions, it is possible to correct for bending and compressing of the push rods and push rod connectors by using a heave compensator.