Introduction to CPT accuracy

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ABSTRACT: CPT practice has an admirable history on benchmarking accuracy of parameter values. A proposed Analytic CPT can serve as a benchmark for true values, independent of deployment-specific CPT features. This paper provides an introduction to CPT accuracy with reference to the proposed Analytic CPT and with reference to CPT standard ISO 22476-1 and its application (accuracy) classes. ISO 22476-1 defines accuracy, where (1) cone resistance, sleeve friction and pore pressure are uncoupled from spatial position and (2) true values depend on permissible deployment-specific features. Uncertainty estimates are presented for favourable and adverse conditions. The adverse case illustrates difficulty in demonstrating compliance with the application classes of ISO 22476-1. Significant epistemic uncertainty is the principal reason for this situation, notably prediction models for transient temperature and measurement error. The uncertainty model provides what may be the first estimate that complies with ISO 22476-1 procedures. Actual accuracy is probably significantly better than calculated.

1. IN SITU PENETRATION TESTING

A supreme in situ penetration tool:

- provides zero measurement uncertainty,
- gives unambiguous soil behaviour identification,
- has a closed-form theoretical interpretation model directly linked to fundamental soil mechanics,
- penetrates at high speed to desirable depths into any type of ground at temperatures between permafrost and volcanic outflow,
- allows cheap operation from a small autonomous vehicle operating on any terrain, above and below water,
- is uniquely standardised.

No such tool exists. The (piezo)cone penetration test (CPT) is closer to this wish list than any of its in situ rivals. A CPT measures soil resistance to penetration of a cone and friction sleeve and, optionally, pore pressure, all at a fairly standardised geometry and a push-in penetration rate of about 20 mm/s.

Cone penetration testing in a real world demands concessions in investing in technology and limiting operational cost. Successful CPT technologies are available in the market place, providing cost-effective support to industry and society at large. Successful may be recognized by accurate measurements even as upholding robustness under extreme physical demands. Is it possible to estimate CPT accuracy?

The following sections provide an introduction to CPT accuracy, exploring and illustrating what is known. Significant epistemic uncertainty remains. Discussions are limited to friction cone and piezocone penetration tests, using cone penetrometers with load cells as force measuring transducers, which probably represents >95% of cone penetration tests in practice. Supplementary tests and systems such as pore pressure dissipation, seismic downhole (seismic cone penetration test) and full displacement pressuremeter (cone pressuremeter test) are excluded from the discussions.

2. USE OF CPT RESULTS IN PRACTICE

Society and industry prescribe design and construction of facilities and the associated engineering risks that are considered to be acceptable. These prescriptions are typically captured by standards and guidelines. Cone penetration tests can be part of design and construction processes, in that they provide geotechnical measurements and are thus part of structure reliability (ISO 1998).

Widely used CPT standards are those published by ISO (2012a) and ASTM (2012), hereafter abbreviated to ISO 22476-1 and ASTM D5778. The following sections include critique on sections of these CPT standards. This is hoped to be constructive. In this regard, the authors wish to stress their appreciation and recognition of the efforts made in standardisation. Work is typically done by only a small core group of dedicated volunteers with limited backing. It is work in progress, never finished. Furthermore, consensus is to be achieved within the core group and, usually, with an active peer group of similar size.

3. BENCHMARKING OF CPT ACCURACY

CPT practice has an admirable history on benchmarking accuracy of parameter values (Table 1). Such ambitions are not yet seriously contemplated for parameter values inferred from soil sampling, sample handling and geotechnical laboratory testing. For example, Ruiter (1975) noted, “without special precautions, under routine field conditions, the possible error in cone resistance is about ± 5 kg/cm^2, with careful calibration before and during the test this can be improved to ± 1 kg/cm^2 cone resistance.” This statement applies to a friction cone penetrometer with strain-gauge load cells. Note that 1 kg/cm^2 is approximately 100 kPa. Also note “routine field conditions”. This rightly recognises the complexity of accurately measuring resistance values differing by typically four orders of magnitude, with no control on measuring environment. This paper continues with this recognition of complexity and introduces the terms “favourable” and “adverse”. Favourable may be compared to a setting that approaches a calibration laboratory. Adverse represents common hostile site conditions and/or a setting with real-world limits on tool control.

Table 1. Historical notes on CPT standardisation – with focus on accuracy.

Year	Notes
1968	Recommended method for “static sounding (static penetration test)” (European Group of the Sub-committee for Static and Dynamic Penetration Test Methods, 1968). Description of method covers just over one page; 1,000 mm^2 for cross sectional area of cone; no geometry requirements for friction sleeve; penetration rate should be constant and <20.8 mm/s
1977	Recommended standard for the cone penetration test (CPT) (ISSMFE 1977). Advancement of 1968 work; detailed requirements for CPTs with friction cone penetrometer; reference cone penetrometer defined with nominal cross sectional area of 1,000 mm^2 and friction sleeve area of 15,000 mm^2; surface roughness for friction sleeve of 0.5 µm with tolerance of 50% in longitudinal direction; measurement requirements for two precision classes: the larger of 5% of measured value and 1% of maximum value of range, respectively 10% and 2%; the term “range” is undefined: measuring range is probably intended; check is required on sensor ze-

Year	Notes
	ro-load drift; cylindrical height of cone defined at 2 mm to 5 mm; penetration rate defined at 20 mm/s ± 5 mm/s; use of (undefined) smaller and larger diameter cone penetrometers permitted
1979	Deep, quasi-static, cone and friction-cone penetration tests of soil (ASTM 1979). First (?) CPT standard published by a national standardisation institute; requirements for friction cone penetrometer with cross sectional area of 1,000 mm^2 and friction sleeve area of 10,000 mm^2 or 15,000 mm^2; bottom of friction sleeve <10 mm above base of cone; use of (undefined) larger cone penetrometers permitted; penetration rate defined at 20 mm/s ± 5 mm/s; accuracy of thrust measuring instrumentation to ± 5% of correct values; statement included on precision estimates for q_c and f_s
1989	International reference test procedure for cone penetration test (CPT) (ISSMFE 1989). Advancement of 1977 work; piezocone test included; cylindrical height of cone defined at 7 mm to 10 mm; maximum height of gap between cone and friction sleeve defined at 5 mm; piezocone filter in conical part of cone (u_1 position) or in cylindrical extension (u_2) with precautions to maintain full saturation; comment on influence of water pressure and area ratios for cone and friction sleeve, requirement on cone penetrometer bending influence; surface roughness of friction sleeve between 0.25 µm < r < 0.75 µm in longitudinal direction; precision of "measurements" and zero drift to be better than the greater of 5% of the measured value or 1% of the maximum value of the measured resistance in the layer under consideration (undefined); depth measurement to an accuracy of 0.1 m; inclinometer may be built into penetrometer; geometry scaling according to cone penetrometer diameter
1996	Dutch standard NEN 5140 Determination of the cone resistance and the sleeve friction of soil – electric cone penetration test (NNI 1996). Advancement of 1989 work; restricted to friction cone penetrometers; requirements for bevelled ends of friction sleeve; practical guidance on penetration interruptions including electronic heave compensator; time-based data recording; four accuracy classes for cone resistance, sleeve friction, inclination and penetration depth; accuracy expressed as the larger of a threshold value (e.g. 50 kPa, 250 kPa or 500 kPa for cone resistance q_c) and percentage of measured value (e.g. 3% and 5% for q_c); accuracy defined with reference to ISO metrological standards; resolution should be better than one third of accuracy; guidance on uncertainty analysis; geodetic requirements; presentation of digital tabular results
1999	International reference test procedure for the cone penetration test (CPT) and the cone penetration test with pore pressure (CPTU) (ISSMGE 1999). Advancement of 1989 and 1996 work; piezocone filter in u_1, u_2 or u_3 (immediately above friction sleeve) position; u_2 filter may be in cylindrical part of cone or in gap between cone and friction sleeve; inclusion of pore pressure dissipation test; four accuracy classes for cone resistance, sleeve friction, pore pressure, inclination and penetration depth; accuracy classes with tighter values for q_c (e.g. 50 kPa, 200 kPa, 400 kPa or 500 kPa for cone resistance) and f_s; threshold values for pore pressure of 5 kPa, 25 kPa or 50 kPa; presentation of corrected cone resistance q_t and pore pressure ratio B_q
2012	ISO standard: electrical cone and piezocone penetration tests (ISO 2012a). Based on 1999 reference test procedure, four application/ accuracy classes (Fig. 18) with stricter values for q_c (35 kPa, 100 kPa, 200 kPa or 500 kPa for cone resistance) and f_s; adjusted values for pore pressure: 10 kPa, 15 kPa, 25 kPa or 50 kPa; normative requirements on maintenance, checks and calibration
2012	ASTM standard: electronic friction cone and piezocone penetration testing of soils (ASTM 2012). Periodic ASTM update, some matches with ISSMGE international reference test procedure; requirements for friction cone and piezocone penetrometers with cross sectional areas of 1,000 mm^2 (reference); cylindrical height of cone plus any filter to be more than 2 mm and less than 20 mm; bottom of friction sleeve between 5 mm and 15 mm above base of cone; friction sleeve with equal end areas; cross sectional areas of 500 mm^2 and 1,500 mm^2 are permitted; penetration rate defined at 20 mm/s ± 5 mm/s; precision of pore pressure sensor of better than ± 14 kPa; permissible zero drift of 2% of full scale output FSO of q_c, f_s and u measurements; depth accuracy of ± 0.1 m; normative annual calibration requirements for laboratory environment under ideal conditions with requirements typically expressed as percentage of FSO: atmospheric axial calibration (no bending) for q_c and f_s, pressure calibration for u, and ambient temperature stability; statement included on precision estimates for q_c, f_s and u expressed in terms of standard deviation as percentage of FSO, refer to Table 2
2014?	ISO standard: marine soil investigations (draft, ISO 2012b). Possible publication year 2014; expected similarities with application classes of ISO (2012a) with adjustments to suit offshore practice

A literature search conducted on behalf of the authors led to many hits on CPT accuracy claims. Early and recent claims are by and large unsubstantiated. No publication provided an elementary estimation of accuracy of cone penetration test results according to ISO (2003) and EA (1999) or equivalent.

What is clear is that many in industry have overrated beliefs in accuracy of geotechnical measurements. CPT measurements are no exception. These overrated beliefs are probably due to researchers and practitioners correlating repeatability with accuracy. A lower accuracy is, in itself, usually not an issue for practice. The belief in a better accuracy than actually achieved can lead to unsafe conclusions:

- There is generally no relationship between precision of a sensor and accuracy of a measurement.
- Geotechnical parameter values usually require combining results from a number of measurements. Derived measurements may be dominated by a weakest-link principle.
- Operating conditions at site often differ significantly from assumptions and calibration laboratory conditions. The success of geotechnical measuring systems designed for a specific set of operating conditions and site conditions triggers wider use, without appropriate recognition of potential limitations.
- Many publications tell of success stories for carefully selected sites showing exceptional simplicity in soil conditions. Errors remain undetected and unexplained observations remain untold.
- Many standards and detailed guidelines have implicit fuzziness about accuracy.

Usually, discussions on CPT accuracy take place without a satisfactory definition for accuracy. Some use accuracy in metrological terms of resolution or repeatability. Others presumably refer to accuracy under calibration laboratory conditions. Many are ambiguous about: (1) coupling of q_c, f_s and u with spatial position xyz and (2) true value related to permissible equipment-specific and procedure-specific features.

Defining accuracy requires a digression into metrology. Metrologists tend to be precise and accurate. Their vocabulary is reflected in JCGM (2012) “international vocabulary of metrology”. Accuracy relates to a “true quantity value of a measurand”; refer to Figure 1 and Glossary of Metrological Terms, Table 5. The following sections show that this true value is generally described in an approximate manner.

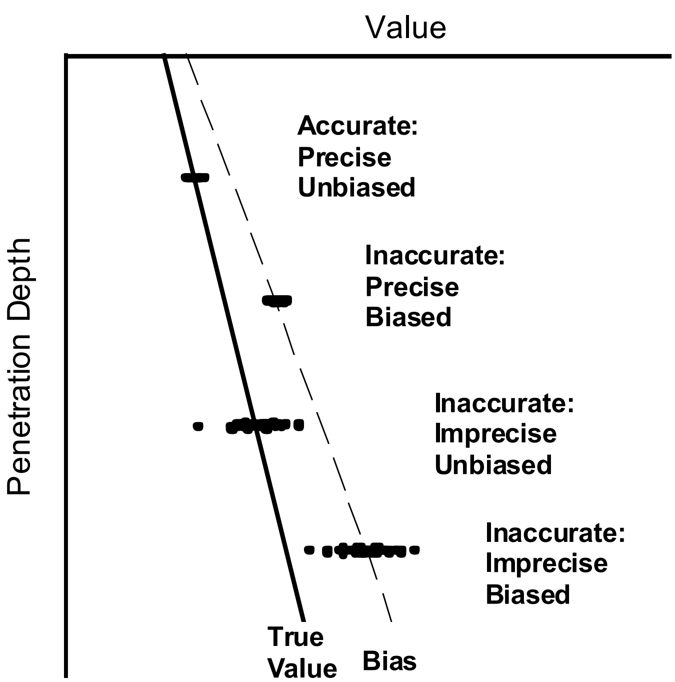

Figure 1. Accuracy, precision and bias.

The issue of true value related to permissible equipment-specific and procedure-specific features may be demonstrated by a proposed “Analytic CPT” that serves as benchmark for true values (Fig. 2). The proposed Analytic CPT complies with ISO 22476-1 and ASTM D5778 and features: (1) exact spatial position xyz where penetration depth z equals penetration length l, (2) penetration rate v of 20 mm/s (3) application of push rod thrust with no influence of thrust machine on ground conditions, (4) an imaginary cone penetrometer with a solid body of uniform geometry with no gaps, no pore pressure filter interference and surface roughness R_a = 5 μm and (5) zero measurement uncertainty.

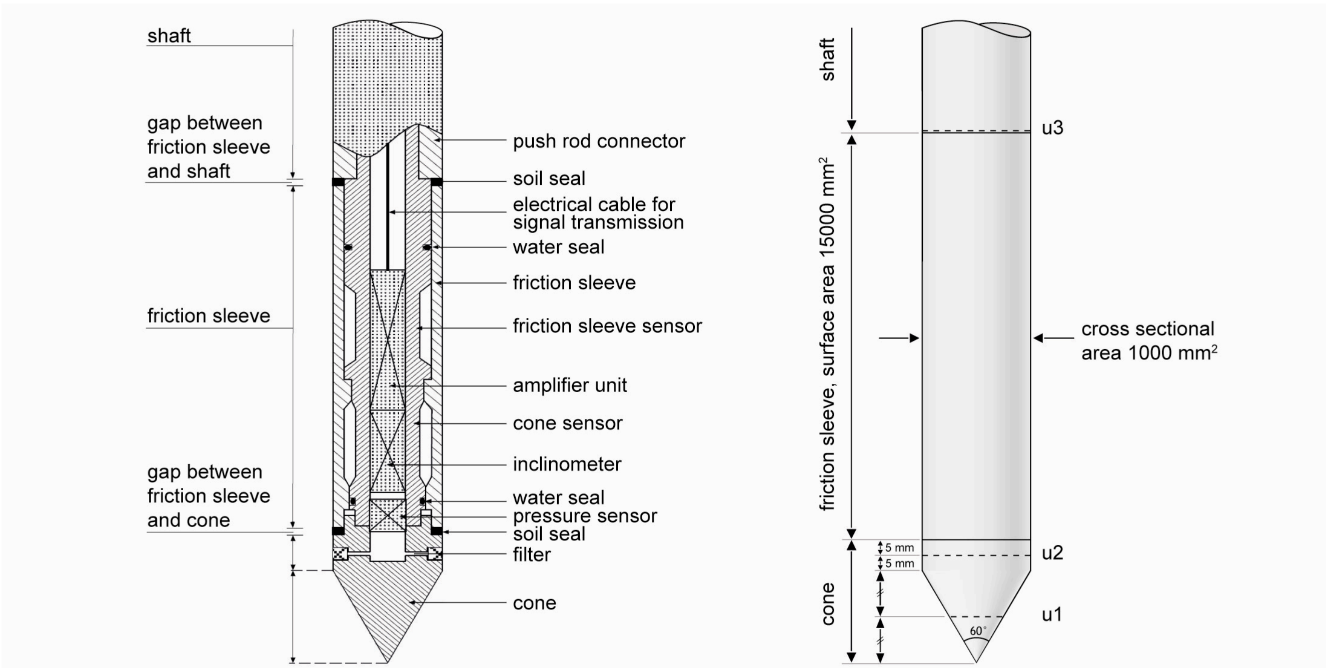

Figure 2. Example cone penetrometer from practice and proposed cone penetrometer for Analytic CPT.

4. CPT ACCURACY IN STANDARDS

The following sections focus on ISO 22476-1 and ASTM D5778. It is interesting to note that ISO 22476-1 uses the term accuracy and ASTM D5778 uses precision.

ISO 22476-1 is a performance-based standard, particularly defining CPT accuracy in terms of accuracy classes. ISO 22476-1 uses the term application class for accuracy class. The performance-based approach aims at a minimum accuracy of test parameter values within a framework of only essential requirements. ISO (ISO/IEC 2011, 2013) encourages a performance-based approach. ISO 22476-1 is remarkable, in that it refers normatively to the VIM (1993), by means of a normative reference to ISO 10012 (2003) "measurement management principles". In comparison, the authors are not aware of other standards for geotechnical tests defining important results in terms of accuracy as defined by VIM (1993). Some that do are in preparation. Note that JGCM (2012) replaced VIM (1993).

ISO (2003) states, "The measurement management system shall ensure that specified metrological requirements are satisfied". ISO 22476-1 expresses metrological requirements in terms of accuracy and error: "If all possible sources of errors are added, the accuracy of the recorded measurements shall be better than the largest of the values given in Table 2. The inaccuracy analyses shall include internal friction, errors in the data acquisition, eccentric loading, temperature (ambient and transient) effects and dimensional errors." The term accuracy assumes knowledge of a true value, i.e. what should be regarded as true value. Note that ISO 22476-1 assigns accuracy requirements to defined parameters, e.g. "measured cone resistance" q_c, "measured sleeve friction" f_s, and "measured pore pressure" u. These measurands depend on actual CPT system characteristics. ISO 22476-1 provides no explicit guidance on inevitable and allowable differences between measuring instruments and measuring practice. In other words, true values obtained by different systems will not be directly comparable. The term error implies a reference quantity value. This probably refers to a value determined in a calibration laboratory or similar, as it is generally impossible to obtain an in situ reference value. For example, calculation of cone resistance requires axial force and cone base area. A reference value for dimensional error for cone base area can be readily established. However, what would be the reference quantity for the influence of a permissible change in cone apex? Also, ISO 22476-1 provides no explicit guidance on coupled measurands (parameters). Presumably, ISO 22476-1 considers a true value of cone resistance to be uncoupled from a true value of pore pressure u and uncoupled from a true value of spatial position xyz below ground surface. Normally consolidated or slightly overconsolidated clay would represent a favourable setting for spatial coupling. Layered soil would represent adverse conditions. In practice, "all possible sources of error" will usually be interpreted as errors listed in Annex E of ISO 22476-1 "uncertainties in cone penetration testing". Note that Annex E offers no guidance on intentions for the words "include but are not limited to".

ASTM D5778 is prescriptive, method-based. Most standards for geotechnical tests are method-based. This implies that the aim is to produce equivalent and competing systems through detailed descriptions of specific apparatus and step-by step methodology. The accuracy of the acquired test parameter values is generally unknown. ASTM D5778 states: "Precision - There are little direct data on the precision of this test method, in particular because of the natural variability of the ground. Committee D-18 is actively seeking comparative studies. Judging from observed repeatability in approximate uniform deposits, persons familiar with this test estimate its precision as follows" (Table 2). ASTM D5778 also states: "Bias - This test method has no bias because the values determined can be defined only in terms of this test method".

Table 2. CPT precision according to ASTM (2012).

15.1.1 Cone Resistance	Provided that compensation is made for unequal area effects as described in 13.2.1, a standard deviation of approximately 2% FSO (that is, comparable to the basic electromechanical combined accuracy, nonlinearity, and hysteresis).
15.1.2 Sleeve Friction - Subtraction Cones	Standard deviation of 15% FSO.
15.1.3 Sleeve Friction - Independent Cones	Standard deviation of 5% FSO.
15.1.4 Dynamic Pore-water Pressure	Strongly dependent upon operational procedures and adequacy of saturation as described in 11.2. When carefully carried out a standard deviation of 2% FSO can be obtained.

Note: a subtraction-type penetrometer has two load cells in series. The lower load cell measures forces on the cone (C) and the upper load cell measures the sum of forces on the cone and the friction sleeve (C+F). The force on the friction sleeve is obtained by subtraction: (C+F)-C. An independent-type cone penetrometer has two load cells that measure forces on the cone and friction sleeve independently.

ASTM (2011) and ASTM (2013) define bias and precision: respectively "a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value" and "the closeness of agreement between test results obtained under prescribed conditions". The term uncertainty is mentioned under measurement, but not explained. ASTM (2011) mentions accuracy but provides no definition. ASTM (2013) refers to bias when looking up accuracy. It may be noted here that NIST (2013) distinguishes between bias and accuracy: "Accuracy is a qualitative term referring to whether there is agreement between a measurement made on an object and its true (target or reference) value. Bias is a quantitative term describing the difference between the average of measurements made on the same object and its true value."

5. CONE RESISTANCE

5.1 Geometry

ISO 22476-1 allows the use of cone penetrometers with cross sectional areas between 500 mm^2 and 2,000 mm^2. Cone penetrometer geometry should be adjusted proportionally to diameter, where dimensions for a 1,000 mm^2 penetrometer serve as reference. Similarly, ASTM D5778 considers cone penetrometers with cross sectional areas of 1,000 mm^2 and 1,500 mm^2. Test results may be used "without the application of correction factors", i.e. need not be accounted for in accuracy statements. However, scale effects will inevitably influence CPT results (De Beer 1963, Diepstraten 2003, Hird & Springman 2006, Meave Silva 1999, Peuchen et al. 2005, Peuchen 2012, Powell & Lunne 2005a, 2005b, Randolph 2004, Titi et al. 2000, Tufenkjian et al. 2010, Vreugdenhil et al. 1994). General comments are as follows.

- Cone resistance q_c in low-permeability (clay) strata may be expected to be within 10% of the reference cone size.
- It is much more difficult to make comparisons between cone penetrometers in sands. Build-up of q_c of a smaller cone penetrometer is faster than that for a larger penetrometer.
- There is some evidence that a smaller cone penetrometer provides higher q_c in strongly dilatant sands and lower cone resistance in sands with contractive behaviour. Differences can partially be explained by elastic theory.
- CPT signature may be affected when effective particle size D_{50} exceeds about 10% of the diameter of the cone penetrometer. Individual particles rather than the soil mass may contribute to the measurements.
- The loading response of a smaller penetrometer to soil layering is more rapid than that of a larger cone penetrometer. This relates to soil failure mechanisms in layered soils. Depending on ground conditions, the smaller probe may show higher peak q_c values and lower base values.
- Soil structure may cause failure mechanisms along zones of weakness. The larger cone penetrometer affects a larger mass of soil. There is a greater potential for soil structure effects. Thus, the larger cone penetrometer may exhibit lower q_c in structured soils.
- A fixed rate of penetration of 20 mm/s will affect transitions between drained, partially drained and undrained soil response to penetrometer penetration. This may be approximately quantified by a non-dimensional parameter V where $V = vd/c_v$, where v is penetration rate, d is cone diameter and c_v is coefficient of consolidation of soil.

The following sections consider cone penetrometers with a nominal cross-sectional area of 1,000 mm^2, unless indicated otherwise.

Measured cone resistance q_c is derived from the cross sectional area A_c of the cone and the axial force Q_c acting on the cone.

Measurement of cross sectional area is typically done by vernier calliper achieving an uncertainty of about ± 0.5% for 1,000 mm^2 cross sectional area under favourable conditions. The 0.5% value considers averaging of three vernier calliper measurements at 120^o, each with a calliper measuring uncertainty of ± 0.1 mm. This results in about ± 0.3% measurement error for cross sectional area. Cross sectional area will also be affected by a difference in temperature at the time of cross section measurement and temperature of a cone penetrometer embedded in soil. This is because of steel expansion/contraction at about 10^{-3}%/^{o}C. This influence is negligible.

Wear of a cone penetrometer is a non-random process. Approximate corrections for wear are feasible but uncommon in practice.

ISO 22476-1 and ASTM D5778 prescribe tolerances for cone geometry. In practice, the diameter of a new cone will be at a permissible (steel) geometry that provides maximum wear before cone replacement, i.e. 36.0 mm for a nominal 1,000 mm^2 cone penetrometer (ISO 22476-1 and ASTM D5778). This provides a cross sectional area that is 1.8% larger than nominal. Note that ISO 22476-1 allows a diameter of 36.1 mm for an u_2 filter, giving 2.4% larger than nominal. ASTM D5778 excludes this permission. A lower limit of 35.3 mm for a worn cone gives a 2.1% smaller area than nominal. These percentage values for area tolerances are upper limits for proportional influence on cone resistance. The influence of cross section variations will generally be less than proportional to cone resistance. This is because of net area ratio, discussed below. CPT processing software commonly considers a fixed cross sectional area at midpoint of wear. This approach results in a measurement error of up to about ± 2%. Note that this fixed area differs from the nominal value of 1,000 mm^2 and takes no account of net area ratio effects.

Tolerances not only affect cross sectional area but also, for example, cone apex and height of cylindrical extension (Fig. 3). ISO 22476-1 appears ambiguous on whether such changes in geometry may be ignored for estimates of accuracy of cone resistance. Effects on cone resistance are primarily significant for clay soils. For example, a 10 mm cylindrical height implies about 3.4% contribution to cone resistance for a typical clay soil and soil-steel friction on the cylindrical height equal to 3% of the cone resistance. ISO 22476-1 allows wear down to 7 mm cylindrical height. This would then imply a reduction in cone resistance of 1% compared to the 10 mm case. ASTM D5778 allows a wider range of cylindrical heights: 3 mm to 15 mm depending on penetrometer design. Contributions to cone resistance will vary accordingly. Changes in cone apex will also affect cone resistance, but probably to a lesser degree than cylindrical height. The authors are not aware of specific study results.

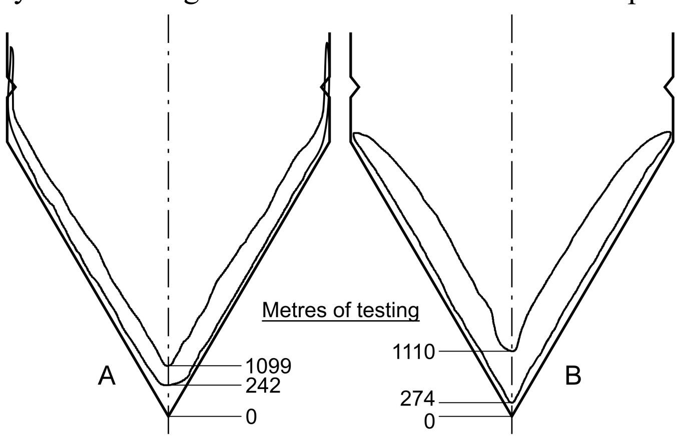

Figure 3. Wear of cones made of different materials after approximately same metres of penetration (Schaap & Zuidberg 1982).

Effects of variations in surface roughness are probably relatively small for cone resistance. It is tentatively estimated that variations in cone resistance are possibly less than ± 0.2% for favourable conditions and less than ± 2% for adverse conditions. The authors are not aware of specific study results. ISO 22476-1 specifies an average surface roughness R_a of <5µm for steel to be determined by a surface profile comparator. The requirement for cone surface roughness applies to the time of manufacture, with the intention that the roughness at manufacture approaches the roughness of a cone acquired upon use in common ground conditions. ASTM D5778 prescribes “The cone is made of high strength steel of a type and hardness suitable to resist wear due to abrasion by soil.” In practice, the ASTM D5778 approach will be equivalent to ISO 22476-1. The presence of a pore pressure filter will additionally affect surface roughness as a function of material type, manufactured geometry tolerances and geometric variations upon soil stresses acting on the filter.

The Analytic CPT has a solid body. In practice, all cone penetrometers incorporate a gap between the cone and the friction sleeve. The gap varies in volume upon cone penetration into soil and affects cone resistance because of deformation/ displacement of a flexible mechanical soil seal and an O-ring water seal and because of stresses induced by soil particles, water and gas in the gap.

A well-designed soil seal affects cone resistance by less than laboratory calibration uncertainty, i.e. no difference is typically observed between calibrations with and without soil seals.

Soil particles in the gap can lead to force transfer from the cone to the friction sleeve, i.e. cone resistance shows an apparent reduction. Sleeve friction will show an apparent increase by a factor 1/15, representing the area ratio of the cone to the friction sleeve. Force transfer can probably be ignored under favourable conditions, i.e. a well-designed soil seal and a nearly constant volume of the gap at a nearly constant force on the cone and the friction sleeve. Highly variable gap volume represents potential for adverse conditions. Such conditions may be expected under strongly variable soil resistance and with low-stiffness penetrometers. In extreme cases, errors in cone resistance may exceed 1 MPa, refer to Section 14. Sleeve friction signature will then typically approach that of cone resistance and accurate separation of cone resistance and sleeve friction will no longer be possible. These extreme cases can often be attributed to particles locking into the gap, possibly exacerbated by high steel-soil temperatures generated during cone penetration.

Soil in the gap will be subject to radial forces and soil-soil shear forces acting in an axial direction. Radial forces may cause particles to show Poisson's effects, the magnitude of which is probably small. The shear forces will largely transfer to the friction sleeve. This will be further discussed below. Schaap & Zuidberg (1982) observed calibration errors for cone resistance in the order of 2% to 3% for cone penetrometers returned to a calibration laboratory. Simple cleaning and maintenance reduced these errors to about 0.4%, indicating significant influence of soil ingress into the gap. The observations by Schaap & Zuidberg presumably applied to air-dried cone penetrometers. Better calibration errors could possibly apply under in situ conditions, with access to water. Jekel (1988) compared 11 CPTs in sand with removal of soil from gaps before start of a test with 7 CPTs without removal. No trend with q_c, f_s or R_f was found. The authors are not aware of other specific studies on cone/friction sleeve interference by soil particles at/in the gap.

Water and gas in the gap affect measured cone resistance. This may be explained by means of $q_t = q_c+(1\text{-}a)u_{2g}$. ISO 22476-1 uses the term corrected cone resistance for corrected cone resistance for q_t. ASTM D5778 use the terms corrected total cone resistance, estimated total tip resistance and total tip stress. The term u_{2g} represents water and/or gas pressure in the gap. It replaces u_2, where u_2 is pore water pressure traditionally derived from an initially saturated pore pressure measuring system positioned near but outside the gap. The term "a" represents net area ratio, i.e. the ratio of the cross-sectional steel area at the gap between cone and friction sleeve to the cone base area. Net area ratio is typically between 0.5 and 0.85. It depends on cone penetrometer design and wear of the cone. Note that wear of a cone from 36.0 mm diameter to 35.3 mm diameter would reduce (1-a) from an initial design value of, say, 0.25 to 0.22, i.e. by 14%. CPT processing software may allow entry of actual cross sectional area and corresponding adjustment in the theoretical value for (1-a).

It may be noted here that CPT standards prescribe measures promoting initial saturation of an u_2 measuring system. No such requirements apply to the gap. The effect of u_{2g} on cone resistance is important for normally and slightly overconsolidated low-permeability soils. The influence of u_{2g} on q_c is very small for dense sands. This small influence is because of high q_c values compared to u_{2g}. Values for u_{2g} depend on:

- initial degree of water/gas saturation in the gap, i.e. at start of test
- soil-induced changes to saturation
- soil seal behaviour
- soil permeability
- static groundwater pressure u_0
- transient pore water and/or gas pressures induced by cone penetration into soil
- volume change of the gap by strongly variable soil resistance and with low-stiffness penetrometers.

Accurate measurement of u_{2g} will be extremely difficult. The authors are not aware of cone penetrometers equipped with sensors for u_{2g} measurement, although recommended by ISO 22476-1 and alluded to by ASTM D5778. Under favourable conditions, u_{2g} will approximate u_2. Favourable conditions may be expected when u_2 values are relatively uniform and exceed about 2 MPa, i.e. at which point any free gas in pore water will be forced into solution (Fig. 4). This point should be reached at the equivalent of about 100 m to 200 m hydrostatic (ground) water head in high-permeability soil, i.e. rarely onshore and frequently offshore. It may possibly be reached at shallower penetration in low-permeability soils (clays and silts) with u_{2g} response exceeding u_0. However, low-permeability soils will allow only limited inflow of water into the gap, causing a delay in saturation. Also, soil particles in the gap may act as a barrier to water inflow. A deeper point applies to soil with $u_{2g} < u_0$, e.g. soil showing undrained and highly dilatant response upon cone penetration.

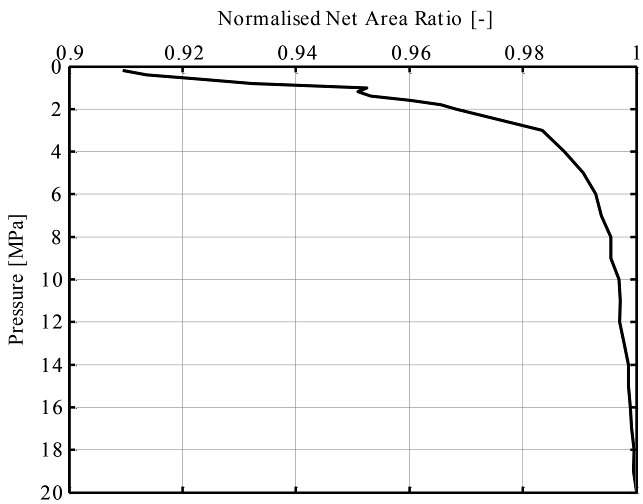

Figure 4. Laboratory water pressure versus normalised net area ratio.

Figure 4 suggests that favourable conditions may be approximated by an equivalent uncertainty for (1-a) and assuming $u_2 = u_{2g}$. Figure 4 presents applied pressure u versus normalised net area ratio, defined as $(1\text{-}a_{measured})/(1\text{-}a_{theoretical})$. Values for $a_{theoretical}$ were derived from manufacturing specifications and values for $a_{measured}$ were derived from q_c/u. An uncertainty in the order of, say, ± 2.5% for normalised net area ratio would give uncertainties for q_c of about ± 0.5% for (1-a) = 0.2 for normally consolidated or slightly overconsolidated clay. The value of ± 0.5% would increase to ± 1.3% for (1-a) = 0.4. Adverse conditions should be expected for most onshore CPTs.

An adverse setting can lead to a bias compared to a theoretical value of (1-a). An equivalent underestimate for (1-a) could then be in the order of, say, 12%. This may be mitigated to an uncertainty of say ± 8% by judicious selection of (1-a) values for data processing. The ± 8% value would give uncertainties for q_c of about ± 1.5% for (1-a) = 0.19. The 1.5% value considers data processing at 95% of the nominal value for (1-a), i.e. 0.19 instead of 0.2. Again this value would apply to normally consolidated or slightly overconsolidated clay. The corresponding uncertainty for q_c would be about 3.8% for (1-a) = 0.38.

An extreme case would be normally consolidated or slightly overconsolidated clay with u_{2g} remaining at atmospheric pressure during penetration. This could possibly apply when low permeability of soil prevents inflow of water into the gap. The corresponding bias would increase cone resistance by about 20% for (1-a) = 0.2 and by about 50% for (1-a) = 0.4, compared to favourable conditions.

Note that a penetration interruption may present an adverse condition. In an extreme case, it may possibly lead to an apparent increase of cone geometry. Examples of inevitable penetration interruptions are adding a push rod and performing a pore pressure dissipation test. The apparent increase may develop because of consolidation of low-permeability soil around a cone and associated to soil/penetrometer adhesion that is sufficient to give an increase in "cone" diameter (Fig. 5). Note that a stationary cone can apply local stresses that approach failure conditions, i.e. to close to net cone resistance or about two times the in situ mean effective stress. Resumption of penetration will usually lead to loss of adhered soil, perhaps within an equivalent distance of a few times the cone diameter. The authors are not aware of specific studies on this topic.

Figure 5. Clay adhering to cone penetrometer after retraction from soil.

5.2 Measuring range

Cone penetrometers used in practice typically match push capacity of common thrust machines and allow penetration into a wide range of soil conditions. Typical nominal measuring ranges for q_c are 0 to 50 MPa for cone penetrometers with cross-sectional areas of 1000 mm^2 and 1500 mm^2. Cone resistance measurements to about 150 MPa may be considered for special cases, for example for penetration of very dense overconsolidated sands by a cone penetrometer with a cross-sectional area of 500 mm^2. Cone penetrometer design typically incorporates an allowance for fully elastic behaviour to twice the nominal range.

Cone penetrometer calibration may be to a lower measuring range than allowable for a load cell. This can be useful for fine-tuning of linear sensitivity coefficients. A fitted curve may also be used. Note that a lower measuring range was historically used for improving resolution limits. This is no longer necessary. For example, a 24bit analogue to digital A/D conversion system would typically provide resolution better than 1 N or 0.01 kPa.

So-called pressure compensation (for example, CEC 1986, Boggess & Robertson 2010) is occasionally adopted for limiting the measuring range for offshore cone penetration tests. The interior of a penetrometer is filled with a fluid and a pressure compensator connects the fluid with tubing to the water at seafloor. The practice of pressure compensation relates to hydrostatic water pressure generating significant values of "cone resistance". Results for uncompensated cone resistance require correction to zero at seafloor. For example, the correction value for cone resistance at a water depth of 1000 m is about 7.5 MPa if the net area ratio of the cone penetrometer is 0.75. For comparison, normally consolidated clay may show a cone resistance q_c-gradient of 30 kPa/m depth, i.e. a cone resistance of 1.2 MPa at 40 m depth. This would imply "measured" cone resistances that are a small fraction of the correction values. In practice, a small-range penetrometer may compromise offshore project economics. Particularly, a larger measuring range for q_c of up to about 50 MPa can avoid penetrometer change-outs when encountering any deepwater hard grounds. For this case, the additional complexity of pressure compensation would not be necessary.

5.3 Force measurement

A well-designed cone penetrometer may show laboratory uncertainty for force (expressed as q_c) in the order of ± [5 kPa + 0.005 q_c] and an additional ± 0.005 $q_{c,max}$ for hysteresis effects. The parameter $q_{c,max}$ is the maximum encountered hysteresis value of q_c prior to reaching penetration depth.

A load cell is made of steel of a shape that suits a cone penetrometer. Its shortening upon loading is measured by strain gauge sensors glued to the steel surface. The strain gauges are connected in a single or double full Wheatstone bridge configuration. The bridge is excited with an electric voltage and the resulting ratio of output voltage to excitation voltage is measured, converted to a digital signal and a force. An accurate load cell requires a process of machining of the steel body, artificial aging by loading and heating processes, meticulous application of the strain gauges and again aging of the adhesives used for gluing the strain gauges. The space for the load cell in the cone penetrometer is typically filled with air, initially at atmospheric pressure. Water seals prevent build-up of internal pressure by external stresses induced by cone penetration. Variation in internal air pressure will occur because of secondary effects, such as cone penetrometer deformation and temperature variation. These secondary effects are assessed to be negligible for a well-designed penetrometer.

Accuracy and repeatability of a load cell are typically described by calibration error, repeatability, non-linearity, hysteresis and zero-load error (ASTM D5778). The sensitivity coefficient of a load cell is the relation of an applied load to the force output of the load cell. The sensitivity coefficient can be optimised by curve fitting or by applying a specific sensitivity coefficient for a specific portion of the nominal measuring range. Internal friction is a main contributor to hysteresis of a load cell. Particularly, transfer of soil resistance to an axial force on a load cell implies inevitable relative movements between the various components of the cone penetrometer. Disturbance of force transfer will occur due to internal friction caused by the water pressure seal(s) on the load cell body. Zero drift of load cell output typically results from shifts in the total calibration curve including its zero load output.

Laboratory calibration for a cone penetrometer is typically for loading/unloading against a reference load cell. Note that a high quality cone penetrometer has characteristics equivalent to a high-quality reference load cell, i.e. calibration results may be limited by the reference load cell. Low-range data may be obtained by incremental application of mass. Low-range data and any loading/ unloading loops provide information for soft soils and for offshore use, where cone resistance is taken as zero at seafloor, with an offset axial force representing water pressure (Peuchen 2000).

Routine laboratory calibration takes place under atmospheric conditions. A high pressure environment affects soil seals and water seals of a cone penetrometer. These seals consist of rubber or similar material. Their reduced elasticity upon in situ pressure increase can thus affect the inevitable relative movements between cone penetrometer components. VanLoon and Schaareman (1991) conducted experiments at an ambient pressure of 30 MPa, equivalent to a water depth of 3000 m. The experiments indicated a measurement error equivalent to about q_c = 4 kPa (2.5%) for an axial force of 250 N (equivalent to q_c = 166 kPa) on a subtraction-type cone penetrometer with a cone base area of 1500 mm^2. Increased error may be expected for low-stiffness penetrometers.

Laboratory-type error for axial loading increases with applied force and with hysteresis. Uncertainty analysis of actual CPTs may incorporate a prediction model for such errors. A simple model would consider the highest force applied at any point before reaching the actual penetration depth. For example, the model would assign low measurement uncertainty for a soil profile showing soft clay overlying dense sand. Conversely, soft clay underlying dense sand would show high measurement uncertainty.

Axial loading is applied during routine laboratory calibration. This represents favourable conditions. Non-axial loading of a cone penetrometer often occurs in practice. Figure 6 presents an example of penetrometer bending moment M inferred from inclination measurements according to Ooi & Ramsey (2003).

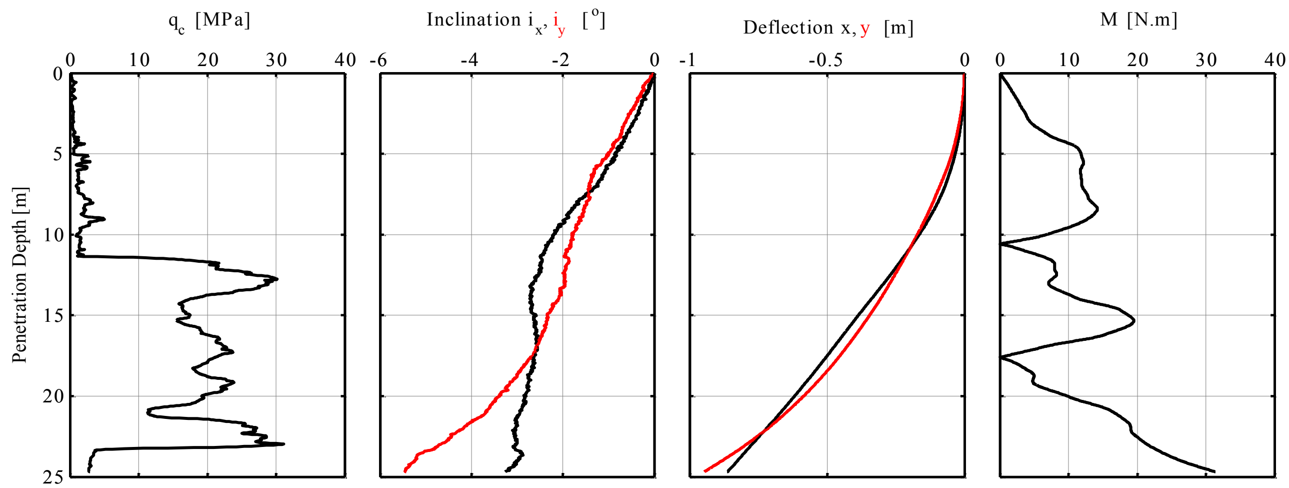

Figure 6. Bending moment inferred from cone penetrometer inclination.

Adverse conditions may be represented by a bending moment in the order of 100 N·m, which approximates a bending radius of 30 m. Figure 7 shows results of laboratory experiments for 1,000 mm^2 subtraction-type cone penetrometers equipped with double-bridge and single-bridge strain gauges. The experiments consisted of fixing a horizontal cone penetrometer just above the friction sleeve and hanging a mass from the cone. No axial force is applied. The directional dependency relates to radial positions of the strain gauges. As expected, higher errors may be observed for cone penetrometers equipped with single-bridge strain gauges. In-house Fugro studies indicate typically 2 to 4 times worse behaviour for single-bridge technology. Higher errors should also be expected for a penetrometer with low bending stiffness, for example for a so-called sensitive or low-range cone penetrometer. A lower bending resistance increases deformation. This can then increase internal friction between a load cell and body of the cone penetrometer, particularly in combination with varying axial force. Note that the diameter of a cone penetrometer is important for bending stiffness. Peuchen et al. (2005) speculated on bending stiffness substantially affecting measurement uncertainty. They reported a bending stiffness ratio (EI) of about 12:1 for subtraction-type cone penetrometers with 1000 mm^2 and 100 mm^2 cross sectional areas. This ratio is for a force (F) normalised to cone base area: $EI_{1000}/F_{1000} = 12\ EI_{100}/F_{100}$.

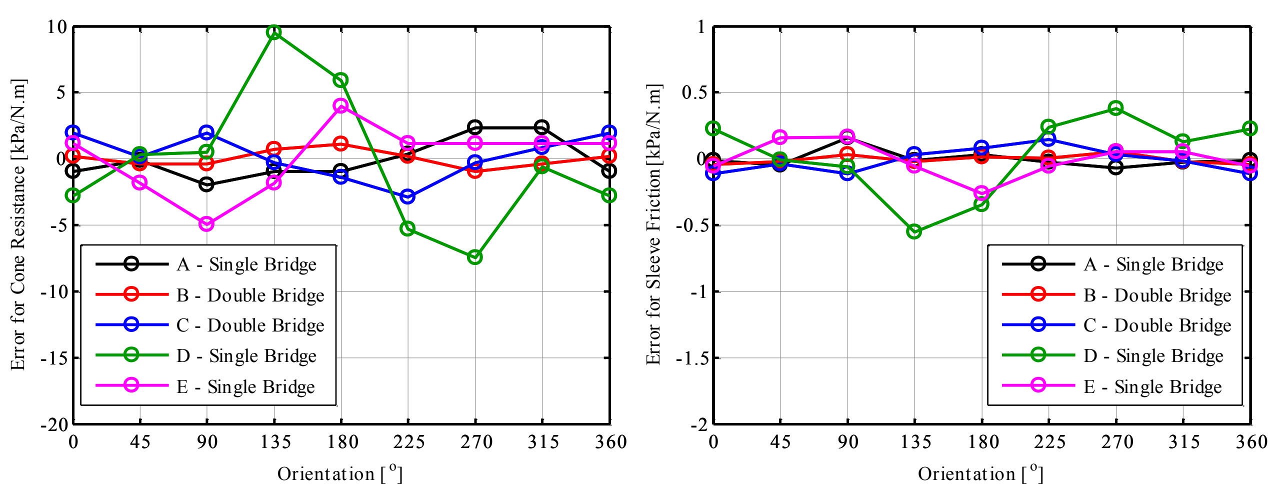

Figure 7. Measurement error due to bending moment - cone resistance (left) and sleeve friction (right).

Steel and strain gauges are subject to creep effects. Such effects are probably more than one order of magnitude less than temperature effects discussed below. Also, they cannot be readily isolated from temperature effects. Stress changes in a water pressure seal may possibly also contribute to apparent creep. Effects are assessed to be negligible for a well-designed cone penetrometer.

Force measurement will include measurement of barometric and gravitational variations taking place during a CPT. These influences can be ignored for a penetration phase of a CPT, which typically takes less than 1 hour. For example, a barometric variation of 5 mbar (high value) and a tide change (gravitational) of 1 m would theoretically affect cone resistance by less than 1 kPa and less than 10 kPa respectively. A long penetration interruption represents a possible adverse condition.

5.4 Temperature

Temperature change causes straining of the steel of a load cell, its strain gauges and their adhesives. Differential thermal strain shows as an apparent cone resistance. Temperature change of a well-designed load cell is a major reason for drift and a minor one for change in sensitivity. Temperature change may be ambient, where it is uniform throughout a penetrometer, with respect to time. Ambient temperature change may result from external air/ water/ soil temperature around a cone penetrometer. Under favourable conditions, ambient temperature change during a penetration phase will be limited to a few degrees. Note that near-surface onshore soils will typically show non-uniform temperature versus depth. A temperature gradient in the order of 0.04°C/m may be expected for deep penetration. An adverse setting may show ambient temperature change in the order of 20°C. Transient temperature gradients will be induced by self-heating of a cone penetrometer and may result from frictional heat during cone penetration and from thermal flux through push rods. Under favourable conditions, transient temperature change during a penetration phase will be close to zero. Uniform soft clays provide a favourable setting. An adverse setting may show transient temperature change in the order of 25°C. Transient temperature variations exceeding 100°C may possibly occur for cone resistance values of >120 MPa during penetration of dense sands (Post & Nebbeling 1995, Peuchen 2012).

Lunne et al. (1986) reported laboratory comparisons of ambient thermal zero drift for 12 cone penetrometers. Most, if not all, of the penetrometers were instrumented for temperature compensation. The measurements showed q_c zero drift ranging between -200 kPa to +760 kPa for $\Delta T = 25^{o}C$. The better penetrometers (6 of 12) showed q_c zero drift between +46 kPa and +100 kPa. Fugro in-house experiments conducted in 2011 and 2012 on penetrometers from three suppliers, including Fugro, showed values and spread comparable to the 1986 study results. Zero drift is approximately linear with temperature (Boylan et al. 2008). Temperature-induced drift under in situ stress pressures and axial loading is probably of similar magnitude to zero drift at atmospheric conditions.

Ambient temperature variation also changes the sensitivity of a load cell. Schaap & Zuidberg (1982) give explanations. They reported <1% change for $\Delta T = 20^{o}C$. Fugro in-house experiments conducted in 2004 for three Fugro penetrometer types confirmed this value for a temperature drop from +20°C to -20°C: -1.4%/40°C, -1.5%/40°C and -1.9%/40°C. The change is proportional to temperature change. Corrections can be applied. To the knowledge of the authors, this is not done in practice.

Boylan et al. (2008) inferred transient temperature influence from laboratory data. Figure 8 shows a laboratory example of variation in q_c for an unloaded penetrometer at an initial temperature of 20°C being immersed in water of 5°C. Note that a period of 250 s corresponds to 5 m continuous penetration. Boylan et al. also discuss in situ results for a cone penetrometer at an initial temperature of about 11°C pushed into soil with a temperature of 7°C at 1 m depth. The results are compared to in situ results from a similar cone penetrometer at an initial temperature of about 7°C. The comparison was expected to lead to a q_c offset of up to about 50 kPa based on laboratory simulations. Boylan et al. quoted 170 kPa offset for the in situ measurements and speculated about reasons for this higher value.

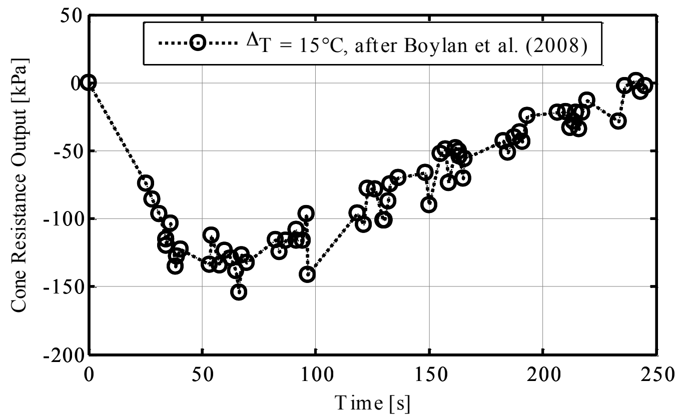

Figure 8. Laboratory variation of q_c upon transient temperature differential (Boylan et al. 2008).

Figure 9 presents ambient temperature influence on cone resistance. The results are for laboratory conditions, no axial loading, with and without temperature compensation. The case of no temperature compensation simulates adverse conditions that may apply in situ upon intense variation in transient temperatures in a penetrometer.

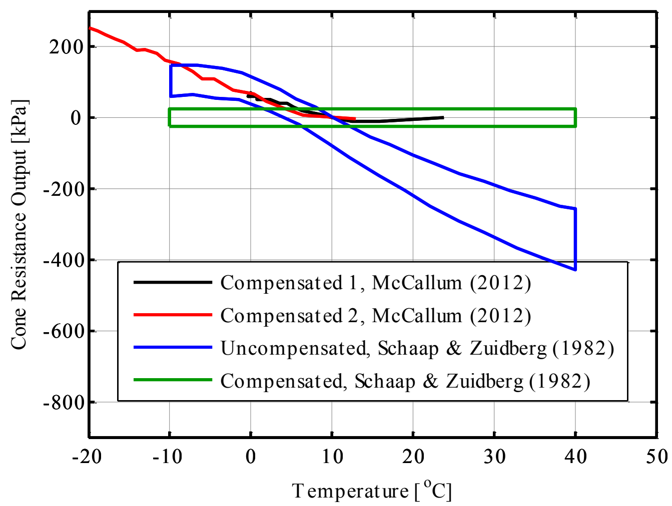

Figure 9. Zero drift of cone load cell caused by ambient temperature change.

Strain gauges and electronics inside a cone penetrometer dissipate power that will lead to heating of load cells. In addition, compression of steel will lead to very small energy dissipation. Resulting transient temperature effects are assessed to be insignificant for a semi-continuous penetration phase of a CPT. Effects may possibly apply after a long interruption, for example after a pore pressure dissipation test. The authors are not aware of dedicated experiments.

Post & Nebbeling (1995) focused on frictional heat. They presented results of field measurements and laboratory simulation for transient temperature effects on cone resistance. The measurements were performed with a Fugro subtraction-type cone penetrometer, routinely instrumented for ambient temperature compensation and specifically equipped with three internal temperature sensors. Post & Nebbeling inferred penetrometer heating in the order of 1^{o}C per 1 MPa increase in cone resistance. This is for an assumed linear relationship between temperature and q_c. The relationship depends on penetrometer type. Furthermore, Post & Nebbeling reported a temporary shift in cone resistance output of about 130 kPa for penetration of a sand layer with a cone resistance of about 25 MPa. This adverse setting represents a 0.5% error for q_c = 25 MPa and a 26% error for q_c = 0.5 MPa, for example for any underlying soft clay.

Heat flux from push rods to a cone penetrometer may occur under adverse conditions. This scenario is generally secondary to dominating effects of frictional heat on a cone penetrometer. It is ignored in practice.

Transient temperature influence may be mitigated by operational adjustments that cause a more or less ambient temperature setting in the cone penetrometer. An example would be a penetration interruption of around 5 minutes before cone penetration from dense sand into soft clay (Post & Nebbeling 1995). It would seem reasonable to mitigate temperature influence by measuring temperatures in load cells and correcting measured data based on laboratory simulation. However, this is complex because of temperature gradients δT with respect to time t ($\delta T/\delta t >>0$) acting concurrently with temperature gradients with respect to space x, y, z ($\delta T/\delta x$, $\delta T/\delta y$, $\delta T/\delta z >0$). The authors are not aware of any successful applications of this approach for strain gauge technology for cone penetrometers. In practice, this means that an error prediction model according to ISO 22476-1 should account for substantial epistemic uncertainty for heat accumulation/dissipation and for load cell response to temperature versus time. For example, the prediction model would consider (1) conservative heat accumulation/ dissipation and (2) maximum temperature bias (Fig. 8) as input for uncertainty.

6. SLEEVE FRICTION

6.1 Geometry

ISO 22476-1 requires a nominal perimeter surface area of 15,000 mm^2 for the friction sleeve. This is for a cone penetrometer with a cross sectional areas of 1,000 mm^2 and implies a length to diameter ratio of 3.75 for the friction sleeve. ISO 22476-1 permits ratios of 3 to 5. ASTM D5778 considers cone penetrometers with cross sectional areas of 1,000 mm^2 and 1,500 mm^2, with nominal surface areas of 15,000 mm^2 and 22,500 mm^2 for the friction sleeve, respectively. Nominal surface areas of 20,000 mm^2 to 30,000 mm^2 are permitted for a cone penetrometer with a cross sectional area of 1,500 mm^2. Scale effects will inevitably influence CPT results, as discussed for cone resistance. The following sections consider cone penetrometers with a nominal perimeter surface area of 15,000 mm^2.

Measured sleeve friction f_s is derived from the perimeter surface area of the friction sleeve and the axial force acting on the friction sleeve. The perimeter surface area is the cylindrical area. This excludes any machined bevelled ends of the friction sleeve. Measurement of surface area is typically done by measuring diameter and length by vernier calliper. Measurement uncertainty will be similar to that for measurement of cross sectional area of the cone.

ISO 22476-1 and ASTM D5778 prescribe tolerances for geometry of the friction sleeve. The authors are not aware of specific studies that quantify the effects of geometry tolerances. Tentative estimates are given below.

In practice, the diameter of a new friction sleeve will be at a permissible (steel) geometry that provides maximum wear before replacement, i.e. 36.1 mm diameter and 135.0 mm length for a nominal 1,000 mm^2 cone penetrometer (ISO 22476-1), giving a surface area that is 2.1% larger than nominal (15,000 mm^2). Lower limits of 35.3 mm and 132.5 mm are permissible in theory. Wear to these limits will not be concurrently achieved in practice. Limits of 35.3 mm and 134 mm would give a surface area that is about 1% smaller than nominal. ASTM D5778 prescribes 15,000 mm^2 ± 2%. CPT processing software may allow entry of measured surface area.

Tolerances not only affect surface area but also, for example, cross-sectional areas of the ends of the friction sleeve and cylindrical shape of the friction sleeve. As for cone resistance, ISO 22476-1 appears ambiguous on whether such geometry variations may be ignored for estimates of accuracy.

The effects of the cross-sectional areas may consider soil flow around the gaps below and above the friction sleeve and a friction sleeve diameter up to 0.35 mm larger than the cone, a tolerance set by ISO 22476-1 and ASTM D5778. Tentative estimates may be inferred from considering cone resistance to apply to this 0.35 mm annulus area at the bottom end of the friction sleeve, i.e. assuming 1x cone resistance would include reverse end bearing at the top of the friction sleeve. An initial friction ratio R_f of 3% for typical clay soil would then result in about 4.4% increase of f_s compared to sleeve friction with no cross-sectional area effects. Re-calculated R_f would be 3.1%. For clean sand, the increase in f_s would be about 19% for a friction ratio of 0.7%. Re-calculated R_f would be 0.83%. The 19% value contributes substantially to a 55% value that triggered geometry studies by Jekel (1988) discussed below. Cemented soils may show very high f_s peaks. Damage to a cone penetrometer may result.

Wear of a friction sleeve will occur during penetration and during retraction. Schaap & Zuidberg (1982) and Jekel (1988) reported studies of the mechanical wear of cone penetrometers and implications for robust cone penetrometer design (Figs 10, 11).

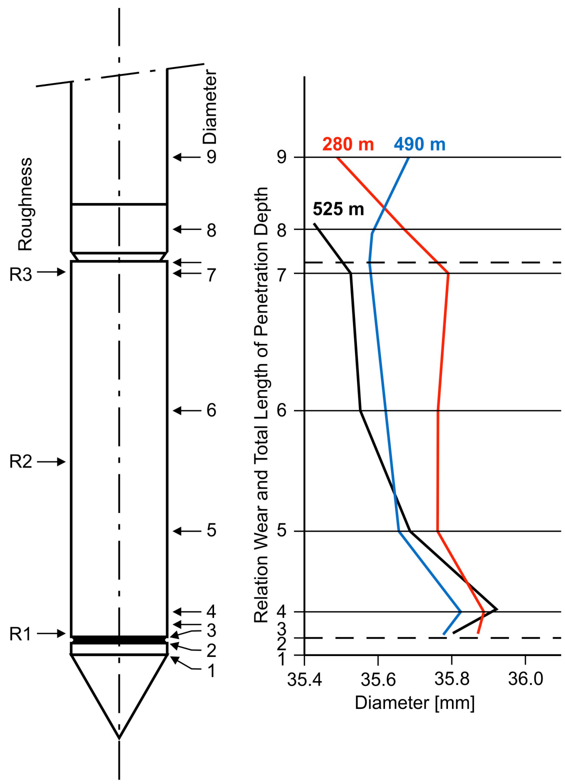

Figure 10. Observed geometry after wear (in sand) of three different cone penetrometers (Jekel 1988).

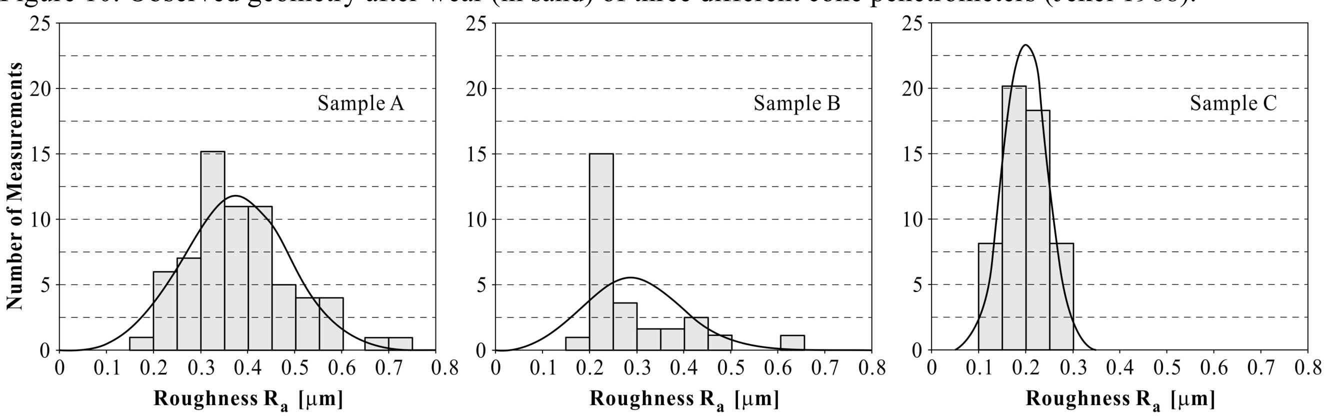

Figure 11. Surface roughness of friction sleeves observed after use (Schaap & Zuidberg 1982).

Jekel (1988) observed non-uniform wear of friction sleeves of cone penetrometers pushed into sand strata. Figure 10 illustrates a diameter reduction from the bottom to the middle of the friction sleeve. The reduced diameter is approximately constant for the upper part of the friction sleeve. Such wear will lead to lower sleeve friction because of reduced radial stresses on a significant length of the friction sleeve, compared to a nominal cylindrical shape. The influence of non-uniform wear is probably secondary to effects of cross-sectional areas of the ends of the friction sleeve. The authors tentatively suggest that adverse non-uniform wear may possibly lead to 10% reduction in sleeve friction. Note that ASTM D5778 limits the diameter of the top of the friction sleeve: it must not be smaller than the bottom diameter. ASTM D5778 also prescribes friction sleeves designed for equal end areas. These combined requirements leave practice with little opportunity to mitigate Jekel's observations with respect to a note by ASTM D5778: "Normally, the top of the sleeve will wear faster than the bottom". Adverse ground conditions may imply replacement or machining of a friction sleeve after each test or a few tests in harsh ground conditions.

Effects of variations in surface roughness of the friction sleeve may be expected to be higher than for cone resistance (Jekel 1988, Uesugi & Kishida 1986, DeJong & Frost 2002). The authors are not aware of study results specifically aimed at the requirements of ISO 22476-1 and ASTM D5778, i.e. an initial average surface roughness R_a of 0.4 µm +/- 0.25 µm upon manufacture. In principle, sleeve friction will depend on effective soil particle size/shape at the soil-steel interface relative to surface roughness. Particle size/shape in the interface zone may be influenced by particle breakdown and smearing upon cone penetration. In an extreme case, clay may adhere to a friction sleeve. A penetration interruption may promote clay adherence to a friction sleeve, as discussed for cone resistance. Clay adherence causes soil-soil shear away from the friction sleeve instead of soil-steel shear at the surface of the friction sleeve. A change in friction coefficient is likely. This change may cause unusually high sleeve friction. The influence of an increase in surface area is likely to be minor. If the increase in surface area is considered only, a uniform increase of 1 mm diameter would result in approximately 3% increase in measured sleeve friction. Additional end effects would account for an additional sleeve friction in the order of 13% for the unlikely case that clay would only adhere to the friction sleeve and not to the cone and not to the shaft.

Sleeve friction will be affected by two gaps: (1) gap between the cone and the bottom of the friction sleeve and (2) gap between the top of the friction sleeve and the shaft. The earlier discussion on cone resistance presents principles on gap influence.

Note that the bottom gap volume depends on relative displacements between the cone and the friction sleeve, each subject to variable axial forces. The volume of the top gap depends on friction sleeve displacement relative to the shaft of the cone penetrometer. The shaft may be regarded as fixed. Gap volume also changes by pressure, notably because of compression and displacement of the water seal.

Soil-soil shear forces acting in an axial direction on the bottom gap will largely transfer to the friction sleeve. A tentative estimate for increase in f_s would be about 3.7%. This is for a gap height of 5 mm and a soil-soil shear resistance assumed equal to f_s. Soil-soil shear forces acting on the top gap may be ignored. They will largely transfer to the shaft, apart from some Poisson's effects.

Water and gas in the gaps affect measured sleeve friction. Similar to cone resistance, this may be explained by means of a modified equation for f_t, corrected sleeve friction:

$$f_t = f_s - \frac{\left(u_{2g} \cdot A_{sb} - u_{3g} \cdot A_{st}\right)}{A_s} \qquad (1)$$

where A_{sb} is the cross sectional area in the gap between the friction sleeve and the cone, A_{st} is the cross sectional area in the gap above the friction sleeve and A_s is the surface area of the friction sleeve.

Note that the above equation assumes a cylindrical friction sleeve. For a non-cylindrical friction sleeve, water and gas pressures will also act on sections in-between the top and bottom of the friction sleeve. This effect is estimated to be secondary and may be ignored in practice. Equal end areas provide a reasonable compromise on gap influence on sleeve friction. ISO 22476-1 is not prescriptive on equal end areas and provides guidance on how to deal with their influence on sleeve friction. ASTM D5778 requires friction sleeve design with equal end areas ($A_{sb} = A_{st}$), which fits a prescriptive approach. ASTM D5778 states: “This will remove the tendency for unbalanced end forces to act on the sleeve”. This probably holds for CPTs in highly permeable soils and for fortuitous situations with $u_{2g} = u_{3g}$. Sleeve friction f_s will be higher in soils with $u_{2g} > u_{3g}$ and lower for $u_{2g} < u_{3g}$, compared to $f_s = f_t$ for the Analytic CPT.

Water and gas pressures will give an apparent increase in f_s for equal end areas of the friction sleeve and normally consolidated to slightly overconsolidated clay. For example, f_s would be about 1.125 f_t for $u_{2g}/f_s = 50$, $u_{2g} = 1.2\ u_{3g}$, $A_{sb}/A_s = A_{st}/A_s = 0.015$ and favourable conditions, i.e. pore water saturation in the gaps. For this case, it should be feasible to correct f_s to f_t to an uncertainty in the order of ± 5% of f_t. Estimation of f_t may consider u_3/u_2 data processing relationships based on soil behaviour type, similar to u_1/u_2 relationships proposed by Peuchen et al. (2010). Note that A_s, A_{sb} and A_{st} will change upon wear of the friction sleeve. This provides additional uncertainty if permissible geometry tolerances are considered with no test-specific measurement of geometry.

Lunne (1986) studied cone penetrometers with $(A_{sb} - A_{st}) / A_s$ ranging from -0.019 to +0.019. A positive value for $(A_{sb} - A_{st})$ will show an apparent increase in f_s compared to a friction sleeve with equal end areas.

6.2 Measuring range

In practice, measuring range for sleeve friction will be designed to match that of cone resistance. This is typically no issue for subtraction-type cone penetrometers. For independent-type cone penetrometers, this would imply a measuring range for f_s of, say, 0 to 1 MPa matching a typical nominal measuring range for q_c of 0 to 50 MPa and a nominal friction ratio of 2%. The corresponding axial forces would be 15 kN for the friction sleeve and 50 kN for the cone.

For offshore use, consideration should be given to force required to overcome (sea)water pressure acting on any unequal end areas of a friction sleeve. For an independent-type cone penetrometer, tension forces in a load cell will be induced if $A_{sb} < A_{st}$. Tension forces are unlikely for a subtraction-type cone penetrometer.

6.3 Force measurement

Principles on force measurement for sleeve friction are as for cone resistance. Independent-type cone penetrometers derive sleeve friction from either compressive or tensile force measurement. Subtraction-type cone penetrometers warrant additional comments: addition and subtraction (compensation) of uncertainties apply to compressive forces measured by two load cells in series. Laboratory uncertainty for f_s may then be expressed as:

$$b \cdot \sqrt{\delta Q_C{}^2 + \delta Q_{C+F}{}^2} \qquad (2)$$

where b is A_c/A_s and δQ_C and δQ_{C+F} are force uncertainties for the C and C+F load cells. A well-designed subtraction-type cone penetrometer shows very small or zero subtraction output under equal loading of the C and C+F load cells. Equal loading applies to routine practice in a calibration laboratory.

During in situ testing, the force on the C+F load cell will exceed the C force. The two load cells will then be at different points of a calibration curve. Hysteresis for the two load cells will be concurrent, leading to subtraction of the two hysteresis errors. For a well-designed penetrometer, it is estimated that the resulting error for f_s will be less than about ± 1.5% under favourable conditions and about ± 3% under adverse conditions.

As for cone resistance, laboratory-type error for axial loading increases with applied force. Uncertainty analysis of actual CPTs may incorporate a prediction model for such error.

Figure 7 illustrates influence of non-axial loading on measured sleeve friction. The examples highlight benefits from double-bridge strain gauge technology. Note that a subtraction-type cone penetrometer may show improved force measurement for sleeve friction under non-axial loading compared to force measurement for cone resistance. This improvement is possible when applying circumferential alignment of the C and C+F strain gauges, causing partial compensation of errors.

6.4 Temperature

The earlier discussion on cone resistance provides the principles for temperature influence on sleeve friction, particularly for independent-type cone penetrometers. Note that temperature influence results in an apparent force in a load cell. The nominal ratio of sleeve friction area to cross-sectional area of the cone is 15. If independent q_c and f_s load cells show equal influence and if R_f is 2%, then the relative error for f_s would be 3.3 times that for cone resistance.

Sensitivity of f_s to temperature effects is typically better than 15 kPa for $\Delta T = 50^oC$ (from -10°C to +40°C) for a well-designed penetrometer.

As discussed for cone resistance, an error prediction model for transient temperature influence should allow for substantial epistemic uncertainty for heat accumulation/ dissipation and for load cell response to temperature versus time. An error prediction model for a subtraction-type cone penetrometer may possibly allow for uncertainty reduction because of subtraction of concurrent uncertainties. For example, predicted bias for cone resistance would apply almost concurrently with that for sleeve friction. Such uncertainty reduction does not apply to independent-type cone penetrometers.

7. PORE PRESSURE

7.1 Geometry

ISO 22476-1 and ASTM D5778 aim at measuring in situ fluid pressure during penetration. ISO 22476-1 uses the term pore pressure. ASTM D5778 defines pore-water pressure. The requirement for measuring in situ fluid pressure implies isolating fluid pressure from soil inter-particle stresses and influence of any gas in soil. In practice, most piezocone penetrometers have measuring systems comprising an internal membrane-type pressure sensor, internal saturation fluid for transmission of pressure and a cylindrical porous filter positioned in a recess of the cone or shaft. One of the functions of the filter element is mitigation of mechanical damage to the pressure sensor. Further discussion will be limited to membrane-type pressure sensors and cylindrical porous filters, i.e. will exclude slot filters (Elmgren 1995) and radial button filters (Peuchen 1998).

Figure 2 presents positions for measured pore pressure. ISO 22476-1 and ASTM D5778 consider u_1, u_2 and u_3, with u_2 commonly quoted as standard, preferred, recommended or reference position. For pore pressure u_2, ISO 22476-1 defines: "u_2 - pore pressure measured on the cylindrical section of the cone (preferably in the gap between the cone and the sleeve)" and recommends: "To correct for 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." The u_2 position points toward two objectives: (1) characterisation of soil behaviour and (2) corrections for cone resistance and sleeve friction related to the gap between the cone and the friction sleeve. The second objective can only be partially met in practice, except under favourable conditions as discussed above for cone resistance. Inherent difficulties with the second objective are often ignored in practice, potentially leading to unnecessary loss of information. For example, onshore characterisation of highly stratified or overconsolidated sands and clays would typically improve when using u_1 data compared to u_2 data. In these conditions, a pore pressure measuring system at the u_2 position can lose saturation where the u_1 position would not. Loss of saturation leads to sluggish pore pressure response and reliable fluid pressure data may not be consistently obtained (Fig. 12).

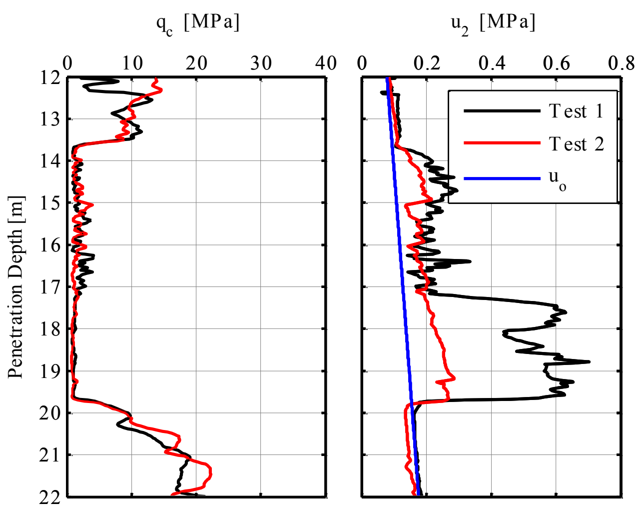

Figure 12. Pore pressure response for two closely spaced CPTs.

Robertson et al. (1986) illustrated typical pore water pressure distribution at the perimeter of cone penetrometers pushed in saturated soils (Fig. 13). Small variations in the precise vertical u_1 and u_3 positions will usually lead to minor differences in recorded pore pressures. Small variations in the u_2 position can lead to major differences in recorded pore pressure during penetration, particularly in sensitive clays and heavily overconsolidated clays. This implies high dependence of u_2 on penetrometer design (Peuchen et al. 2010).

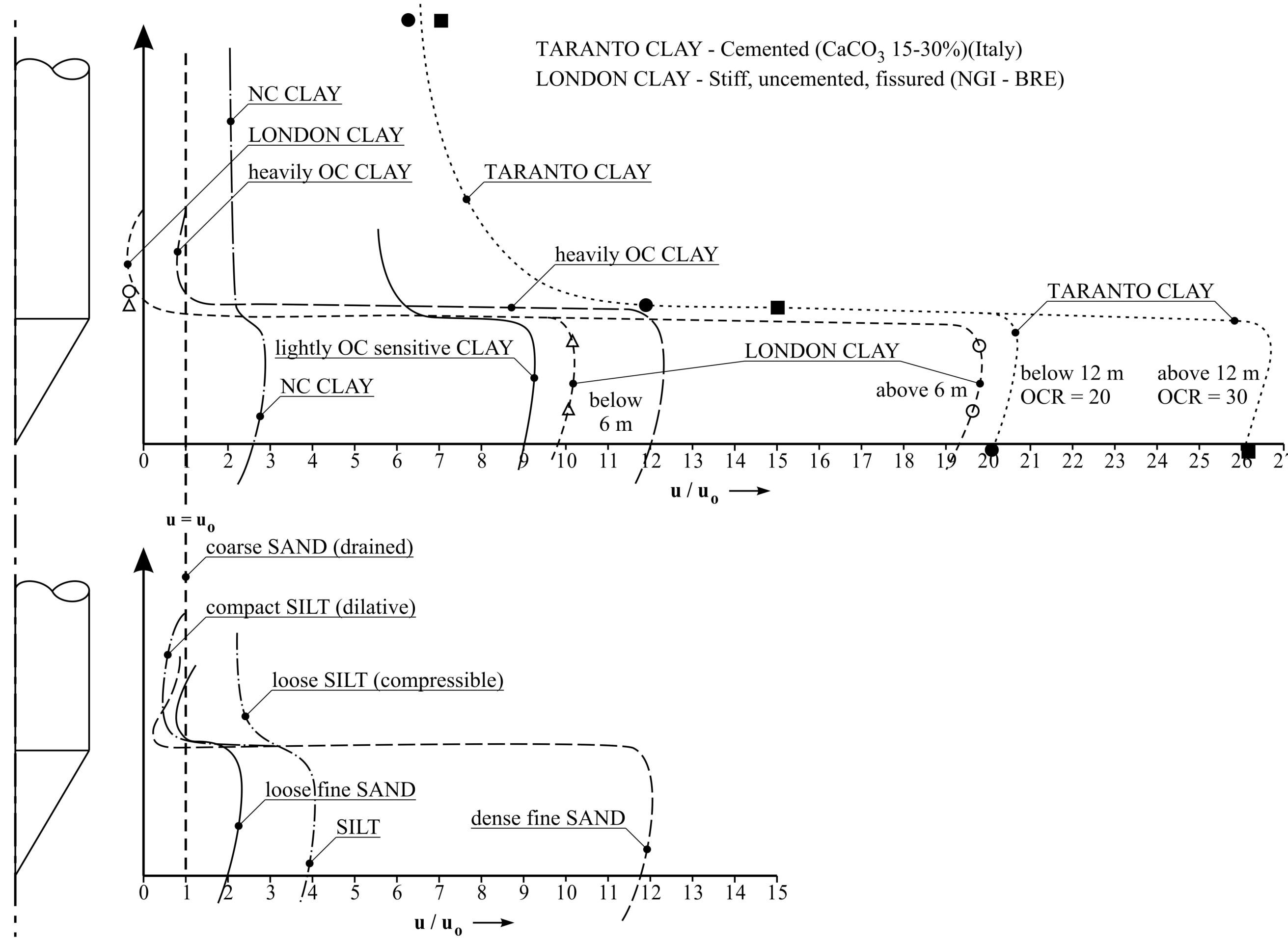

Figure 13. Pore pressure distribution in saturated soil (adapted from Robertson et al. 1986).

ISO 22476-1 and ASTM D5778 provide no specific requirements for external surface area of the filter element. Cone geometry and resistance against penetrometer wear provide indirect limitations. Surface areas for most piezocone penetrometers are determined by filter heights between about 3 mm and 6 mm.

The external surface of the filter element will not be perfectly flush with the steel of the cone or shaft and its surface roughness will differ from that of steel. ISO 22476-1 specifies external geometric tolerances for filter element diameter. ASTM D5778 does not. The ISO 22476-1 tolerances are relative to diameters of the cone and the friction sleeve. They apply to the start of a test, as geometry of a filter element may change during a test as a result of soil/fluid/gas pressures, shear and friction-induced temperature. Inevitably, a filter element represents a discontinuity in a flow field of soil around the cone penetrometer. Discontinuities represent stress concentrations. Micro fractures and localised shear zones cannot be excluded. This should generally be of little interest, but may possibly be important for any redistribution of dissolved or free gas in soil, as discussed below. Dissolved gas is defined here as gas dissolved in pore water with no occurrence of free gas. Free gas is defined as dissolved gas in pore water plus gas contained in bubbles or vacuoles. The occurrence of dissolved gas and free gas depends on factors such as gas concentration and solubility in pore water and ambient pressure. Methane and carbon dioxide are common types of gas in shallow soils below the ground water table.

Pore pressure may be affected by surface roughness of a u_1 or u_2 filter element, compared to steel of the cone. Filter diameter and roughness will also affect cone resistance and sleeve friction. The section on cone resistance provides comments. The authors are not aware of specific studies on these geometry topics. It is tentatively estimated that these influences are secondary to the precise u_1, u_2 or u_3 positions discussed above and material type discussed below.

The response time of a pore pressure measuring system will be affected by shape and volume of the internal space between the pressure sensor and the outside perimeter area of the filter element. Shape and volume affect initial fluid saturation of internal voids, retention of fluid saturation during penetration, fluid displacement required for pressure measurement and fluid displacement for accommodating inevitable system compliance effects such as deformation of the steel of the cone and the filter element material.

ISO 22476-1 and ASTM D5778 provide guidance on filter material types, filter pore sizes and fluid types for initial saturation of the measuring system. Choice of filter material type represents a compromise of competing requirements on geometric stability, robustness and pore size. The requirements for pore size typically compete on separation of in situ soil from saturation fluid, flow characteristics of saturation fluid and mitigation of formation of free gas within the pore pressure measuring system. Conventional Fugro practice is to use (ductile) high-density polyethylene HDPE cylindrical filter elements with an initial average pore size of 10 μm (Fig. 14). This type of filter material is robust and maintains its geometry reasonably well under favourable conditions, notably soft soil. Filter material compression and filter element deformation will inevitably occur upon penetration of competent soils. This will change pore size of the filter element and fluid flow paths at the interface of the filter element and its steel recess. Fugro trials with ceramic filter elements under adverse conditions showed frequent cracking or complete absence of the filter element upon recovery of the penetrometer. Trials with sintered steel showed a decrease in magnitude response due to pressure changes, compared to HDPE or ceramic filters.

HDPE | Stainless Steel | Ceramic

Figure 14. Filter elements (u_2) after use.

7.2 Measuring range

A piezocone penetrometer typically incorporates an off-the-shelf pressure sensor. The sensor housing may allow selection between sensors with different measuring ranges. Adverse conditions will typically require a measuring range of -0.1 MPa to 5 MPa. The -0.1 MPa limit relates to cavitation taking place at negative one atmosphere. Exceptionally harsh ground conditions may require a pressure sensor of >10 MPa.

A larger measuring range may be required for offshore use. This is because of additional (sea)water pressure. For example, a water depth of 100 m corresponds to a pressure of about 1 MPa. Some offshore CPT systems allow use of a differential pressure sensor that negates (sea)water pressure.

7.3 Pressure measurement

A membrane-type pressure sensor is similar to a load cell for force measurement in that it relies on strain gauge technology and typically incorporates compensation for ambient temperature variation. A well-designed pressure measurement system differs favourably from axial force measurement with respect to absence of influences from bending stresses and inner friction caused by water pressure seals. A high-quality pressure sensor may show laboratory uncertainty in the order of $\pm$ [1 kPa + 0.002 u + 0.0025 u_{max}] where u_{max} is the maximum encountered hysteresis value of u prior to reaching penetration depth.

As for cone resistance, laboratory-type error for pressure measurement increases with applied pressure. Uncertainty analysis of actual CPTs may incorporate a prediction model for such error.

Routine laboratory calibration takes place in a pressure vessel filled with tap water, with no filter fitted. This approach inevitably provides only partial simulation of in situ conditions. However, some information on any cross-talk for pressure measurement can be obtained by monitoring zero-load output of the pressure sensor during axial force calibration of a cone penetrometer.

Measuring in situ *fluid* pressure is a major challenge in practice. What is measured may comply with ISO 22476-1 or ASTM D5778, yet can fail to meet intentions. Particularly, accurate measurement of fluid pressure may not be feasible under adverse conditions that are not avoidable in practice. Examples of adverse conditions are: (1) soil with free gas, where induced fluid pressures at the measuring location (u_1, u_2 or u_3) are less than required for bringing free gas into solution and (2) cone penetration into soil with dissolved gas, where induced fluid pressures at the measuring location are lower than equilibrium in situ pore pressures. The first situation may occur locally, for example near ground surface or within a permeable soil layer with free gas in-between impermeable layers with no free gas. The second situation refers to exsolution where dissolved gas forms free gas. Gas diffusion may be ignored as a possible adverse situation. This is because of the relatively short time required for a CPT compared to a diffusion process.

Response time may generally be regarded as immediate for a measuring system with saturated fluid and no free gas (Rad 2003). However, rapid variations in pore pressure will cause inevitable expulsion of saturation fluid and entry of in situ pore fluid or gas, as discussed above. Low permeability of soil near the filter/soil interface may delay entry of fluid and cause a lag in pore pressure response.

Ideally, a pore pressure measuring system retains its initial fluid saturation during rapid variations in pore pressure or when locally encountering free gas. A u_1 position has the better prospects. Entry of free gas can affect measured pressure and response time. Laboratory studies by Nageswaran (1983) suggested that the error of the measured pressure should be less than 5 kPa for a well-designed pore pressure measuring system, even if the system becomes sufficiently gas charged for discontinuous fluid passage. Observations of in situ test data suggest possible error exceeding 5 kPa. Effects of free gas on response time depend on the characteristics of the pore pressure measuring system and the soil conditions. A response delay of less than a few seconds will often remain unnoticed. Sluggish response may become visible in uniform soils, for example upon regain of saturation during further penetration or during a penetration interruption.

If critical, loss of saturation of the pore pressure measuring system may be mitigated by an additional CPT, preceded by pre-drilling or pre-pushing to below the soil zone causing loss of saturation.

7.4 Temperature

A high-quality pressure sensor has built-in temperature compensation. Its thermal stability compares favourably to that of a load cell. A thermal stability in the order of $\pm$ 0.5 kPa/°C or better is feasible under ambient temperature variation. Response time to transient temperature variation is assessed to be in the order of seconds. This is because of small size and mass of a pressure sensor, which limit thermal differentials.

8. INCLINATION

ASTM D5778 recommends measurement of inclination i, but provides no requirements. ISO 22476-1 limits inclination of the penetrometer to 15^{o} from vertical and provides accuracy requirements of 2^{o} for Application Classes 1 and 2 and 5^{o} for Application Class 3. Off-the-shelf inclinometers should meet these requirements under adverse conditions including transient temperature variation. Fixing the verticality of an inclinometer in a cone penetrometer is probably the principal source of uncertainty. A typical measurement uncertainty in the order of 1^{o} can be achieved in practice. Omni-directional inclinometers and bi-directional inclinometers are common. Bi-directional inclinometers provide some opportunity for mapping horizontal position of a cone penetrometer. Gyro measurement may be necessary for accurate horizontal position, for cases with limited control of rotation of push rods. Figure 6 includes a spatial trajectory for a CPT profile in terms of lateral deflection.

Directional drift cannot be avoided. Comments are as follows.

– Engineered ground and young sedimentary deposits often exhibit soil layering that is close to horizontal. Inclined sub-bedding may still apply, for example as a result of spigoting practice, wind or wave action. Close-to-vertical penetration can often be observed.
– Older sedimentary deposits and residual soils may show inclined bedding and associated soil anisotropy. A cone penetrometer will incline toward a path of least resistance, which may not be vertical.
– Non-axial loading of a cone penetrometer can be expected in soils with significant heterogeneity at, say, 10 mm to 100 mm scale. Examples are locally cemented soils and soils containing gravel-size particles and larger.
– The conical shape of a cone penetrometer contributes to directional stability, albeit probably less than a bullet shape.

9. SPATIAL POSITION

9.1 Horizontal position

CPT parameters such as cone resistance require a geodetic position xyz in space and time. Ideally, accuracy of spatial position is coupled to accuracy of a CPT parameter. In practice, this dependency is left to geotechnical judgement.

ISO 22476-1 and ASTM D5778 provide no accuracy requirements for horizontal position xy. Typical uncertainties for xy position of an antenna of a location-specific GNSS global navigation satellite system would be ± 1 m to ± 2 m for DGPS differential global positioning system, ± 0.2 m for high-accuracy DGPS and ± 0.05 m for real time kinematic RTK DGPS. Additional uncertainty will apply because of uncertainty in antenna offset to the vertical axis of the thrust machine and because of directional drift of the cone penetrometer. An upper limit for horizontal drift may be derived from measurement of omni-directional inclination and assuming that the cone penetrometer is following a single horizontal direction. A multi-direction trajectory would imply a penetrometer position closer to the axis of the thrust machine than calculated.

9.2 Penetration depth

Users of CPT data typically have more interest in penetration depth z than horizontal position. This is because of many soils showing small correlation distances for the vertical direction compared to horizontal directions. ISO 22476-1 defines penetration depth as "vertical depth of the base of the cone, relative to a fixed point". ISO 22476-1 provides requirements for penetration length l defined as "sum of the lengths of the push rods and the cone penetrometer, reduced by the height of the conical part, relative to a fixed horizontal plane". The accuracy requirements are 0.1 m or 1% of penetration length and 0.2 m or 2% (Fig. 18). This implies transition points from a fixed value to a percentage value at penetration lengths of 10 m and 20 m respectively. It may be noted that the combined ISO 22476-1 requirements for accuracy of penetration length and inclination imply a permissible uncertainty for penetration depth that increases with penetrometer inclination. ASTM D5778 requires a depth accuracy of ± 0.1 m, where "depth" probably has the ISO 22476-1 meaning of penetration length and "accuracy" probably has the meaning of bias. Note that ASTM D5778 also uses the terms sounding depth, vertical depth and penetration depth.

Accuracy estimates for penetration depth depend on tool-specific deployment features, which typically focus on achieving maximum penetration at lowest cost (Table 3).

Table 3. Achieving penetration.

Practice	Freq.	Notes
Increasing thrust range		
Allowable push from thrust machine	*****	Increased push requires additional considerations for anchoring/ ballasting/ suction resistance (offshore) of thrust machine; buckling of push rods may become limiting factor particularly for soft-over-hard ground conditions
Measuring range for penetrometer force and pressure sensors	*****	Cone penetrometers used in practice typically match push capacity of common thrust machines and allow penetration into a wide range of soil conditions
Reducing friction along push rods		
Casing installation (drilling, free fall etc.) and short-push penetration from bottom of casing or drill pipe	***	Good track record; frequently applied in offshore cone penetration testing
Drill-out or full displacement hole formation, followed by installation of casing and push from ground surface	**	Residual friction on push rods remains; use of low-friction spacers in casing can largely eliminate casing-push rod friction; external soil-casing resistance may reduce ballasting or anchoring requirements for thrust machine
Continuous drill-out with fixed-length push rod latched in drill bit	*	Difficult to achieve in practice because of control required on penetration rate
Ground loosening or full displacement hole formation, followed by push from ground surface	*	Residual friction on push rods remains; percussion penetration of penetrometer can allow by-passing of competent zones at expense of no CPT data
Cyclic displacement of push rods	*	Residual friction on push rods remains; can be effective in combination with friction breaker
Friction breaker at short distance above cone penetrometer	*	Effectiveness approximates that of 1500 mm^2 cone penetrometer with 1000 mm^2 push rods
1500 mm^2 cone penetrometer with 1000 mm^2 push rods	***	Routinely used in practice for deep surface-push deployment; 1500 mm^2 penetrometer acts as friction breaker for 1000 mm^2 push rods
500 mm^2 cone penetrometer	**	Routinely used in practice for short or shallow penetration; push rod considerations dominate for deep surface-push deployment
Low-friction fluid or gas injection into soil above cone penetrometer	*	Some reported successes; appears to have some potential for narrow range of soil conditions; increased deployment complexity
Change of in situ soil conditions above cone penetrometer	*	For example change of in situ soil by high pressure water jetting, osmosis, thermal processes, vibratory liquefaction; the authors are not aware of use in practice

Practice	Freq.	Notes
Temporary and local change of laws of physics	*	Imagination
Frequency of use: * = less than 0.01% of CPTs, ** = between 0.01% and 0.1% of CPTs, *** = between 0.1% and 1% of CPTs, **** = between 1% and 10% of CPTs; ***** = more than 10% of CPTs.		

Uncertainty assessments for penetration depth require consideration of uncertainty in establishing a fixed horizontal plane and uncertainty in the actual trajectory of a cone penetrometer, relative to this horizontal plane. The following section discusses onshore CPTs with direct push from ground surface. ISO (2012b) presents guidance on penetration depths for CPTs deployed from a jack-up platform and from a floating vessel.

Ideally, the horizontal plane is a geodetic geoid, accurately fixed to a reference point for the push rods. Location-specific GNSS can provide information in real time to an uncertainty of about ± 10 mm to ± 20 mm (in real time) or better (static measurements). In routine practice, a horizontal plane is frequently determined relative to location-specific ground surface and local geodetic monuments. For many countries, uncertainty for elevation relative to geodetic monuments is probably in the range 5 mm to 10 mm. Uncertainty of elevation measurement relative to location-specific ground surface depends on factors such as ground surface slope, surface smoothness and ground conditions. Slope and smoothness relate particularly to offsets in horizontal positioning: a slight offset in horizontal positioning relative to a target position may render a higher or lower horizontal plane. Ground conditions can affect uncertainty for the horizontal plane by, for example, vertical displacement of a ballasted thrust machine operating on soft ground. Such displacement will take place during initial positioning of the thrust machine and during the test phase with variable force transferred from the thrust machine to the push rods. Measurement of and correction for such displacements are feasible, albeit infrequently performed in routine practice. In practice, uncertainty for a fixed horizontal plane is assessed to be in the order of ± 20 mm for favourable conditions. Uncertainty values exceeding ± 100 mm may be expected for unfavourable conditions.

Measurement of penetration length the trajectory of a cone penetrometer typically includes an inclinometer in the cone penetrometer and one or more of the following tools:

– Tape measure
– Mechanical distance sensor
– Optical distance sensor
– Fluid-flow distance sensor
– Acoustic distance sensor.

Length or distance measurement is typically between a push rod above ground surface and a fixed point on the thrust machine. Adverse conditions may impact length measurement, particularly: a) vertical movements of the thrust machine relative to a fixed horizontal plane, b) length variation and bending of the push-rod string.

Vertical movements of the thrust machine depend on system stiffness and ground conditions. For example, stiffness, including any slack, of a thrust machine can be important for an anchored system. Soft ground can give an adverse setting for a thrust machine relying on ballast. The thrust machine may initially settle. Heave may subsequently occur upon transfer of force from the thrust machine to the push rods. Settlement of the ground surface by force transfer to the push rods is assessed to be negligible for common adverse conditions. Force transfer will predominantly relieve the initial pressure imposed by the thrust machine on the ground surface. Equivalent stiffness may be in the order of 2.5 kN/m for adverse conditions.

Length variation and bending-type deformation of the push-rod string may take place when a cone penetrometer reaches a competent zone. Axial stiffness is assessed to be in the order of $1.6 \cdot 10^5$ kN/m of initial length of a push rod string consisting of 36 mm diameter, 1 m long thick-walled push rods. This implies push rod shortening of 0.06 % for a uniform axial force of 100 kN. It is assessed that bending can possibly result in similar error under adverse conditions. Examples of adverse conditions are a laterally unsupported section and soft soil with limited lateral support. Thermal effects are assessed to be negligible.

It may be inferred that a depth sensor on a thrust machine may incorrectly assume some non-existent penetration upon build-up of soil resistance during cone penetration. Similarly, a penetrometer that moves from a competent zone to a weak zone may show (very) rapid (unrecorded) penetration due to compressive strain release. Some of these effects may be captured during a penetration interruption, for example if required for addition of a push rod. NNI (1996) describes a so-called electronic heave compensator for penetration interruptions. The tool provides data for correction for relative movements between the push rod string and the thrust machine.

It is assessed that CPTs with direct push from ground surface would typically provide trajectory data to an uncertainty of ± 50 mm plus ± <1% of penetration length. These values are for favourable conditions. For penetration depth, the value of ± <1% may increase by ± 0.5% for an average inclination of the cone penetrometer of 4^{o}, measured to ± 1^{o} uncertainty. Values may double for adverse conditions. Note that common interpretation of ISO 22476-1 requirements will typically assume zero uncertainty for determination of a fixed horizontal plane. The value of ± 50 mm would then reduce to about ± 30 mm.

Accuracy improvement may be feasible by displacement modelling of a complete CPT system or selected parts. In most cases, thrust applied to the push rods would be an important input parameter. Thrust may be correlated to actual CPT measurements.

10. PENETRATION RATE

Penetration rate v is penetration length l normalised to (clock)time. ISO 22476-1 and ASTM D5778 specify permissible limits of ± 5 mm/s for a nominal penetration rate of 20 mm/s.

ISO 22476-1 requires data recording at lengths of ≤ 20 mm for Application Classes 1 and 2 and ≤ 50 mm for Application Classes 3 and 4. ASTM D5778 requires ≤ 50 mm. Increased frequency of data recording can provide better stratigraphic detail and may provide opportunities for improved processing of recorded data.

A typical thrust machine provides a push speed with an uncertainty within ± 5 mm/s under favourable conditions. Under adverse conditions, penetration rates may be outside ISO 22476-1 and ASTM D5778 limits. The push speed may vary or reduce under adverse conditions, for example with strongly varying thrust and towards the thrust limit of a thrust machine. In addition, the penetration rate is not equal to the push speed because of vertical movements of the thrust machine and length variation and bending of the push-rod string. The above section on penetration depth provides comments.

Influence of penetration rate on CPT parameters is particularly important where soil behaviour during penetration shows domain shifts: drained, partially drained and undrained (DeJong et al. 2012). Figure 15 presents an extreme example for loss of penetration rate v at 74.1 m below ground surface. The parameters Δu_2 and I_c are excess pore pressure (u_2 - u_0) and soil behaviour type index according to Robertson & Wride (1998). The presented penetration rates include no post-processing for influence of data point intervals.

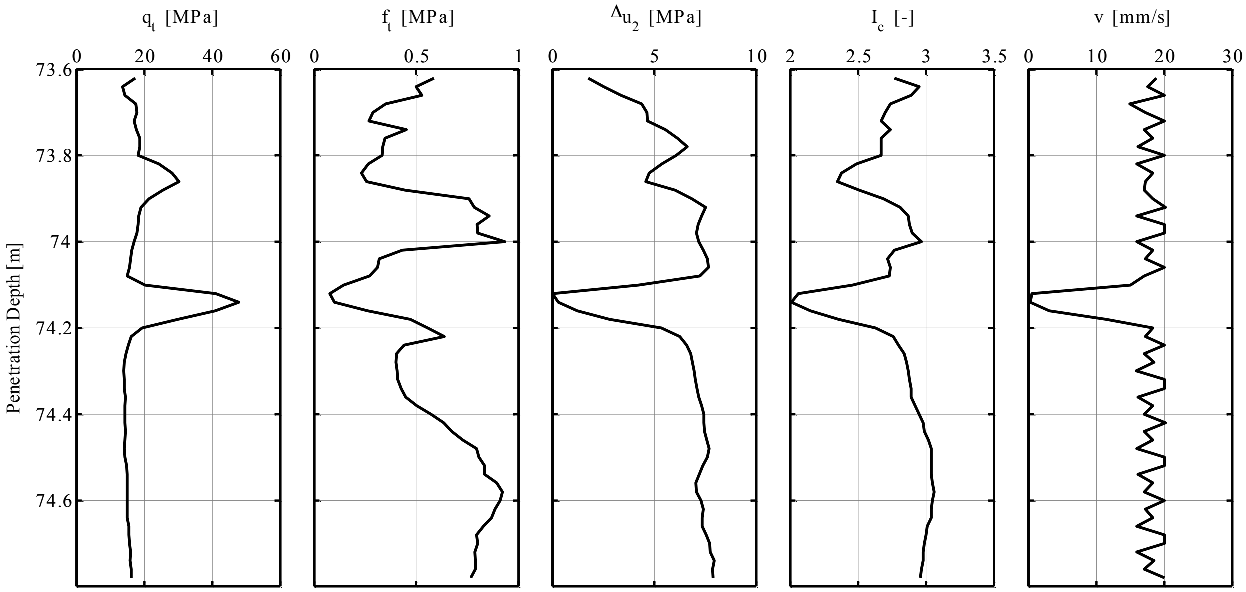

Figure 15. Example of penetration rate affecting CPT parameters for chalk (Peuchen & Balthes 2013).

11. DATA ACQUISITION

A sensor requires stable or known electric input. Sensor output typically consists of a ratio of electrical output versus input signal, expressed as mV/V or mV/mA. This signal is transmitted by wiring to an electronic system that converts this analogue signal to a digital value, i.e. A/D conversion. Apart from averaging or filtering, measurements expressed in digital counts are definitive after A/D conversion.

Excitation voltage and sensor output can be affected by deficiencies in the transmission system. Older data acquisition systems will typically include a relatively long cable transmitting signals between the cone penetrometer and electronics positioned on or near the thrust machine. Transmission may then be influenced by external electric noise, moisture, temperature, mechanical strain and insulation issues for wiring/cable etc. A voltage stabilizer and a signal amplifier in the cone penetrometer can mitigate such influences. On-site checks on data acquisition influence can be made by a signal simulator replacing a cone penetrometer. Older A/D conversion systems may have limits on resolution, for example 10 kPa on cone resistance. Workarounds in practice may include built-in amplification in combination with 16bit or 12bit A/D converters.

Newer systems incorporate electronics for excitation voltage and A/D conversion at or very close to the measuring sensors, i.e. within the cone penetrometer. Digital data transfer to a recording unit then takes place without loss of data quality. As discussed above for cone resistance, resolution presents no limiting factor for 24bit A/D conversion.

Temperature variations in a cone penetrometer affect built-in electronics, such as the A/D converter. Fugro experiments for cone resistance show an influence of about ± 0.001%/ºC plus a zero drift of ± 0.35 kPa/ºC. These values are an order of magnitude less than temperature sensitivity of a load cell or pressure sensor.

12. CORRECTED, INFERRED AND NORMALISED PARAMETERS

ISO 22476-1 considers accuracy for measured parameters: q_c, f_s, u, i, l and v. ISO 22476-1, ASTM D5778 and others also describe data processing for corrected, inferred and normalised parameters such as friction ratio and pore pressure ratio. Uncertainty estimates for such parameters can be inferred from the elementary considerations described above. The following paragraphs summarise selected topics. Note that some corrections and normalisations require external data and their corresponding uncertainty estimates. For example, net cone resistance q_n requires an estimate of in situ vertical stress. An additional uncertainty estimate is then required for the in situ vertical stress.

Many CPTs are without measurement of pore pressure u. The Netherlands probably hold a record for CPT metres per person per year, yet pore pressure measurement applies to about 5% of the CPTs (Long 2010). This low percentage may be attributed to perceived cost/benefit, bias to end-bearing piles and well-known soils that typically provide adverse conditions for pore pressure measurement, notably u_2. Nevertheless, an absence of u measurements should still allow fair confidence for derivation of corrected, inferred and normalised parameters, particularly for well-known soils.

ISO 22476-1 and ASTM D5778 require graphical presentation of q_c, f_s and u data. In addition, ISO 22476-1 requires presentation of tabular q_c, f_s and u data for Application Classes 1 and 2. In practice, presentation of these data may be versus time, length or depth intervals. Presentation at a fixed interval may consider a nearest data record. Fixed-interval reporting may also rely on interpolation and averaging techniques. The actual procedure will have little impact if CPT data are relatively uniform with depth. Differences should be expected for strongly layered soils. For example, a peak in pore pressure captured by high frequency recording may be missed or averaged by reporting to 50 mm length intervals.

ISO 22476-1 provides no specific requirements for vertical shift of measured sleeve friction to penetration depth z defined relative to the base of the cone. ASTM D5778 suggests the midpoint of the friction sleeve and the point of the cone. Consideration may be given to a matching cone resistance with measured sleeve friction at a point slightly below the midpoint, allowing for a non-uniform distribution of friction along the axis of the friction sleeve. Weighted averaging of multiple values of measured sleeve friction is also used in practice.

A penetration interruption will lead to loss or change of penetration data, compared to continuous penetration. Penetration rate will inevitable vary during the deceleration and acceleration of the penetrometer. The penetration interruption itself can lead to local or persistent change in q_c, f_s and u, as discussed above. In practice, data clips and smoothing will provide look-alike continuous penetration. Figure 16 shows an example of data as measured (unclipped) and processed data (data clips added where penetration rate is close to zero and re-interpolated for penetration depth at 20 mm spacing.

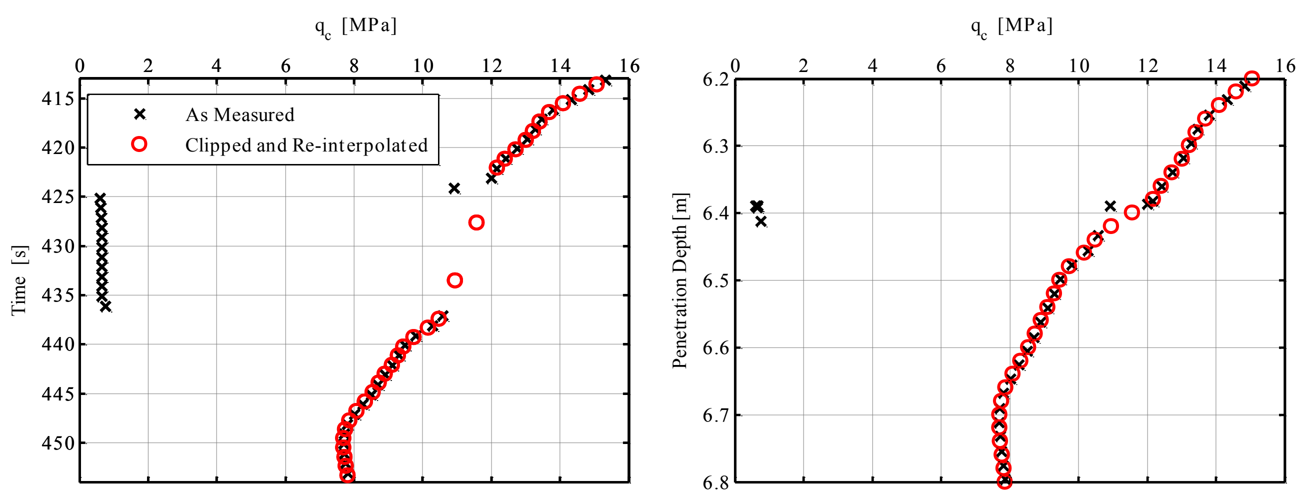

Figure 16. Penetration interruption - cone resistance q_c versus time (left) and q_c versus penetration depth (right).

Drift of a sensor for q_c, f_s or u will occur during a CPT. ISO 22476-1 and ASTM D5778 consider zero drift as indicator for possible anomalies in performance of a data acquisition system. In most cases, zero drift will probably be incurred as a result of temperature variations and creep. For example, increasing the penetration depth could imply penetration of harsh ground, temperature increase in the cone penetrometer and consequent increase in zero drift. The incurred zero drift would not apply to any shallow soft soil. The ISO 22476-1 connection between zero drift and application class is doubtful and may lead to unnecessary effort, for example conducting a drill-out to limit zero drift for a soft soil zone requiring Application Class 2. Zero values at the start of the test should normally be assigned to the full penetration phase. Also, it is incorrect to assume zero drift as proof of meeting a particular application class.

A thrust machine may apply significant and variable stress conditions to the soil to be tested. In practice, no corrections are applied to obtain equivalent free-field conditions. Influence of external stress conditions may be estimated from continuum mechanics such as elastic theory, where horizontal stress change is likely to dominate change of q_c and f_s. Use may also be made of correlations for correcting q_c for a change in ground surface level.

A non-vertical trajectory ($i > 0^o$) of a penetrometer can influence measured soil resistance, particularly where coefficient of earth pressure at rest $K_0 \neq 1$. ISO 22476-1 and ASTM D5778 provide no requirements for correction of measured soil resistance for inclination of a cone penetrometer. Figure 17 shows q_c and u_1 for non-vertical penetration in clay with K_0 values ranging between 0.4 and 1. The results consider calibration chamber tests and finite element modelling.

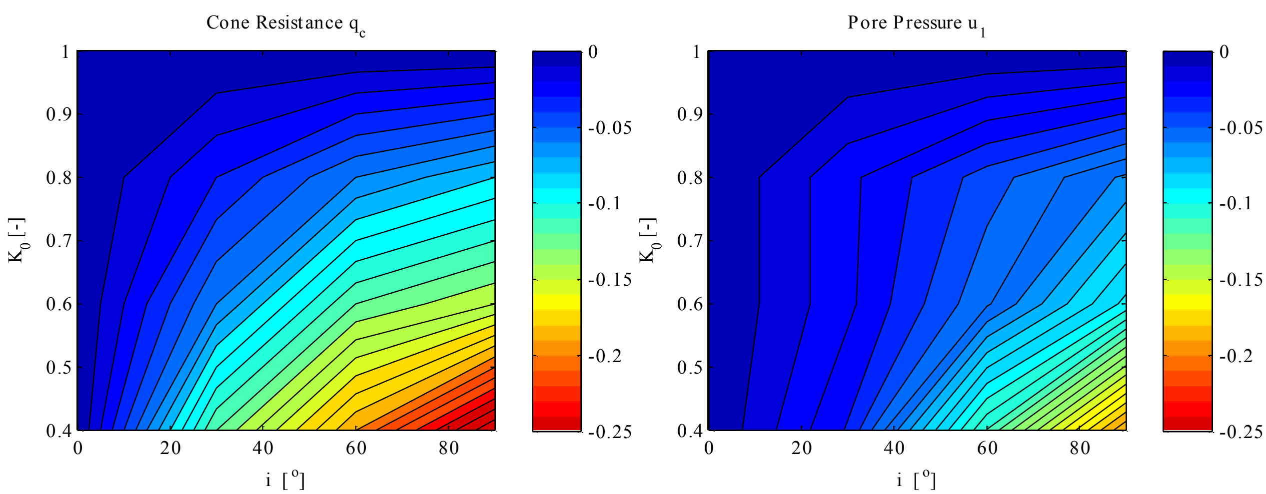

Figure 17. Influence of non-vertical trajectory on cone resistance q_c (left) and pore pressure u_1 (right), expressed as fraction of $K_0 = 1$ and $i = 0°$ (scale for colour bars is 0 to -0.25), after Wei et al. (2005).

ISO 22476-1 and ASTM D5778 require u_2 for calculation of corrected cone resistance q_t. These standards provide no guidance on resolving any differences between u_2 and u_{2g}, discussed earlier. In practice, this implies that q_t will usually depend on cone penetrometer design. The presumed $u_{2g} = u_2$ requirement is in conflict with needs from practice.

13. EXAMPLE ESTIMATION OF CPT ACCURACY

The current state of knowledge suggests that it will be difficult in practice to demonstrate compliance with any of the application classes of ISO 22476-1, except under favourable conditions.

Table 4 shows example input values for uncertainty estimates according to Type B evaluation (EA 1999). Actual values for a particular CPT system may be better or worse.

For favourable conditions, it may be inferred that the selected example values would result in meeting Application Class 1 of ISO 22476-1. This confirms current understanding derived from excellent test repeatability under uniform, favourable soil conditions (Fig. 18). Figures 19 and 20 show results for adverse conditions: layered sands and clays. The examples may possibly represent first-ever estimates that comply with ISO 22476-1 and its normative reference to ISO (2003).

The accuracy calculations for the adverse case show that the example CPT, as a whole, would fail to meet any of the application classes of ISO 22476-1. Significant epistemic uncertainty is the principal reason for this situation. Particularly, the prediction models for transient temperature and measurement error take account of lack of understanding and are necessarily conservative. The example test profile considers a single push from ground surface. Penetration interruptions for transient heat dissipation would improve results. Actual accuracy is probably significantly better than calculated. Further study is recommended.

Table 4. Example input for CPT accuracy estimates.

Cone Resistance, q_c	
Cone Load Cell, $\delta q_{c,trans}$	$5kPa + 5 \cdot 10^{-3} \cdot q_{c(i)}$ where $q_{c(i)}$ is measured cone resistance
Cone Load Cell, $\delta q_{c,hys}$	$5 \cdot 10^{-3} \cdot q_{c,max}$ $q_{c,max}$ is the maximum encountered hysteresis value of q_c prior to reaching penetration depth
Cone Area, δq_{Atip}	$0.02 \cdot q_{c(i)}$
Temperature, δq_{temp}	$\Delta T \cdot \left(10kPa \cdot ^\circ C^{-1} + 5 \cdot 10^{-4} \cdot ^\circ C^{-1} \cdot q_{c(i)}\right)$ where ΔT is change in temperature in degrees centigrade at load cell position; ΔT may be estimated from measured cone resistance[1)] or measured
Non-axial Loading, δq_{bend}	$M \cdot 10kPa \cdot N \cdot m^{-1}$ where M is bending moment at load cell position; M may be inferred from cone penetrometer trajectory[2)], or measured
Sleeve Friction, f_s	
Sleeve Friction Load Cell, $\delta f_{s,trans}$	$0.067 \cdot \sqrt{\delta q_{c,trans}{}^2 + \delta q_{c+f,trans}{}^2}$ where $\delta q_{c+f,trans}$ is as for $\delta q_{c,trans}$, except with added frictional force, for a substraction-type cone penetrometer
Friction Sleeve Area, $\delta f_{Asleeve}$	$0.015 \cdot f_{s(i)}$ where $f_{s(i)}$ is measured sleeve friction
Temperature, δf_{temp}	$\Delta T \cdot \left(1kPa \cdot ^\circ C^{-1} + 7 \cdot 10^{-4} \cdot ^\circ C^{-1} \cdot f_{s(i)}\right)$
Non-axial Loading, δf_{bend}	$M \cdot 0.5kPa \cdot N \cdot m^{-1}$
Pore Pressure, u	
Pressure Sensor, δu_{trans}	$1\,kPa + 2 \cdot 10^{-3} \cdot u_{(i)} + 2.5 \cdot 10^{-3} \cdot u_{max}$ where $u_{(i)}$ is measured pore pressure and u_{max} is the maximum encountered value of u prior to reaching penetration depth
Temperature, δu_{temp}	$\Delta T \cdot \left(0.5\,kPa \cdot ^\circ C^{-1} + 5 \cdot 10^{-4} \cdot ^\circ C^{-1} \cdot u_{(i)}\right)$
Inclination, i	
Inclination Sensor, δi_{trans}	$\delta i_{trans} = 1^\circ + 1 \cdot 10^{-3} \cdot i_{(i)}$

Penetration Length, l	
Penetration Length Sensor, δl_{trans}	$5 \cdot 10^{-3}\,\mathrm{m} + 5 \cdot 10^{-3} \cdot l_{(i)}$ where $l_{(i)}$ is measured penetration length
Sampling Frequency and Penetration Rate, δl_{samp}	$0.5 \cdot v_{(i)} \cdot \frac{1}{f_{samp}}$ were $v_{(i)}$ is penetration rate calculated from penetration length sensor
Push Rod Compression and Bending, $\delta l_{compression}$	$12 \cdot 10^{-6}\,\mathrm{kN}^{-1} \cdot Q_{thrust} \cdot l_{(i)}$ where Q_{thrust} is total thrust on the push rods; Q_{thrust} may be measured or estimated[3)]
Thrust Machine Stiffness, $\delta l_{thrust\ machine}$	$10^{-4}\,\mathrm{m} \cdot \mathrm{kN}^{-1} \cdot Q_{thrust}$
Elastic Soil Relaxing, δl_{relax}	$4 \cdot 10^{-4}\,\mathrm{m} \cdot \mathrm{kN}^{-1} \cdot Q_{thrust}$
Fixed horizontal Plane, δl_{plane}	0.05 m

Notes:

1) Temperature ΔT may be estimated from cone resistance according to $\Delta T = T_{soil} + \left(T_{cone} - T_{soil}\right) \cdot e^{-r \cdot \Delta t}$ and $T_{cone} = 1^{\circ}\mathrm{C} \cdot \mathrm{MPa}^{-1} \cdot q_{c(i)}$. The factor r depends on local convection heat transfer coefficient, the area over which convection occurs, cone penetrometer density and heat capacity. A (forward) smoothing function may account for delay effects in generation of frictional heat and transition to a load cell location.
2) Bending moment may be inferred from Young's modulus, second moment of area and curvature of a cone penetrometer trajectory according to $M = E \cdot I \cdot \psi$
3) Thrust on push rods may be estimated by $Q_{thrust} = q_{c(i)} \cdot A_{tip} + \frac{1}{R} \cdot \int_0^l f_{s(i)} \cdot \pi \cdot d_{rod}\,dl$, where R typically ranges from 3 to 7.

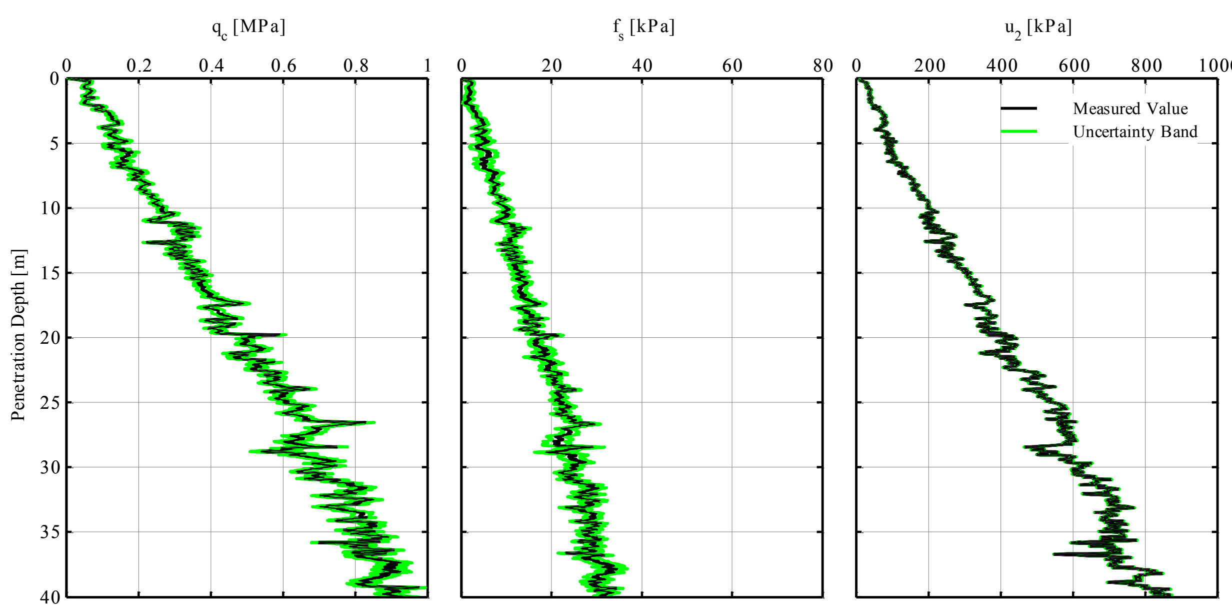

Figure 18. Uncertainty estimates according to ISO 22476-1 for CPT values measured under favourable conditions of homogeneous slightly overconsolidated clay.

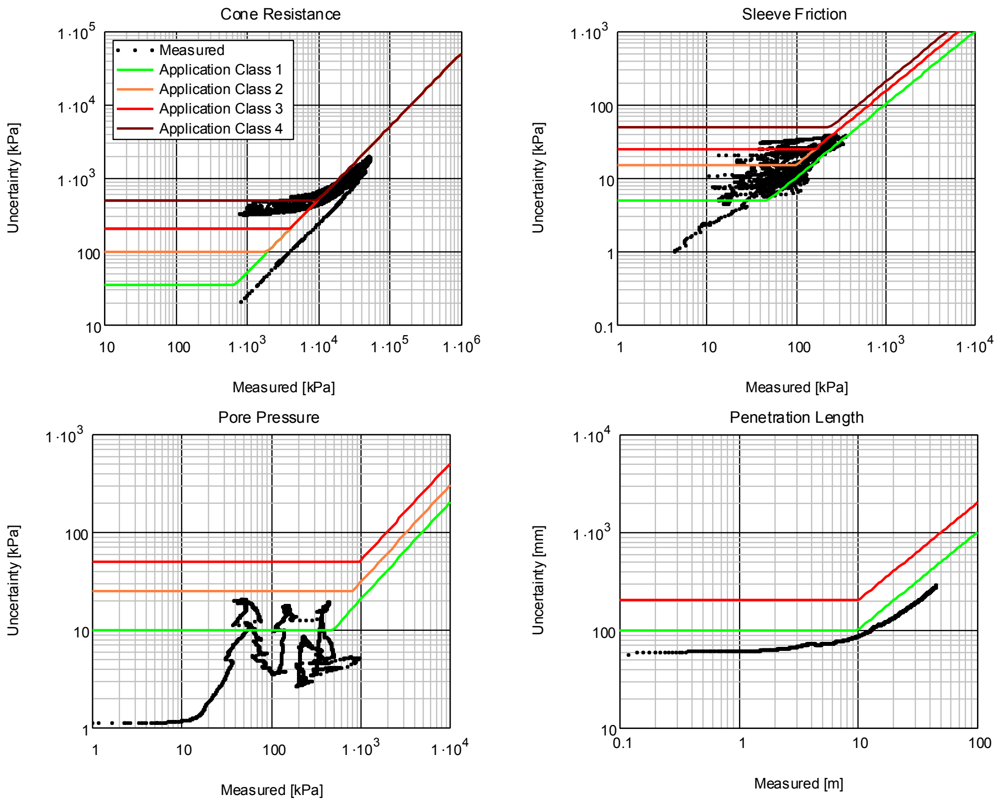

Figure 19. Uncertainty estimates according to ISO 22476-1 for CPT values measured under adverse conditions of layered sands and clays.

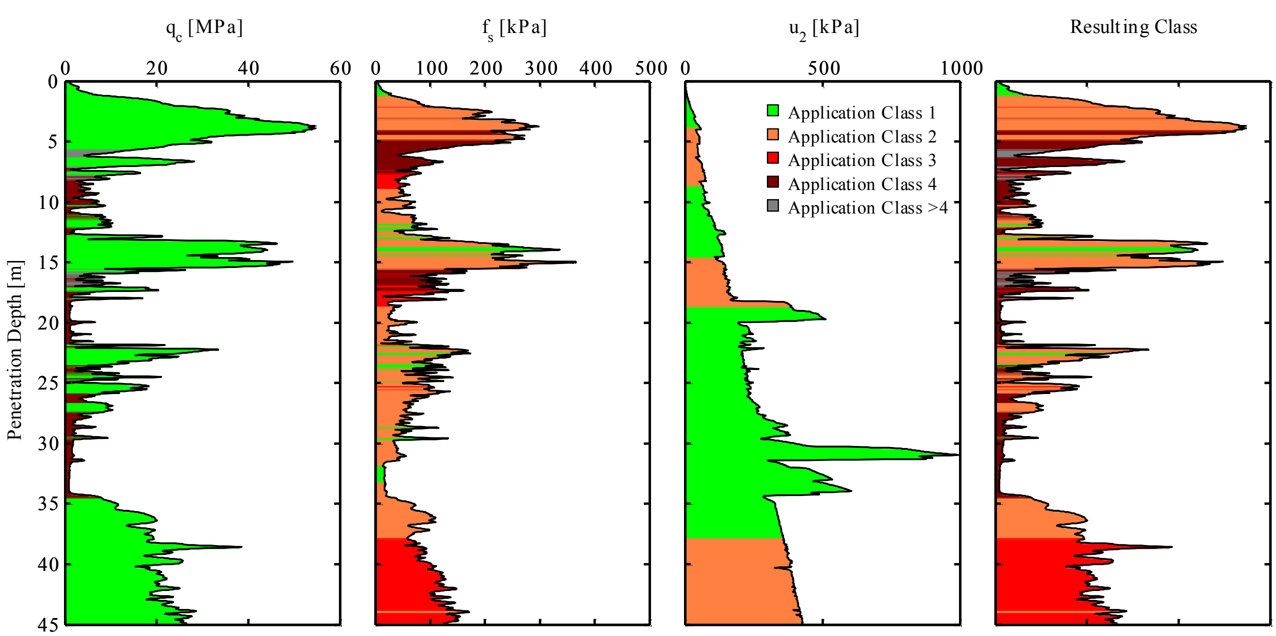

Figure 20. Demonstrating compliance to ISO application classes, for adverse conditions of layered sands and clays.

14. CHALLENGES IN MEASURING PRACTICE

This section presents examples of challenges faced in measuring practice.

Figure 21 illustrates difficulty in conclusively distinguishing in situ soil behaviour from CPT measurement error. Values for q_t and f_t show unusual reductions at a penetration depth of about 17 m. Corrected friction ratio R_{ft} and pore pressure ratio B_q also show significant variations. Pore pressure u_2 shows an approximately linear increase from ground surface to 40 m penetration depth.

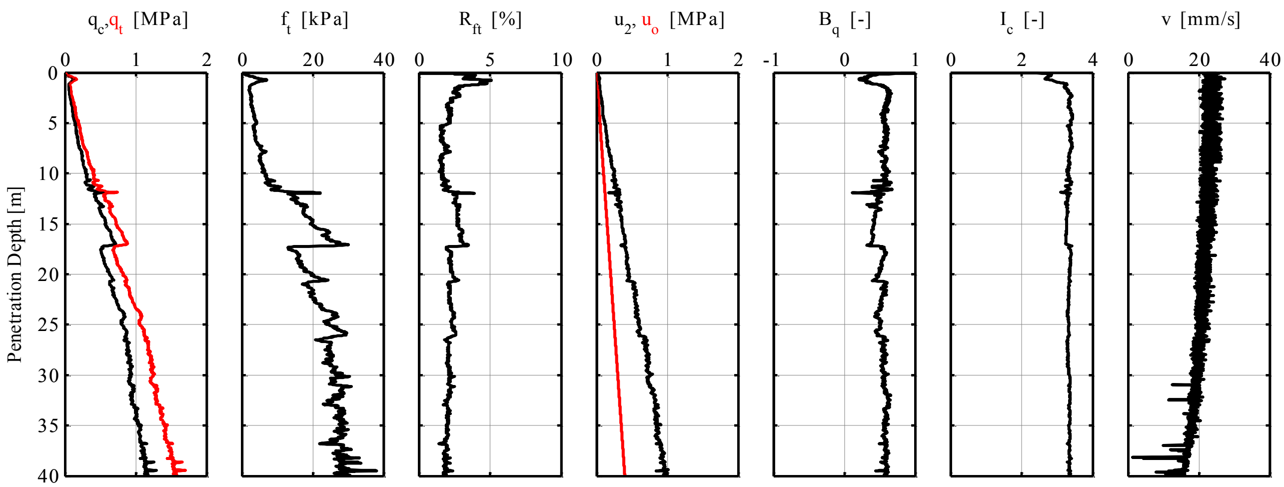

Figure 21. Unusual reduction in q_t and f_t at 17 m penetration depth.

Comments are as follows.

- CPT deployment was by single push from ground surface, with no interruptions for push rods.
- Quality monitoring records were according to expectations. Zero drift values for q_c, f_s and u_2 were +15 kPa, +2 kPa and +4 kPa respectively.
- The q_t trends with depth have negative intercepts at ground surface for penetration depths between about 12 m and 17 m and between 17 m and 24 m. This is unusual for normally consolidated to slightly overconsolidated clay, but may possibly reflect depositional regimes.
- A similar profile was observed for a nearby location.
- The 12 m level shows evidence for a depositional discontinuity: locally increased cone resistance and reduced pore pressure. This zone may have triggered build-up of clay adhering to the cone penetrometer. However, the plausibility of this hypothesis seems low.

Figure 22 illustrates challenges with measuring pore pressures at the u_2 location, instead of u_1. Particularly, u_2 shows negative values as low as -1800 kPa upon penetration of soil depositional discontinuities.

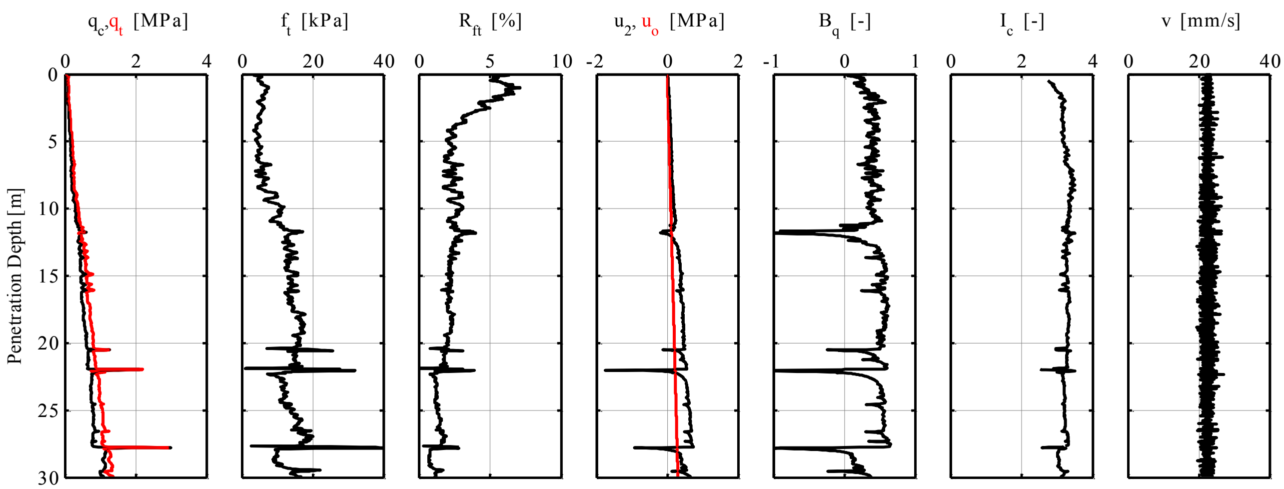

Figure 22. Negative u_2 values (-1800 kPa).

Comments are as follows.

- CPT deployment was offshore and included a single push from seafloor, with no interruptions for push rods.
- Quality monitoring records were according to expectations. Zero drift values for q_c, f_s and u_2 were +16 kPa, 0 kPa and -1 kPa respectively.
- A negative u_2 value is followed by pore pressure recovery to positive values. The recovery distance is at least 0.5 m or about 25 seconds. The delay in pore pressure recovery is probably a function of low permeability of soil that inhibits fluid movement required for pore pressure measurement.
- The u_2 values for the recovery period appear to give a reasonable representation of pore pressure u_{2g} in the gap between the cone and the friction sleeve. This may be inferred from comparison of q_c and q_t values.
- An onshore test would have been limited in measuring negative pore pressures to around -100 kPa. Pore pressure recovery would have been uncertain and estimation of u_{2g} would have been difficult.

Figure 23 illustrates deployment challenges for a cone penetrometer, particularly very soft clay overlying claystone.

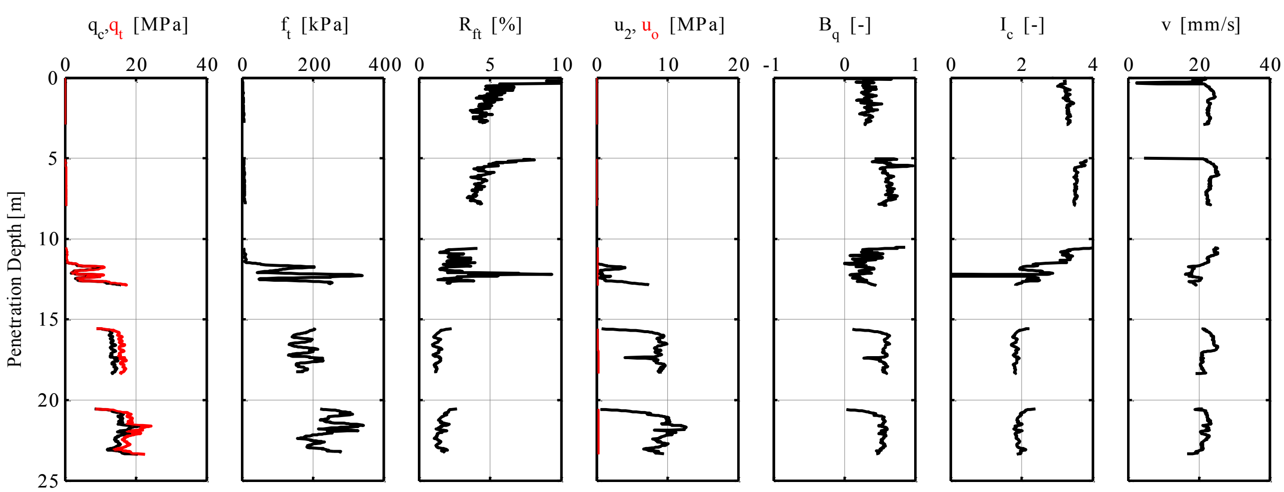

Figure 23. Deployment challenges for a cone penetrometer.

Comments are as follows:

– Discontinuous CPT profiles were acquired by multiple short-push penetrations from the bottom of a drill pipe.
– Quality monitoring records were according to expectations. Zero drift values for q_s, f_s and u_2 for tests in very soft clay were typically +50 kPa, +1 kPa and +1 kPa respectively. For the underlying claystone, these values were typically -50 kPa, +1 kPa and +1 kPa. The claystone shows a soil behaviour type index I_c of about 2, equivalent to sandy very clayey silt according to Robertson (1990).
– Values for q_c and u_2 differ by factors of 300 and 420 respectively between 1 m and 22 m penetration depths.
– The data acquisition system for pore pressure fails between 22 m and 23 m penetration depth. The measured pore pressure then exceeds 12,000 kPa, which is the equivalent of a water column with a height of 1200 m.
– Duration of a short-push test is less than 3 minutes. Temperature response to build-up of frictional heat will be complex for the load cells for q_c and f_s. Simple prediction models for transient temperature may considerably overestimate measurement error for this situation.

Figure 24 illustrates an extreme case of transfer of axial force on the cone to the friction sleeve.

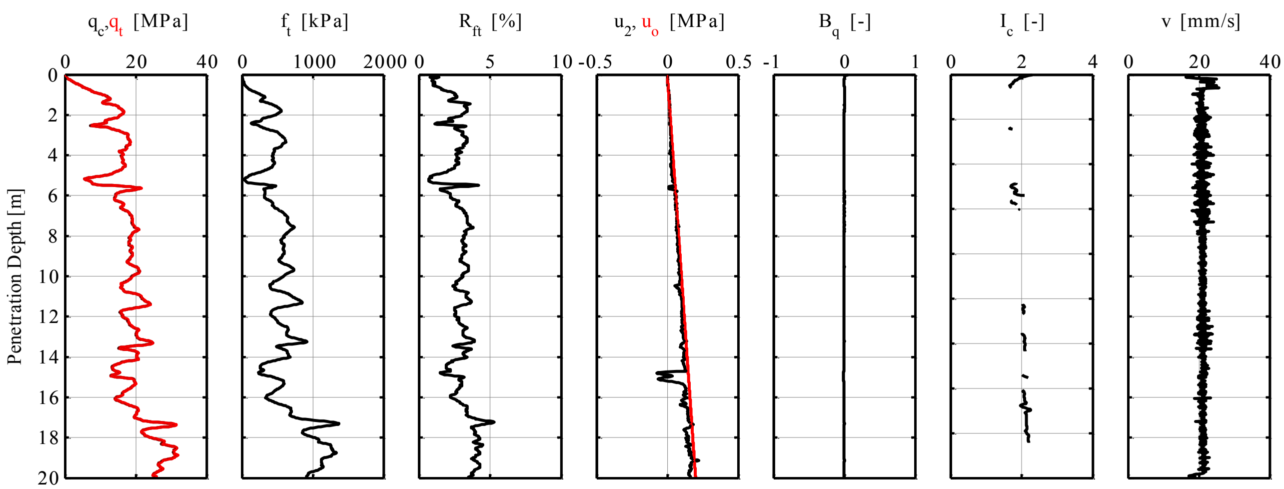

Figure 24. Transfer of axial force on the cone to the friction sleeve.

Comments are as follows:

– CPT deployment was by single push from ground surface, with no interruptions for push rods.
– Zero drift values for q_c, f_s and u_2 were -31 kPa, +3 kPa and -4 kPa respectively. These values show no evidence for anomalies. Force transfer was confirmed by post-project laboratory checks.
– It is difficult to detect minor cases of force transfer. Extreme force transfer is evident from credibility checks on f_t signature replicating q_c signature, with supplementary confirmation from friction ratio and soil behaviour type index I_c. Note that the force transfer causes I_c to be mostly outside of classification limits indicated by Robertson & Wride (1998).
– The sum of the axial forces on the cone and friction sleeve should be approximately correct. For example, it may be inferred that a presumed friction ratio of 1% at 10 m penetration depth would increase q_c from about 19 MPa to about 24 MPa and decrease f_t from about 600 kPa to 240 kPa.
– Measured pore pressure u_2 shows robust response for testing in very dense sands. The difference between measured pore pressure and expected hydrostatic pore pressure is <50 kPa at 20 m penetration depth.

15. CONCLUDING REMARKS

An ideal in situ penetration tool would provide:

- zero measurement uncertainty,
- unambiguous soil behaviour identification,
- closed-form theoretical interpretation directly linked to fundamental soil mechanics,
- rapid penetration to desirable depths into any type of ground at wide range of temperatures,
- inexpensive operation from a small autonomous vehicle operating on any terrain, above and below water, and,
- unique standardisation.

Although no such tool exists, the CPT is closer to this wish list than any of its in situ rivals.

CPT practice has an admirable history on benchmarking of accuracy of parameter values. Such ambitions are not yet seriously contemplated for parameter values inferred from soil sampling, sample handling and geotechnical laboratory testing.

Estimation of CPT accuracy may distinguish "favourable" and "adverse" settings. The proposed favourable setting is comparable to a calibration laboratory. Homogeneous, slightly overconsolidated clay would be an example of favourable conditions. The proposed adverse setting represents common hostile site conditions and/or a setting with real-world limits on tool control. A setting of strongly layered dense sands and soft clays with ground water at depth would be an example of adverse conditions. Particularly, adverse conditions recognise the complexity of accurate measurement of resistance values differing by typically four orders of magnitude, with no control on measuring environment. Furthermore, it may occasionally be difficult to distinguish CPT measurement error from in situ soil behaviour.

Usually, discussions on CPT accuracy take place without a satisfactory definition for accuracy. Some use accuracy in metrological terms of resolution or repeatability. Others presumably refer to accuracy under calibration laboratory conditions. Many are ambiguous about: (1) coupling of q_c, f_s and u with spatial position xyz and (2) true value related to permissible equipment-specific and procedure-specific features.

A proposed Analytic CPT can serve as benchmark for true values, independent of equipment-specific and procedure-specific CPT features. The proposed Analytic CPT features zero measurement uncertainty and an imaginary cone penetrometer with a solid body of uniform geometry with no gaps.

Widely used CPT standards are ISO 22476-1:2012 (2012a) and ASTM D5778-12 (2012). ISO 22476-1 defines accuracy, where (1) q_c, f_s and u are uncoupled from spatial position xyz and (2) true values depend on permissible equipment-specific and procedure-specific features. This means that compliance with an application class of ISO 22476-1 only provides a first indication of accuracy required for geotechnical practice. Further processing will be necessary to obtain fit-for-purpose accuracy, i.e. with benchmarking against the Analytic CPT or equivalent. ASTM D5778 has no aspirations on defining accuracy. It considers precision and bias.

The ISO 22476-1 connection between zero drift and application class is doubtful and may lead to unnecessary effort in practice. Typically, zero drift reflects a wide range of test conditions. It cannot be isolated for the penetration phase applicable to a particular soil stratum.

The current state of knowledge suggests that it will be difficult in practice to demonstrate compliance with the application classes of ISO 22476-1, except under favourable conditions. This is illustrated by two examples of uncertainty estimates. The examples may possibly represent first-ever estimates that comply with ISO 22476-1 and its normative reference to ISO (2003). The first example (Fig. 18) considers favourable conditions, i.e. homogeneous slightly overconsolidated clay. The uncertainty estimate indicates feasibility of meeting Application Class 1 of ISO 22476-1 and confirms current understanding derived from excellent test repeatability under uniform, favourable soil conditions. The second example (Fig. 20) considers routine adverse conditions: layered sands and clays. The accuracy calculations for the adverse case show that the example CPT, as a whole, would fail to meet any of the application classes of ISO 22476-1. Significant epistemic uncertainty is the principal reason for this situation. Particularly, the prediction models for transient temperature and measurement error take account of lack of understanding and are necessarily conservative. Actual accuracy is probably significantly better than calculated. Further study is recommended.

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GLOSSARY OF METROLOGICAL TERMS

Table 5. Glossary of metrological terms.

Term	Definition	Notes
Accuracy, measurement accuracy, accuracy of measurement	closeness of agreement between a measured quantity value and a true quantity value of a measurand	
Accuracy Class	class of measuring instruments or measuring systems that meet stated metrological requirements that are intended to keep measurement errors or instrumental uncertainties within specified limits under specified operating conditions	- An accuracy class is usually denoted by a number or symbol adopted by convention. - Accuracy class applies to material measures.
Bias, Measurement Bias	estimate of a systematic measurement error	
Bias	ASTM[2]: *bias, [Unit of Measure]—in measurements*, a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value	
Drift, Instrumental drift	continuous or incremental change over time in indication, due to changes in metrological properties of a measuring instrument	Instrumental drift is related neither to a change in a quantity being measured nor to a change of any recognized influence quantity.
Error, Error of measurement, Measurement error	measured quantity value minus a reference quantity value	- The concept of 'measurement error' can be used both when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of a measurement standard with a measured quantity value having a negligible measurement uncertainty or if a conventional quantity value is given, in which case the measurement error is known, and b) if a measurand is supposed to be represented by a unique true quantity value or a set of true quantity values of negligible range, in which case the measurement error is not known. - Measurement error should not be confused with production error or mistake.
Full scale output, FSO	the specified maximum output value for which the stated accuracy condition applies	
Hysteresis	ISRM[4]: incomplete recovery of strain during unloading cycle due to energy consumption	ASTM[2]: hysteresis is the dependence of a system not only on its current environment but also on its past envi-

Term	Definition	Notes
		ronment.
Measurement	process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity	
Measurand	quantity intended to be measured	
Metrology, metrological confirmation	science of measurement and its application	- Metrology includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application - Metrological confirmation generally includes calibration and verification, any necessary adjustment or repair, and subsequent recalibration, comparison with the metrological requirements for the intended use of the equipment, as well as any required sealing and labelling. - Metrological confirmation is not achieved until and unless the fitness of the measuring equipment for the intended use has been demonstrated and documented. - The requirements for intended use include such considerations as range, resolution and maximum permissible errors. - Metrological requirements are usually distinct from, and are not specified in, product requirements.
Precision, measurement precision	closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions ASTM[2]: *precision, [Unit of Measure]—in measurements*, the closeness of agreement between test results obtained under prescribed conditions.	- Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement. - The ‘specified conditions’ can be, for example, repeatability conditions of measurement, intermediate precision conditions of measurement, or reproducibility conditions of measurement (see ISO 5725-3:1994/Cor.1:2001). - Measurement precision is used to define measurement repeatability, intermediate measurement precision, and measurement reproducibility. - Sometimes “measurement precision” is erroneously used to mean measurement accuracy.
Quantity	property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference	
quantity value	value of a quantity value number and reference together expressing magnitude of a quantity	
Random Measurement Error, Random error, Random error of measurement	component of measurement error that in replicate measurements varies in an unpredictable manner	- A reference quantity value for a random measurement error is the average that would ensue from an infinite number of replicate measurements of the same measurand. - Random measurement errors of a set of replicate measurements form a distribution that can be summarized by its expectation, which is generally assumed to be zero, and its variance. - Random measurement error equals measurement error minus systematic measurement error.

Term	Definition	Notes
Range	ASTM[2]: *range (of a deformation-measuring instrument)* — the amount between the maximum and minimum quantity an instrument can measure without resetting/ overloading. In some instances provision can be made for incremental extension of the range.	
Repeatability, Measurement repeatability	measurement precision under a set of repeatability conditions of measurement	
Resolution	smallest change in a quantity being measured that causes a perceptible change in the corresponding indication	Resolution can depend on, for example, noise (internal or external) or friction. It may also depend on the value of a quantity being measured.
Stability, stability of a measuring instrument	property of a measuring instrument, whereby its metrological properties remain constant in time	Stability may be quantified in several ways. EXAMPLE 1 In terms of the duration of a time interval over which a metrological property changes by a stated amount. EXAMPLE 2 In terms of the change of a property over a stated time interval.
Systematic Error, Systematic measurement error, Systematic error of measurement	component of measurement error that in replicate measurements remains constant or varies in a predictable manner	- A reference quantity value for a systematic measurement error is a true quantity value, or a measured quantity value of a measurement standard of negligible measurement uncertainty, or a conventional quantity value. - Systematic measurement error, and its causes, can be known or unknown. A correction can be applied to compensate for a known systematic measurement error. - Systematic measurement error equals measurement error minus random measurement error.
Type A evaluation of measurement uncertainty	evaluation of a component of measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions	
Type B evaluation of measurement uncertainty	evaluation of a component of measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty	EXAMPLES Evaluation based on information: - associated with authoritative published quantity values, - associated with the quantity value of a certified reference material, - obtained from a calibration certificate, - about drift, - obtained from the accuracy class of a verified measuring instrument, - obtained from limits deduced through personal experience.
Trueness, measurement trueness, trueness of measurement	closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value	- Measurement trueness is not a quantity and thus cannot be expressed numerically, but measures for closeness of agreement are given in ISO 5725/ Cor.1:2001) - Measurement trueness is inversely related to systematic measurement error, but is not related to random measurement error. - Measurement accuracy should not be used for 'measurement trueness' and vice versa.

Term	Definition	Notes
Uncertainty, Uncertainty of measurement, Measurement uncertainty	non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used	- Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated. - The parameter may be, for example, a standard deviation called standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, having a stated coverage probability. - Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information. - In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.
Zero Error	datum measurement error where the specified measured quantity value is zero	Zero error should not be confused with absence of measurement error.
Zero Adjustment of a measuring system	adjustment of a measuring system so that it provides a null indication corresponding to a zero value of a quantity to be measured	

Notes:
1. Definitions are according to JCGM (2012), except where shown
2. ASTM (2011)
3. ISO (2012)
4. ISRM (1972)
5. EA (1999)

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