

Metrology in geotechnical standards for in situ testing and geophysical survey

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Abstract – This paper presents an overview of achievements and hurdles in international standardisation of geotechnical practice for in situ testing and offshore geophysical survey. Standardisation of in situ testing is progressing from a historic, specification-type approach to a performance-based approach. The tools for actual demonstration of achieving the performance-based requirements for accuracy are shown to be lagging behind. Work is now underway for standardisation of sub-seafloor geophysical surveys for geotechnical applications. Standardisation of metrology issues proves challenging. The survey industry is generally familiar with specifying equipment and procedures, with few systematic tools for estimating data point uncertainty.

I. INTRODUCTION

Standards for in situ testing and geophysical survey, including associated geodesy, are important for safe and

economical design structures. They are typically part of a chain of standards for verification of structures. For example, offshore in situ test measurements are covered by ISO 19901-8 [1]. Note that ISO 19901-8 is also available as European Standard EN ISO 19901-8 [2]. Offshore geophysical survey is planned to be incorporated in a future update of ISO 19901-8.

ISO 19901-8 connects normatively to ISO 19900 [3], which in turn has a normative link with ISO 2394 [4].

The following sections discuss metrology for standardisation of offshore in situ tests and offshore geophysical survey.

II. IN SITU TESTING

International standardisation of the cone penetration test (CPT) has led to a transition from specification-type of standardisation to performance-type of standardisation for in situ tests (Table 1).

Table 1. CPT standardisation – with focus on metrology (after [5, 6]).

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) [7]. Advancement of 1968 work; detailed requirements for CPT 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 zero-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 [8]. 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) [9]. 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

Year	Notes
	influence of water pressure and area ratios for cone and friction sleeve, requirement on cone penetrometer bending influence; surface roughness of friction sleeve between $0.25 \mu\text{m} < r < 0.75 \mu\text{m}$ 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 [10]. 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) [11]. 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 [12]. Based on 1999 reference test procedure, four application/ accuracy classes 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 [13]. Periodic ASTM update, some matches with ISSMGE international reference test procedure; requirements for friction cone and piezocone penetrometers with cross sectional areas of $1,000 \text{ mm}^2$ (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 $1,500 \text{ mm}^2$ are permitted; penetration rate defined at $20 \text{ mm/s} \pm 5 \text{ mm/s}$; precision of pore pressure sensor of better than $\pm 14 \text{ kPa}$; permissible zero drift of 2% of full scale output FSO of q_c , f_s and u measurements; depth accuracy of $\pm 0.1 \text{ m}$; 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 [1]. Based on [12], normative requirements on maintenance, checks and calibration; with three application classes to suit offshore practice, with values for cone resistance q_c (35 kPa, 100 kPa or 200 kPa) and values for pore pressure: 25 kPa, 50 kPa or 100 kPa
2015	EN ISO standard: marine soil investigations [2], equivalent to [1]

ISO and EN require a performance-based approach that covers metrology by accuracy requirements as specific values, with or without accuracy classes and application classes. The tools for actual demonstration of achieving the performance-based requirements for accuracy are shown to be lagging behind. They require further development. Furthermore, practice shows important clauses of standards to be subject to more than one interpretation.

Peuchen & Terwindt [6] and [14] summarise some metrological features. The main points for the ISO

standards [12] and [1] are as follows:

- (1) A normative reference to ISO 10012 [15] “measurement management principles” applies. This approach encourages uniformity in metrological approach.
- (2) Standards appear to give requirements for uncertainty estimation for which no robust and efficient technology is available or for which such technology has not been tested in practice. [16] presents introductory work for offshore depth accuracy. Fig. 1 presents an example of

introductory work on uncertainty estimation for CPT parameters q_c , f_s and u .

- (3) The CPT parameters q_c , f_s and u are uncoupled from spatial position xyz .
- (4) A cone penetration test meets a particular application class only by consideration of its complete CPT profile. For example, Application Class 1 can be selected for “very soft to soft soil deposits”, which is approximately equivalent to $q_c < 0.5$ to $q_c < 1$ MPa. In other words, Application Class 1 should not be selected for “mixed bedded soil profiles with weak to strong layers”.
- (5) The terms error and accuracy are used. These terms can lead to interpretative differences in practice. 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. Accuracy assumes knowledge of a true value, i.e. what should be regarded as true value.
- (6) True values depend on permissible equipment-specific and procedure-specific features. This means that compliance with a CPT application class only provides a first indication of accuracy required for geotechnical practice [17]. Further processing will be necessary to obtain fit-for-purpose accuracy, i.e. with benchmarking against the Analytic CPT (Fig. 2) or equivalent. To the knowledge of the author, such benchmarking is yet to be demonstrated.
- (7) The connection between application class and sensor reference readings at start and end of a test can be subject to more than one interpretation. In any case, such connection should be viewed with

caution [6].

A trend towards a performance-based approach for standardisation can be observed for other in situ tests. Table 2 shows examples from [1]. Note the accuracy classes for depth below seafloor.

Table 2. Accuracy requirements – in situ tests.

Test Method	Accuracy Specification
Depth below seafloor	Five accuracy classes, Z1 to Z5
Cone penetration test	Three application classes for q_c , f_s , u
Pore pressure dissipation test	Three application classes for u
Ball penetration test	5% or 20 kPa for $q_{m\text{ball}}$, whichever is larger
T-bar penetration test	5% or 20 kPa for $q_{m\text{T-bar}}$, whichever is larger
Seismic CPT	10% for v_s , straight-line slant distance
Field vane test	Three application classes

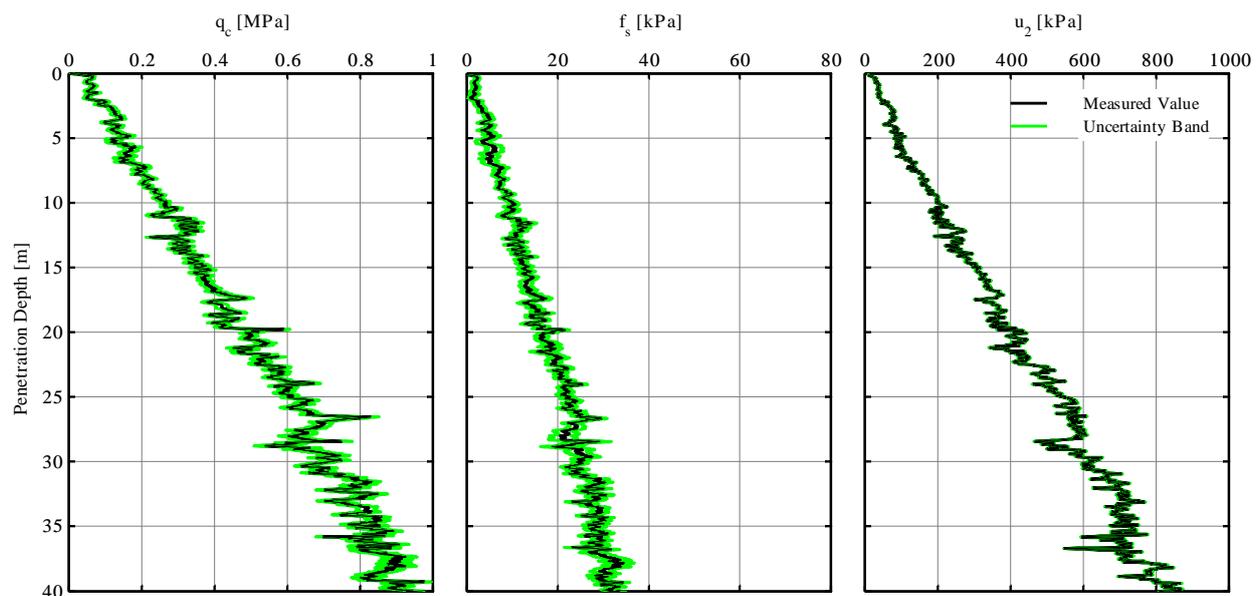


Fig. 1. Calculated uncertainty estimates for CPT values measured under favourable conditions [6].

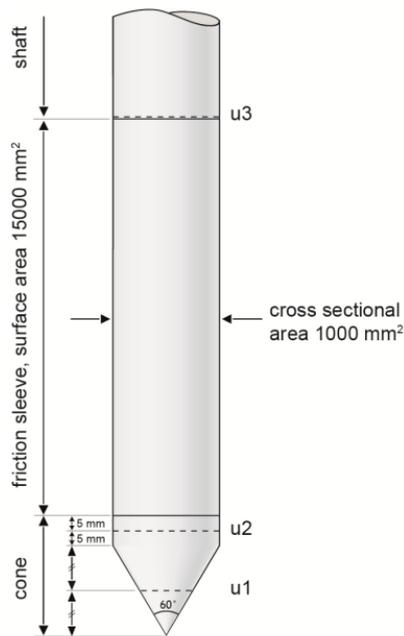


Fig. 2. Analytic CPT [6].

III. GEOPHYSICAL SURVEY

International standardisation of offshore geophysical survey started with seafloor surveying. A first edition of IHO Special Publication 44 for bathymetry and seafloor objects was published in 1968. Table 3 summarises the 5th Edition [18]. The 5th Edition includes a detailed list of

sources of uncertainty to consider for metrological confirmation. It provides no examples and no references to examples of actual demonstration of meeting the metrology requirements.

Work is now underway for international standardisation [19] of sub-seafloor surveys for geotechnical applications. The following methods are common for sub-seafloor surveys for geotechnical applications in water depths greater than about 20 m: seismic reflection 2D High Resolution (HR), ultra HR, and subbottom profiling by pinger, boomer and sparker. Seismic refraction and ocean bottom cables/ nodes OBC/OBN for seismic reflection surveys are increasingly used in very shallow water, i.e. surf zone and nearshore.

Standardisation of metrological confirmation proves challenging. Examples of challenges include:

- (1) As for in situ testing, robust and efficient technology may not be available for uncertainty estimation or may not have been tested in practice. Some combination of specification-type requirements and performance-based requirements may initially be inevitable. Industry is generally familiar with specifying equipment and procedures, with no systematic tools for estimating data point uncertainty.
- (2) Geodesy (xyz position) is critical to most sub-seafloor survey types. It cannot readily be decoupled from other parameters, such as done for in situ testing.

Table 3. Summary of IHO Classification

IHO Order	Special	1 a	1 b	2
Description of Areas	Areas where under-keel clearance is critical	Areas shallower than 100 m where under-keel clearance is less critical but features of concern to surface shipping may exist	Areas shallower than 100 m where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area	Areas generally deeper than 100 m where a general description of the seafloor is considered adequate
Maximum Allowable Total Horizontal Uncertainty 95% Confidence Level	2 m	5 m + 5% of depth	5 m + 5% of depth	20 m + 10% of depth
Maximum Allowable Total Vertical Uncertainty 95% Confidence Level	a = 0.25 m b = 0.0075	a = 0.5 m b = 0.013	a = 0.5 m b = 0.013	a = 1.0 m b = 0.023
Full Seafloor Search Feature Detection	Required Cubic features > 1 m	Required Cubic features > 2 m in depths up to 40 m; 10% of depth beyond 40 m	Not required Not applicable	Not required Not applicable
Recommended Maximum Line Spacing	Not defined as full seafloor search is required	Not defined as full seafloor search is required	3 x average depth or 25 m, whichever is greater	4 x average depth

Note: The use of coefficients a and b is as follows:

$$\pm \sqrt{[a^2 + (b * d)^2]}$$

where:

- a coefficient, representing that portion of uncertainty that does not vary with depth
- b coefficient, representing represents that portion of uncertainty that varies with depth
- d (water) depth

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