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Calibration of cone penetrometers according to International Organization for Standardization requirements

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ABSTRACT: Detailed requirements for calibration of piezocone penetrometers are incorporated in standards published by International Organization for Standardization (ISO). The use of these standards can provide input for comparisons of cone penetration test (CPT) systems deployed in practice by means of cone penetrometer classes. It is important that parties specifying or supplying CPT data take note of the implications of the new requirements and the opportunities and benefits of appropriate selection of cone penetrometer classes. In addition, the information available from calibration and verification of a particular cone penetrometer can provide input into estimation of uncertainties of data points in CPT profiles used for design of structures.

This paper focusses on background information about topics considered for development of the ISO requirements. These topics included (1) practical and economical test methods achievable in a calibration laboratory, (2) assessment of differences in exposure conditions applied in the calibration process and site conditions likely to be encountered during actual cone penetration testing, and (3) cone penetrometers that incorporate ancillary sensors and algorithms for reducing the influence of temperature on CPT results.

1 INTRODUCTION

Detailed requirements for calibration of cone penetrometers are incorporated in (draft) standards published by ISO, International Organization of Standardization, particularly ISO/DIS 22476-1:2021 for cone penetration tests (CPT) conducted onshore and nearshore. The same calibration requirements are incorporated in ISO/DIS 19901-8:2021 for CPTs in offshore settings. The use of these standards (hereafter abbreviated to ISO 22476 and ISO 19901) can provide input for comparisons of CPT systems deployed in practice. In addition, the information available from calibration and verification of a particular cone penetrometer can provide input in estimation of uncertainties of data points in CPT profiles used for design of structures.

Earlier versions of ISO 22476 and ISO 19901 (ISO 22476:2012 and ISO 19901-8:2014) considered performance specifications by ‘application classes’, whereby requirements were given for accuracy of in-situ CPT results without detailed step-by-step procedures or method specifications. Application of these performance specifications proved difficult in practice (Lunne et al. 2017, Peuchen & Parasie 2019). For this reason, ISO changed to a method specification, particularly providing detailed requirements for calibration and verification of cone penetrometers in a calibration laboratory. The calibration and verification results provide the required information for assignment of a cone penetrometer to one of multiple ‘cone penetrometer classes’ specified in ISO 22476 and ISO 19901. A further step in method specification is required: monitoring and logging of

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acquired test data, followed by assignment of test results in 'test categories'.

This paper focusses on background information about topics considered for development of the ISO requirements for calibration and verification of cone penetrometers. These topics included (1) practical and economical test methods achievable in a calibration laboratory, (2) assessment of differences in exposure conditions applied in the calibration process and site conditions likely to be encountered during actual cone penetration testing, and (3) cone penetrometers that incorporate ancillary sensors and algorithms for reducing the influence of temperature on CPT results.

ISO 22476 is a draft international standard (DIS). It was published by ISO in June 2021. Where applicable, this paper considers country feedback received for this DIS. Final published version of ISO 22476 and ISO 19901 can differ from the information presented here.

2 CALIBRATION AND VERIFICATION REQUIREMENTS

2.1 *Overview*

Table 1 presents an overview of calibration and verification requirements for cone penetrometers. The ISO column refers to both ISO 22476 and ISO 19901; ASTM refers to ASTM D5778-20.

Note that the required presentation of results of the ISO verifications covers the influences of temperature and bending on the parameters q_c, f_s, and u. Here, temperature influence is about the internal temperature in the cone penetrometer possibly affecting sensor performance.

The ISO reporting requirements for calibration and verification include assignment of the cone penetrometer to one of the cone penetrometer classes.

Table 1. Overview of calibration and verification requirements for cone penetrometers.

Item	ISO	ASTM
Calibration laboratory*	N	I
Measuring intervals for calibration	N	N
Penetrometer geometry*	N, C, U	N, V
Cone resistance*, q_c	N, C, U	N, C
Sleeve friction*, f_s	N, C, U	N, C
Pore pressure*, u	N, C, U	N, C
Net area ratios*, a and b	N, C	I, C
Temperature, T	-	I, C
Inclination, i	N, C, U	I, C
Influence of ambient temperature*	N, V	N, V
Influence of transient temperature*	N, V	-
Influence of penetrometer bending	N, V	-

C = calibration; I = informative; N = normative; U = uncertainty calculation; V = verification; * = details in sections following; - not covered.

The primary differences between ISO and ASTM are related to (1) detailed requirements for a calibration laboratory, (2) metrological calculation of calibration uncertainties and (3) normative (mandatory) versus informative (recommended) text. It can be noted that a calibration laboratory that invested in calibration and verification apparatus according to ISO 22476 and/or ISO 19901 should be able to provide the normative calibration and verification information according to both ISO and ASTM. The reverse can require additional investment.

2.2 *Calibration laboratory*

A normative reference to ISO/IEC 17025 provides the basic requirements for the calibration laboratory. ISO/IEC 17025 covers laboratory quality management, including detailed reporting requirements for calibration certificates.

2.3 *Measuring intervals for calibration*

ISO 22476 and ISO 19901 include normative text with respect to measuring intervals for calibration. For example, a minimum range is specified for inclination. Recommendations (informative) are given for selection of measuring intervals for calibration of q_c, f_s and u.

2.4 *Cone resistance and sleeve friction*

Calibration for q_c and f_s requires application of a series of axial loading and unloading series to the cone penetrometer, similar to ISO 376:2011. A notable requirement is the logging and supplementary presentation of output values of the penetrometer other than those for q_c or f_s, for the purpose of checking for any unwanted effects of axial loading on output of sensors other than the one selected for calibration.

Estimation of calibration uncertainty is prescribed in detail. Uncertainties cover those related to: (1) reference force, (2) geometry of the cone penetrometer and (3) uncertainties related to force sensor in the cone penetrometer, particularly reproducibility, repeatability, resolution, zero drift, interpolation, reversibility and apparent load transfer from cone to friction sleeve (and vice versa). Calculation equations consider standard uncertainties, combined standard uncertainties and expanded measurement uncertainties defined according to ISO/IEC Guide 99:2007.

Table 2 presents a selection of example output according to ISO requirements.

2.5 *Pore pressure and net area ratios*

Calibration for pore pressure u takes place with the cone penetrometer in a pressure vessel. A series of increasing and decreasing pressure series are applied.

Table 2. Example summary of laboratory calibration uncertainties for q_c, according to ISO requirements.

F_r [kN]	u_1 [kN]	u_2 [kN]	u_3 [kN]	u_4 [kN]	u_5 [kN]	u_6 [kN]	u_7 [kN]	u_8 [kN]	u_c [kN]	u_c [kPa]	u_{dim} [mm^2]	$u_{c,dim}$ [kPa]	U_{qc} [kPa]
0	0.0150	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0150	14.65	0.3024	14.65	29.31
8	0.0390	0.0006	0.0000	0.0000	0.0004	0.0154	0.0344	0.0000	0.0543	52.96	0.3024	53.01	106.02
16	0.0630	0.0012	0.0012	0.0000	0.0008	0.0064	0.0419	0.0000	0.0759	74.11	0.3024	74.25	148.51
24	0.0870	0.0007	0.0007	0.0000	0.0012	0.0026	0.0453	0.0000	0.0982	95.80	0.3024	96.05	192.10
32	0.1110	0.0004	0.0004	0.0000	0.0016	0.0119	0.0468	0.0000	0.1210	118.13	0.3024	118.48	236.97
40	0.1350	0.0013	0.0013	0.0000	0.0020	0.0182	0.0473	0.0000	0.1442	140.76	0.3024	141.23	282.46
48	0.1590	0.0009	0.0009	0.0000	0.0024	0.0195	0.0482	0.0000	0.1673	163.27	0.3024	163.85	327.70
56	0.1830	0.0027	0.0027	0.0000	0.0028	0.0135	0.0488	0.0000	0.1899	185.34	0.3024	186.04	372.07
64	0.2070	0.0032	0.0032	0.0000	0.0032	0.0028	0.0476	0.0000	0.2125	207.35	0.3024	208.17	416.34
72	0.2310	0.0049	0.0049	0.0000	0.0036	0.0159	0.0474	0.0000	0.2364	230.73	0.3024	231.66	463.31
80	0.2550	0.0045	0.0045	0.0000	0.0040	0.0409	0.0000	0.0000	0.2583	252.10	0.3024	253.15	506.31

F_r: reference force; u_1: standard uncertainty, reference force; u_2: standard uncertainty, reproducibility; u_3: standard uncertainty, repeatability; u_4: standard uncertainty, resolution; u_5: standard uncertainty, zero drift; u_6: standard uncertainty, interpolation; u_7: standard uncertainty, reversibility; u_8: standard uncertainty, load transfer; u_c: combined standard uncertainty, calibration;; u_{dim}: combined standard uncertainty, cross-sectional area of cone tip; $u_{c,dim}$: combined standard uncertainty, u_c and u_{dim}; U_{qc}: expanded measurement uncertainty, calibration u_c and u_{dim}; cross-sectional area of cone tip used for calculation of uncertainties: 1024.74 mm^2

The procedure and presentation of results are generally similar to those for q_c and f_s. The estimation of calibration uncertainty considers a reduced number of uncertainties.

Net area ratios a and b for the cone and the friction sleeve are also determined with the cone penetrometer in the pressure vessel. Values of a and b typically show slight pressure dependence. ISO determines these values at $u = 2$ MPa.

2.6 *Temperature influence*

Verification of a cone penetrometer for temperature influence requires two water-filled baths, one at a temperature of 0 °C and one at 30 °C. The baths are at atmospheric conditions. A prescribed alternating sequence applies for immersion of the cone penetrometer in the two thermostat baths. The cone penetrometer is thus subjected to induced change in ambient temperature as well as transient temperature cycling, see Figure 1. The 'measured temperature' shown in Figure 1 refers to temperature measured by a sensor in the cone penetrometer.

The verification procedure specifically allows for optional, explicit correction of force (q_c and f_s) and pressure (u) data for temperature influence. Uncorrected and corrected results must be reported for this case. For example, cone penetrometer class 1+ of ISO 22476 includes requirements for incorporation of a temperature sensor in the cone of the cone penetrometer. The temperature (T) data can then be used for correction of temperature influence on q_c, f_s and u.

Reporting of results is mainly by key performance indicators that relate variation of the parameter of interest (for example q_c) to the temperatures of the water baths and to time.

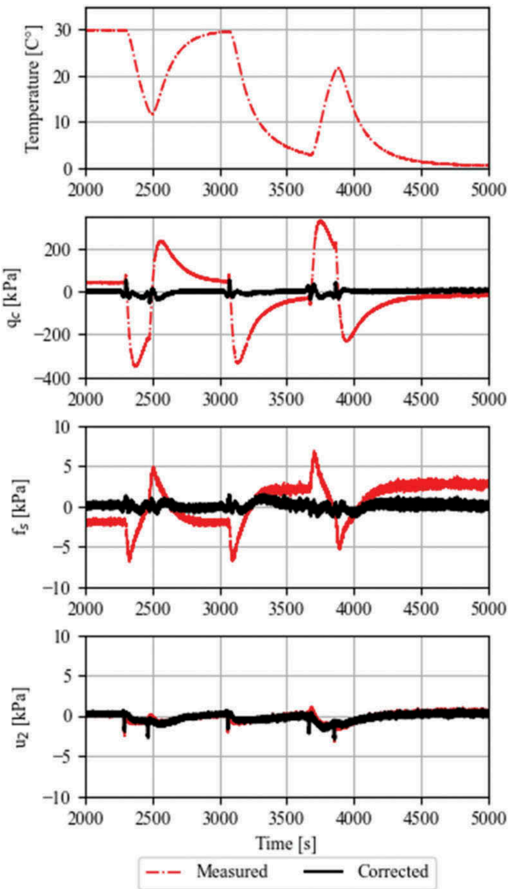

Figure 1. Example of verification data for temperature influence.

3 DISCUSSION

3.1 *Use of results*

ISO 22476 and ISO 19901 distinguish between (1) records of calibrations and verifications and (2) test report or calibration certificate.

The records include substantial data files, particularly as they include time-based logging files for a logging frequency of ≥ 1 Hz. The logging applies to output of each of the primary sensors of the cone penetrometer, for the durations of the various calibration and verification activities. The records are retained by the calibration laboratory. Inspection of the records can provide valuable information for quality management, particularly if the records are tracked for multiple calibrations of a single cone penetrometer and if the records are compared for multiple cone penetrometers.

A test report or calibration certificate covers a summary of the records. The summary is adequate for use in practice, i.e. understanding the performance of the cone penetrometer at the time of calibration.

3.2 *Exposure conditions*

Simulated exposure conditions for a cone penetrometer in the calibration laboratory will, inevitably, differ from in situ exposure conditions. Particularly, laboratory calibration and verification consider particular characteristics in isolation, see Table 1.

Laboratory checks would be challenging for assessing the potential influence of in situ exposure conditions, such as (1) ambient and induced stress conditions imposed by soil and water, (2) soil displacement relative to the cone penetrometer, (3) temperature exposure varying from freezing to, say, 60 ° C, (4) combined and variable axial (compressive and tensile), torsional and moment loading imposed on the cone penetrometer. Common combinations of these influences cannot be readily quantified in a laboratory setting. Robust design and quality monitoring of cone penetrometers remains important (e.g. Peuchen & Terwindt 2014; Peuchen et al. 2020).

ISO 22476 and ISO 19901 capture quality monitoring by means of test categories, as discussed above. This is normative. Additional (informative) guidance and recommendations are also provided.

3.3 *Uncertainty calculations*

The calibration requirements include prescriptive uncertainty calculations, i.e. a combination of detailed calibration procedures and detailed requirements for calculation of uncertainties. This approach allows easy comparison of cone penetrometers, regardless of manufacturer/ supplier.

The uncertainty calculation approach presented in the ISO standards includes equations that (1) follow metrological principles (ISO, 2008) and premises and (2) apply to the specified laboratory setting. One of the premises is that the standard uncertainty of the reference, for example the measurement unit for force reference, has much better uncertainty characteristics than the force sensor of the cone penetrometer. If this is not the case, then the results of uncertainty calculations can be dominated by the uncertainty of the reference and will not necessarily reflect the actual laboratory performance of the cone penetrometer. This dominating influence can apply to the top end of the cone penetrometer classes, where requirements for cone penetrometers can approach performance of commonly available reference measurement units.

3.4 *Temperature stability of primary sensors*

Figure 1 includes an example of temperature correction of q_c by post-processing. The approach for f_s and u would be as for cone resistance.

The case of Figure 1 is for a subtraction-type cone penetrometer equipped with strain-gauge load cells with conventional temperature compensation for ambient temperature influence. This particular cone penetrometer also includes a temperature sensor within the cone penetrometer. The acquired records of temperature (T) data versus time (t) are additional to the primary CPT parameters and at the same frequency. The correction method uses a temperature model that mathematically increases (or reduces) values of q_c. This model is penetrometer-specific and parameter-specific (in this case q_c). The temperature model relies on a polynomial best-fit of q_c and T (and their derivatives in time), derived from the data recorded in the calibration laboratory.

During cone penetration testing, T and q_c are recorded versus t. The temperature model is subsequently applied by post-processing of the complete CPT dataset, such that both uncorrected (raw data) and corrected q_c data are retained.

It can be seen from Figure 1 that significant reduction of temperature influence can be achieved in the laboratory. Robust design of a cone penetrometer and tested algorithms should also achieve significant reduction of temperature influence during actual cone penetration testing under conditions differing from those in the laboratory.

4 CONCLUSION AND RECOMMENDATIONS

The International Organization of Standardization published (draft) standards ISO/DIS 22476-1:2021 and ISO/DIS 19901-8:2021. These documents include detailed requirements for calibration and verification of piezocone penetrometers. These requirements are believed to be practical and economical, nevertheless exceed the extent of calibration activities that represents current (2022) industry practice.

It is recommended that parties supplying CPT data take note of the implications of the new requirements. Furthermore, it is recommended that parties involved in specifying CPTs take note of the opportunities and benefits, notably by means of appropriate selection of cone penetrometer classes.

Standards tend to follow, not lead, technology developments or widespread application of a particular technology. A technology example for CPTs would be the incorporation of ancillary sensors and algorithms for reducing the influence of temperature on CPT results, now covered by the ISO standards. The resulting standardisation has influenced the cone penetrometer classes introduced in the ISO standards. In turn, the cone penetrometer classes allow easy comparison of cone penetrometers for use in practice, regardless of manufacturer/ supplier.

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