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Challenges for CPT accuracy classes

Défis pour les classes d‘exactitude des CPT

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ABSTRACT: Accuracy classes for cone penetration tests (CPT) have been in use since 1996. From 2012, industry use of CPT accuracy classes rapidly increased, when this type of classification system was included in the international standard ISO 22476-1:2012 on the electric cone and piezocone penetration test. The ISO standard adopted the term “application classes”, bringing together accuracy classes and applications for use of CPT results. Differences in interpretation about compliance with the ISO box values for accuracy became gradually apparent. Unfortunately, the interpretational challenges emerged from contractual disputes, unnecessary re-work and CPT results assigned higher confidence than actual. This paper reviews multiple interpretations and adaptations on compliance with the CPT accuracy/ application classes of ISO 22476-1:2012. Implications for practice are addressed and suggestions are given for future direction.

RÉSUMÉ: L’utilisation des classes d‘exactitude sur les mesures d’essais de pénétration au cône (CPT) a débuté en 1996. En 2012, l’intégration de cette classification dans la norme internationale ISO 22476-1:2012, a conduit à une demande croissante de son application par le monde de l’industrie pour les tests piézométrique et cônes électriques. La norme ISO a donc introduit la notion de “classe d’application”, regroupant les classes d‘exactitude et leur critère d’applications pour les CPTs. Malheureusement, des divergences d’interprétations sont apparues lors de l’utilisation des classes d’applications telles que présentées par la norme ISO. S’en suivirent des contestations contractuelles, menant à un travail supplémentaire inutile et à la classification des résultats CPT dans une catégorie plus précise qu’en réalité. Cet article passe en revue les différentes interprétation et adaptation en accord avec la norme ISO pour les classes d‘exactitude/ application. Les conséquences sur l’utilisation sont abordées et des suggestions proposées pour des instructions futures.

Keywords: CPT; accuracy; measurement uncertainty

1 INTRODUCTION

Cone penetration tests (CPTs) provide valuable input for safe and economical design of many structures (ISO, 2015). The annual number of CPT data points is possibly in the order of 50 000 000 (Peuchen et al., 2018). The high value of CPT results to stakeholders, including society at large, can be attributed to low cost per data point, continuous profiling, (near) real-time results and data robustness for most types of soils and weak rocks that allow cone penetration.

The primary data set acquired by a CPT consists of values of cone resistance q_c, sleeve friction f_s and pore pressure u versus depth. As for any measurement, each of these values can be expressed in terms of measurement uncertainty, defined as a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used (JCGM 200:2012). Note that the metrological vocabulary used in this paper is generally in line with JCGM 200:2012, which defines measurement accuracy as the closeness of agreement between a measured quantity value and a true quantity value of a measurand, noting that the concept “measurement accuracy“ is not a quantity and not given a numerical quantity value.

Uncertainty estimates for CPT data points are feasible (Figures 1 and 2), but not embedded in current (2019) practice. Instead, CPTs are generally performed according to standards and guidelines that consider accuracy classes. Accuracy classes for cone penetration tests have been in use since 1996 (NEN, 1996; ISSMGE, 1999). In 2012, the international standard ISO 22476-1:2012 adopted the term “application classes”, bringing together accuracy classes and applications for use of CPT results. ISO 19901-8:2014 largely copied the application classes of ISO 22476-1:2012. These ISO standards are widely used.

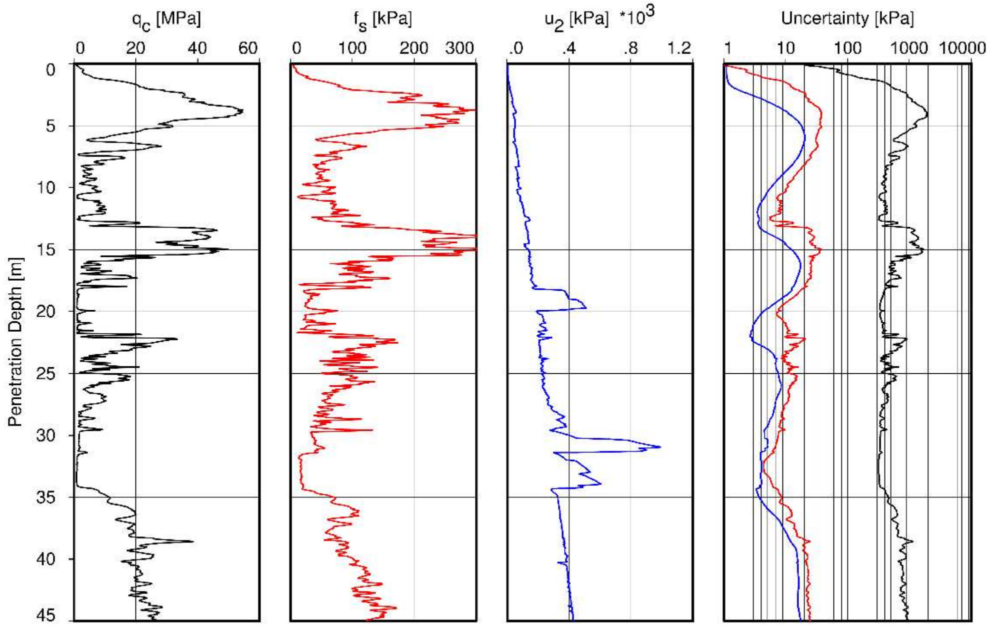

Figure 1. CPT profile for adverse conditions of strongly layered sands and clays, including values of expanded uncertainty, adapted from Peuchen and Terwindt (2014)

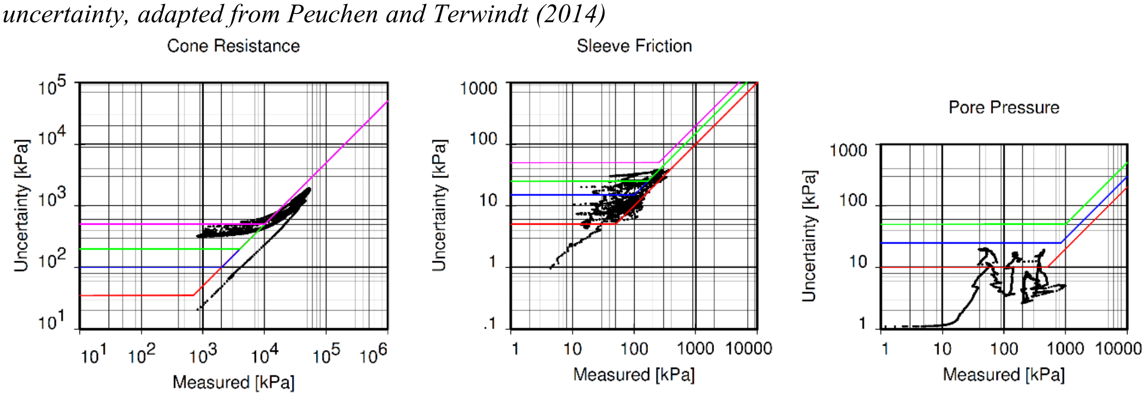

Figure 2. Expanded uncertainty of Fig. 1, plotted relative to limiting values for ISO 22476-1:2012 Application Class 1 (red), Application Class 2 (blue), Application Class 3 (green) and Application Class 4 (purple)

Table 2 of ISO 22476-1:2012 shows four application classes with box values for q_c, f_s, u, inclination and penetration length. Allowable minimum accuracy is expressed as the larger of threshold box values (e.g. 35 kPa, 100 kPa, 200 kPa or 500 kPa for q_c) and box values calculated as a percentage of the measured values (e.g. 5% for q_c). The ISO box values for q_c, f_s, u are graphically included in Fig. 2.

Differences in interpretation about compliance with the ISO box values for accuracy became apparent after publication of ISO 22476-1:2012 and, subsequently, publication of ISO 19901-8:2014. Unfortunately, the interpretational challenges emerged from contractual disputes, unnecessary re-work and CPT results assigned higher confidence than actual. The current (2019) status is that compliance with a particular application class provides little indication of accuracy of the CPT results.

The following subsections provide comments that illustrate the interpretational difficulties. The multiple interpretations of the application classes of ISO 22476-1:2012 can be related to the following:

- Definition of application class
- Requirements for accuracy analysis
- Decision rules for the ISO box values and zero drift

2 COMMENTS ON APPLICATION CLASSES

2.1 Definition of Application Class

ISO 22476-1:2012 and its normative reference to ISO 10012:2013 provide no explicit definition of application class. Instead, Clause 5.2 of ISO 22476-1:2012 uses a range of descriptive indicators, such as:

- "For given soil profiles and use of CPT results, the application class specifies the needed minimum accuracy and the maximum length between measurements, with an associated degree of uncertainty. The use of CPT results is stated in terms of profiling, material identification and definition of soil parameters"
- "Application Class 2 is intended for precise evaluation for mixed bedded soil profiles…".

It can be inferred that ISO 22476-1:2012 merges the use of results for specific applications with a concept of accuracy classes. The term accuracy class is well defined in metrology: "class of measuring instruments or measuring systems that meet stated metrological requirements that are intended to keep measuring errors or instrumental measurement uncertainties within specified limits under specified operating conditions" (JCGM, 2012).

The ISO box values can be interpreted to apply to (1) selected CPT measuring systems capable of meeting specific metrological requirements and (2) as-recorded measurements for any in situ conditions. A deemed-to-comply approach for (1) would be to compare laboratory calibration values for the cone penetrometer with the ISO box values, excluding all other measurement uncertainties. In practice, this has led to the informal terms "Class 1 cone" and "Class 2 cone penetrometer".

2.2 Requirements for accuracy analysis

Clause 5.2 of ISO 22476-1:2012 includes the following text: "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 of ISO 22476-1:2012. The accuracy analyses shall include internal friction, errors in the data acquisition, eccentric loading, temperature (ambient and transient) effects and dimensional errors". ISO 22476-1:2012 uses the term "accuracy analyses" only in this "shall" section of ISO 22476-1:2012. No definition of "accuracy analyses" is given in ISO 22476-1:2012 and its normative references ISO 10012:2003 and VIM (1993).

Note that VIM (1993) is an earlier version of JCGM 200:2012.

A possible interpretation is to define "accuracy analysis" as synonym of "uncertainty analysis" covered by Annex E of ISO 22476-1:2012. Annex E includes the following statement: "An uncertainty statement resulting from an uncertainty analysis can be presented. In this uncertainty analysis, uncertainties can be presented in accordance with WECC DOC. 19-1990 [5] and ISO 10012". Note that Annex E considers uncertainty analysis as a possibility (can), not a requirement (shall) for compliance.

The uncertainty approach suggested by Annex E is according to usual metrological principles. Peuchen and Terwindt (2014) demonstrate its feasibility for CPTs, using spreadsheet-type calculations. The result of such uncertainty analysis is measurement uncertainty for each data point of a CPT. To the knowledge of the authors, no adequate uncertainty analyses (or accuracy analyses) for CPT results are currently (2019) performed in practice.

The selection of appropriate input values for uncertainty analysis probably presents significant challenges to many CPT operators. One of the more important input values is the uncertainty of calibration for cone resistance, which includes the uncertainty of the reference. The reference is typically a reference load cell with metrological traceability to a national measurement standard. The characteristics of a reference load cell are usually approximately equivalent to those of a load cell for measuring cone resistance (e.g. Peuchen et al., 2018). The uncertainty of the reference is ignored by some, for example by Lunne et al. (2017) who refer to ASTM (2012). This simplification can be inadequate for uncertainty analysis according to Annex E of ISO 22476-1:2012, as shown below.

2.3 Decision rule for the ISO box values

The decision rule for the ISO box values relates to the following part of Clause 5.2: "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".

Compliance with this clause is obviously easier if the CPT accuracy criteria are applied per test compared to individual data points. In practice, the CPT accuracy criteria per test would usually mean that the percentage values of Table 2 of ISO 22476-1:2012 would apply to q_c and f_s. For example, assume Application Class 2 and a highest q_c value q_{cmax} = 7.8 MPa recorded for a test. For this case, the minimum accuracy that should be achieved for any data point of the test would be 390 kPa (5% of 7.8 MPa).

2.4 Decision rule for zero drift

The decision rule for zero drift relates to Clause 5.10 of ISO 22476-1:2012: "if the zero drift of the measured parameters is larger than the allowable minimum accuracy according to the required application class of Table 2, then the results should be neglected, or the test can be assigned to a lower application class".

Two interpretations are used in practice for values of permissible zero drift: (1) values calculated as function of the maximum measured value of a parameter recorded for a test and (2) the relevant fixed values of Table 2 of ISO 22476-1:2012. For the above example of Application Class 2 and q_{cmax} = 7.8 MPa, this would give permissible zero drift values of up to 390 kPa and up to 100 kPa, for the first and second interpretation methods respectively.

Practice shows that zero drift is influenced by the range of measured values during a test (Peuchen and Terwindt, 2014). A decision rule based on fixed values would be difficult to justify, except for cone resistance of Application Class 1 which can be interpreted to be limited to q_c < 3 MPa.

In practice, some use zero drift as proof of compliance with a particular application class. This practice possibly assumes that zero drift can represent the result of “accuracy analyses” referred to in Clause 5.2 of ISO 22476-1:2012. This is contrary to common metrological understanding, where zero drift is one of many contributing factors to uncertainty. For example, the zero drift values for the two synthetic profiles of Fig. 3 will be approximately the same, i.e. will not reflect differences in achieved uncertainty levels for individual data points versus penetration depth. This can be compared with uncertainty analysis, that will typically show excellent values of uncertainty for the q_c profile on the right. Uncertainty of the q_c values of the left profile of Fig. 3 would be dominated by hysteresis effects. Note that the q_c values of Fig. 1 at about 33 m depth, would similarly be dominated by hysteresis effects, estimated as 0.05 $q_{c,max}$ in the calculation example of Peuchen and Terwindt (2014). The term $q_{c,max}$ is the maximum encountered hysteresis value of q_c prior to reaching penetration depth.

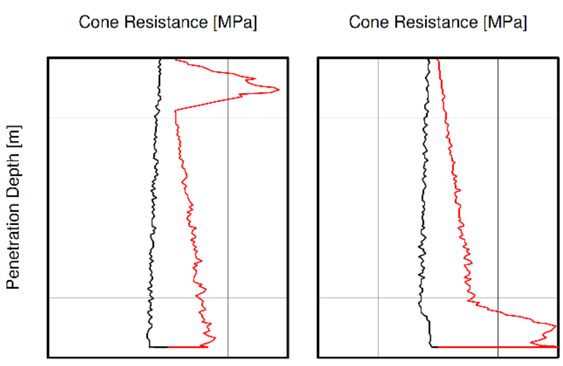

Figure 3. Limitation of zero drift criterion; the red curves represent cone penetration and the black curves represent retraction

2.5 Example of calibration uncertainty

The CPT industry currently (2019) has a general lack of accreditation for calibration of cone penetrometers. To the knowledge of the authors, only Fugro operates an accredited calibration laboratory (Peuchen et al., 2018).

Table 1 presents a detailed example of uncertainty analysis, according to procedures endorsed by a national accreditation body. The example is for a single data point (q_c = 8 MPa) on a calibration curve for cone resistance for, say, 2 %, 5 %, 10 %, 25 %, 50 %, 75 % and 100 % of the required measuring interval. The example illustrates the use of EA-04/02 M:2013 and highlights the dominance and importance of including the uncertainty of the reference. The standard uncertainty of the reference value is the major contribution to the expanded uncertainty value of the device under test (DUT), which is typical for cone penetrometer calibration (Peuchen and Terwindt, 2014). It is believed that significant reduction of calibration uncertainty can be achieved if the uncertainty of the reference value can be improved.

Note that ISO 22476-1:2012 and its normative reference to ISO 10012:2003 refer to a 2005 version of ISO/IEC 17025:2017 “General requirements for the competence of testing and calibration laboratories”. ISO/IEC 17025:2017 requires that a calibration certificate includes the measurement uncertainty of the reference. Expression of the measurement uncertainty in calibration can be done according to European accreditation document EA-04/02 M:2013. This document is specific for calibrations, where JCGM 200:2012 is a more general document for expression of measurement uncertainty.

Table 1. Example of expanded uncertainty calculated for 8 MPa cone resistance

Quantity X_i	**Estimate x_i** (MPa)	**Standard uncertainty $u(x_i)$** (kPa)	**Probability distribution; coverage factor k** (-)	**Sensitivity coefficient c_i** (-)	**Uncertainty contribution $u_i(y) = c_i.(u(x_i)/k)$** (kPa)
$M_{reference}$	8.000	39.0	2.0	1	19.5
$\delta M_{measurement}$	0.000	1.3	√3	1	0.8
$\delta M_{repeatability}$	0.000	1.0	√3	1	0.6
$\delta M_{reversibility}$	0.000	-1.7	√3	1	-1.0
$\delta M_{resolution}$	0.000	0.0372	2√3	1	0.0107
$\delta M_{zero\text{-}drift}$	0.000	0.0040	√3	1	0.0023
δM_{noise}	0.000	0.0001	1.00	1	0.0001
			Combined uncertainty:		19.7 kPa
			Degrees of freedom:		50
			Coverage factor:		2.050
			Expanded uncertainty:		40.4 kPa
M_{DUT}	**8.00± 0.04 MPa**				

Calculation of measurement uncertainty associated with a measured quantity value Y is according to $Y = f(X_1, \ldots, X_n)$, where $X_1, \ldots, X_n$ are input quantity values. The measurement function for a cone penetrometer calibration can be formulated as:

$$M_{DUT} = M_{reference} + \delta M_{measurement} + \delta M_{repeatability} + \delta M_{reversibility} + \delta M_{resolution} + \delta M_{zero\text{-}drift} + \delta M_{noise}$$

The device under test value (M_{DUT}) is the quantity value indicated by the DUT, in this example the load sensor of the cone penetrometer.

The reference value ($M_{reference}$) is the quantity value indicated by the reference. Note that the reference value also has a measurement uncertainty which is included in the measurement uncertainty calculation of the DUT (Table 1).

The measurement error ($\delta M_{measurement}$) is the measured quantity value (DUT value) minus the reference quantity value (reference value).

For less than ten repeated measurements, the repeatability error ($\delta M_{repeatability}$) is defined as the maximum DUT value minus the minimum DUT value of repeated measurements with the same reference value.

The reversibility error ($\delta M_{reversibility}$) or hysteresis is defined as the difference in the DUT value at a constant reference value when the load increases and when the load decreases. Interpolation can be used to allow for comparison between a certain increasing and decreasing value of the reference, with a constant reference value. Extrapolation is allowed for the lowest value. Note that $\delta M_{reversibility}$ at maximum load is always zero. At zero load, $\delta M_{reversibility}$ is the zero drift error.

The resolution error ($\delta M_{resolution}$) is the smallest change in a quantity being measured that can be presented by the DUT.

The zero drift error ($\delta M_{zero\text{-}drift}$) is the difference in the indicated value by the DUT at zero “load” before and after applying a non-zero measurement “load”.

The noise error (δM_{noise}) is the quadratic mean (root-mean-square or RMS) of the values indicated by the DUT when no load is applied.

Zero adjustment (offset) of the cone penetrometer should be performed prior to data recording for measurement uncertainty calculations. The applied zero load offset value should be presented on the calibration certificate.

Furthermore, measurements should be repeated at least 3 times (three cycles) to be able to calculate repeatability and reversibility errors. The average of the 3 quantity values can be used to calculate, for example, the difference between the cone resistance value and the reference value.

Examples of other measurement uncertainties which could be considered for cone penetrometer uncertainty are operator error and temperature error. The operator error is the measurement uncertainty caused by the operator. This error can be considered negligible if the whole measurement process is automated. The temperature error is the measurement uncertainty caused by fluctuations in temperature. This error can be neglected when calibrations are performed in a temperature-controlled laboratory.

3 SUGGESTED WAY FORWARD

Industry feedback indicates fundamental difficulties with the use of the application classes of ISO 22476-1:2012. Satisfactory resolution of the difficulties may not be feasible and the concept may have to be abandoned for the forthcoming revision of ISO 22476-1:2012.

Two replacement approaches are suggested: (1) prescriptive, method-based requirements and (2) performance requirements based on data point uncertainty. Both approaches would allow a system of ranking/classes. The suggested approaches are not necessarily exclusive; consideration can be given to allow the user of the standard to select one of them.

The first approach implies an attempt to classify equivalent and competing systems through detailed descriptions of specific apparatus and step-by-step methodology, as suggested by Deltares (2016) and Lunne et al. (2017). This conventional approach is used for most standards for geotechnical tests. The Deltares document was commissioned by the Dutch government for use in dike stability assessments in the Netherlands. The document includes prescriptive, method-based requirements that are more comprehensive and thorough than, say, ASTM (2012), but limited to soft soil applications.

The second approach is according to Annex E of ISO 22476-1:2012. This approach should be preferred, as it is of high value and desired by users of CPT results. Annex E is informative, i.e. providing guidance by “should” and “can” statements. A future revision of ISO 22476-1:2012 can provide normative text, i.e. include “shall” statements. It is suggested that a ranking system considers a number of benchmark CPT profiles, each with criteria for uncertainty, say, based on cumulative density functions (CDF). CPT systems can be tested against the benchmark CPTs and the corresponding CDF criteria.

To promote industry uniformity, it is suggested to provide open access to “handbook” type guidance that can be referenced by CPT standards. The guidance should be developed to provide good practice that is specific to CPTs and according to ISO 10012:2003 and ISO/IEC 17025:2017. The guidance can cover both the method-based approach and the performance-based approach. It can be noted here that the performance based approach typically derives its input values from prescriptive procedures of the method-based approach.

4 REFERENCES

ASTM International, 2012. *ASTM D5778-12 Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils.* West Conshohocken: ASTM International.

Deltares 2016. *Protocol sonderen voor Su-bepaling.* Report 1220083-010 to Rijkswaterstaat - Dutch ministry of public works, 33 p. (in Dutch).

European Co-operation for Accreditation of Laboratories 2013. *Expression of the Uncertainty* *of Measurement in Calibration*. European Accreditation, [s.l.], 79 p. (Publication; EA-4/02 M:2013).

International Organization for Standardization, 2003. *ISO 10012:2003 Measurement Management Systems - Requirements for Measurement Processes and Measuring Equipment*. Geneva: ISO.

International Organization for Standardization, 2012. *ISO 22476-1:2012 Geotechnical Investigation and Testing – Field Testing – Part 1: Electrical Cone and Piezocone Penetration Tests*. Geneva: ISO. (With Technical Corrigendum 1, January 2013). (With amendment, 15 January 2013)

International Organization for Standardization, 2014. *ISO 19901-8:2014 Petroleum and Natural Gas Industries - Specific Requirements for Offshore Structures – Part 8: Marine Soil Investigations*. Geneva: ISO.

International Organization for Standardization, 2015. *ISO 2394:2015 General principles on reliability for stuctures*. Geneva: ISO.

International Organization for Standardization, 2017. *ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories*. Geneva: ISO.

International Society for Soil Mechanics and Geo-technical Engineering. 1999. International reference test procedure for the cone penetration test (CPT) and the cone penetration test with pore pressure (CPTU): Report of the ISSMGE Technical Committee 16 on Ground Property Characterisation from In situ Testing. In F.B.J. Barends et al. (eds.), *Geotechnical engineering for transportation infrastructure; Proceedings of the twelfth European conference on soil mechanics and geotechnical engineering, Amsterdam, Netherlands, 7-10 June 1999, Vol. 3*: 2195-2222. Rotterdam: A.A. Balkema.

JCGM Joint Committee for Guides in Metrology 2012. *International vocabulary of metrology – Basic and general concepts and associated terms (VIM).* 3rd edition, 2008 version with minor corrections, JCGM 200:2012.

Joint Committee For Guides In Metrology (JCGM), 1993. *International vocabulary of metrology: basic and general concepts and associated terms (VIM)*. JCGM.

Lunne, T., Santos, R. and Brink Clausen, 2017. Guidelines for Use of CPTU Application Classes According to ISO 19901-8: (2014). In: Society For Underwater Technology Offshore Site Investigation and Geotechnics Committee, ed. *Offshore Site Investigation and Geotechnics: Smarter Solutions for Future Offshore Developments: Proceedings of the 8th International Conference 12-14 September 2017, Royal Geographical Society, London, UK: Volume 2*. London: Society for Underwater Technology, pp. 300-307.

Nederlands Normalisatie-instituut NEN. 1996. *Geotechnics. Determination of the cone resistance and the sleeve friction of soil. Electric cone penetration test*. Dutch Standard NEN 5140. Delft: Nederlands Normalisatie-instituut. (in Dutch).

Peuchen, J. and Terwindt, J. 2014. Introduction to CPT accuracy, *Keynote in 3rd International Symposium on Cone Penetration Testing CPT'14*. May 12-14, 2014 – Las Vegas, Nevada, 45 p.

Peuchen, J., Kaltsas, D. and Sinjorgo, G. 2018. Calibration of cone penetrometers in accredited laboratory. In Hicks, M.A., Pisanò, F. and Peuchen, J. eds. *Cone Penetration Testing 2018: Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT'18): Delft, The Netherlands, 21-22 June 2018*. Boca Raton: CRC Press, pp. 513-517.