Technical note on calibration for cone penetration testing in soft soils

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ABSTRACT

Even the most experienced geotechnical engineer is likely to assume that the results of cone penetration tests are unquestionably accurate, reliable and repeatable. There are, however, multiple factors, some that have nothing to do with the soil properties, that need to be carefully addressed prior to testing if the equipment is to return results that can be relied on for design purposes. In soils which are very soft or soft, cone penetration test results can be particularly sensitive to the method of calibration. A high degree of rigour to the calibration process is required, otherwise there is a risk that the results obtained could be inaccurate and adversely impact on the reliability of the interpretation of design soil strength profiles. In this technical note sources of error in cone calibration are discussed. Reference is made to ISO 22476-1 which was revised in 2022, with the addition of a defined approach to calibration. Examples are used to demonstrate the typical errors that could be introduced during calibration.

Keywords: Cone penetration test; calibration; uncertainty; error; accuracy; repeatability; ISO22476-1

1. Introduction

In most applications the cone penetration test provides reliable and repeatable test results, particularly when compared to the standard penetration test. However, it is important to understand the factors that can limit the accuracy and reliability, particularly in soft soils. Accurate and reliable test data requires close attention to the processes for calibrating and testing.

The reliability of cone penetration testing (CPT) is subject to limitations of the electronic data capture systems, in which errors can be introduced through a range of factors. Lunne et al (1997) and Schaap and Zuidberg (1982) present potential errors sources in the results of CPT (Figure 1), as follows:

During calibration:

- accuracy of measurements
- repeatability of measurements
- hysteresis of loading and unloading
- zero offsets
- linearity of data (or ability to fit a single coefficient to the data), and
- range of calibration pressures not suitable for the strength of soils being tested.

During each CPT test:

- zero drift errors – i.e. any difference between zero readings taken before and after each CPT test
- temperature effects
- poor saturation of the piezocone, and
- wear on the CPT.

Correction of test results prior to plotting:

- inaccuracies in the measurement of the net area ratio (a), and
- inaccuracies in the correction for zero drift error.

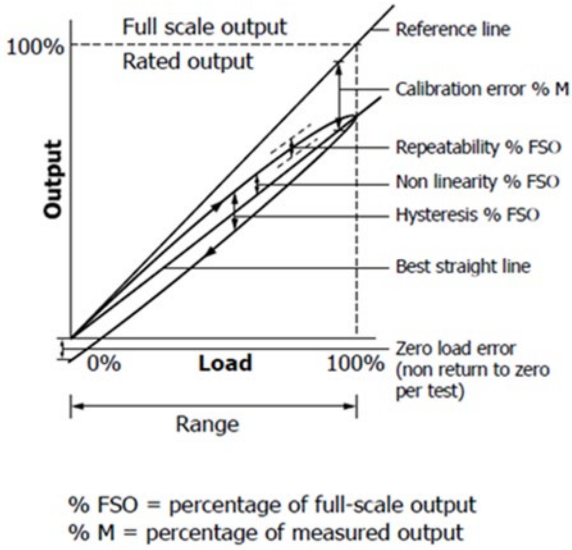


Figure 1. Definition of calibration characteristics (from Schaap and Zuidberg 1982, as presented in Lunne et al 1997)

Accuracy is broadly defined as the difference of a measured value to the true value of the quantity being measured as a percentage of the measured value.

Linearity is the difference between the measured value and best fit straight line through the calibration points as a percentage over the calibrated load range.

Repeatability is the difference between repeated sets of measurements at the same load to each other. The repeatability can be determined by loading (and unloading) multiple times.

Peuchen and Terwindt (2014) provided a comprehensive discussion that addresses in detail the potential sources of errors in CPT. Their ideal "supreme" in situ testing tool would provide zero measurement uncertainty, return unambiguous soil behaviour identification, have a closed form theoretical interpretation model linked to fundamental soil mechanics, penetrate at high speed in a wide range of ground conditions, with extremes of temperature, would be of low cost and operate on any terrain (above and below water) and have a unique method of standardisation. No such tool exists but they concluded that the CPT comes closest to meeting these aspirational objectives.

The impact of potential errors in CPT is most significant for the design of engineering structures in "soft" soils. For the purpose of this technical note "soft" soils are broadly considered to be soils with a shear strength less than 50 kPa.

This technical note explores the reliability of cone penetration testing, specifically focusing on the calibration procedures for engineering applications in soft soils. Design refinement of some structures, for example tailings dams, offshore seabed structures and submerged tunnels, can be sensitive to the interpreted soil strength. Uncertainty about the reliability of the CPT results could influence the degree of design conservatism.

In this note, examples are given of the potential impact of errors in shear strengths calculated from CPT data. However, it is beyond the scope of this technical note to discuss the reliability of the interpretation of CPT data, for example, in estimating shear strength and other design parameters, and predicting soil classification. Errors due to variations in temperature, cone dimension and inclination effects are also not discussed.

2. Test data

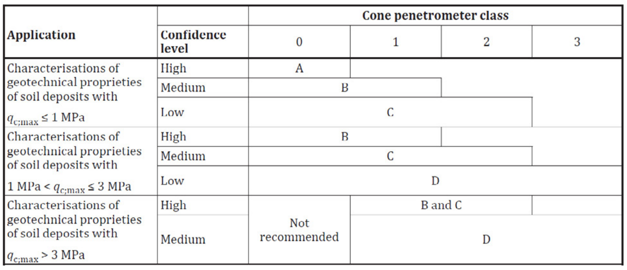
This technical note makes reference to data from testing carried out in 2017 and 2019 for a proposed infrastructure project in Sydney, drawing on prevoius work by Scholey and MacGregor (2022). The project anticipated construction of immersed tube tunnels in Sydney Harbour. CPTs were carried out in the seabed sediments using a seabed reaction frame lowered from a dynamically-positioned vessel. The pushing force available from the seabed reaction frame was sufficient to push the cone to 100 MPa cone tip resistance. The cones used were standard sized cones with a cone diameter of nominally 35.7 mm, a cone end area of 1,000 mm^2 and a sleeve area of 15,000 mm^2.

3. Cone test specifications

Recommended procedures for cone penetration testing are provided in International Standard ISO 22476-1 – Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone test". This standard has recently been updated (ISO22476-1:2022/AC:2023) but the Sydney Harbour work was done under the previous version (ISO22476-1:2012/AC:2013). In the new version of the standard there are two parameters that define the level of "uncertainty" in cone penetration test data:

- Cone Penetrometer Class, which classifies cones into Class 0, 1, 2 or 3 according to their measurement uncertainty, as defined from calibration in controlled laboratory conditions, and
- Test Category, which is based on a combination of the Cone Penetrometer Class, difference in "reference" values (the "zero" readings at the start and finish of a test) and output stability, with categories A to D, A providing the highest level of certainty, D the greatest uncertainty.

Whilst a certain Test Category can be targeted by selecting a cone of appropriate Cone Penetrometer Class, the Test Category can only be known after a field test has been completed and the difference in the reference readings is known. In ISO22476-1:2023 use of a Class 1 cone penetrometer is expected to provide a low to medium confidence level (Test Category B or C) in soil deposits with cone resistance, $q_c < 1$ MPa, as shown in Figure 2.



Application	Confidence level	Cone penetrometer class			
		0	1	2	3
Characterisations of geotechnical proprieties of soil deposits with $q_{c;max} \leq 1$ MPa	High	A			
	Medium	B			
	Low	C			
Characterisations of geotechnical proprieties of soil deposits with 1 MPa < $q_{c;max} \leq 3$ MPa	High	B			
	Medium	C			
	Low	D			
Characterisations of geotechnical proprieties of soil deposits with $q_{c;max} > 3$ MPa	High	Not recommended	B and C		
	Medium		D		

Figure 2. Definition of cone penetrometer class (from ISO22476-1:2023)

Previously ISO22476-1:2012 used the terminology "Application Class", which is effectively equivalent to the Test Category in the updated version of the standard, as it is a measure of the overall certainty of the test. For the Sydney Harbour work, Application Class 1 was the intended test outcome, specified by following accuracy (difference in reference values):

- Cone resistance (q_c) – the larger of 35 kPa or 5% of the measured value
- Sleeve friction (f_s) – the larger of 5 kPa or 10% of the measured value
- Pore pressure (u) – the larger of 10 kPa or 2% of the measured value.

To demonstrate the potential variation in calculated shear strengths that are possible depending on the outcomes of the test, consider the two cases below based on results from actual testing:

Case 1 – soil layer at 15 m depth with measured q_c = 500 kPa and pore pressure, u2 = 375 kPa. The allowable range of q_c for Application Class 1 is 500 kPa +/- 35 kPa, which after applying corrections for the unequal area behind the cone and adopting an N_k factor of 15 yields calculated shear strengths in the range 31 to 35 kPa, a variation of +/-6%. If the achieved test result was Application Class 2 with an allowable range for q_c of 500 kPa +/- 100 kPa the calculated shear strength is in the range 26 to 40 kPa which is +/- 20% variation.

Case 2 – soil layer at 2 m depth with measured q_c = 125 kPa and pore pressure, u2 = 20 kPa. The allowable range of q_c for Application Class 1 is 125 kPa +/- 35 kPa, which after applying corrections for the unequal area behind the cone and adopting an N_k factor of 15 yields calculated shear strengths in the range 7 to 10 kPa, a variation of +/-15%. If the test outcome was Application Class 2 with an allowable range for q_c of 125 kPa +/- 100 kPa the calculated shear strength is in the range 1 to 14 kPa, +/-100% variation.

4. Calibration Factors and Cone Calibration

Calibration factors (sometimes referred to as “coefficients”) define the relationship between the load on the cone and the measured pressure output from the cone sensors. The electrical output from the cone sensors is a voltage, and the voltage is converted to engineering units using “calibration factor”. The calibration factor is derived from the slope of the line of “best fit” through the calibration points, as shown schematically in Figure 3 for typical calibration of cone penetration resistance, q_c for a cone with a full-scale range of 0 to 100 kN.

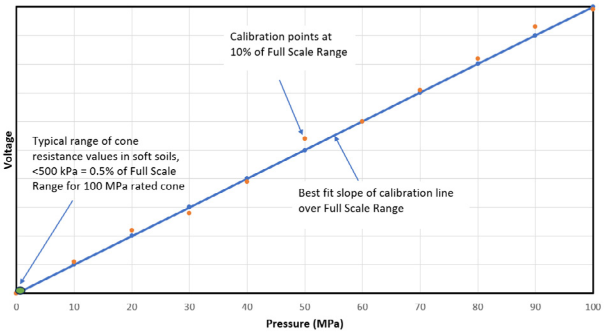


Figure 3. Derivation of calibration factor (in mv/MPa) for q_c for 100 MPa cone

Visibility over the value of the calibration factor depends on the cone supplier and how they present their calibration data, so it is not always clear how the calibration factor was determined. The factor is often embedded in the acquisition software (or the cone), so that the output is seen directly as a load or pressure. There is a difference in the way that suppliers present calibration data, some tabulating load versus voltage and calculated pressures, and presenting the derived calibration factor. ISO22476-1:2023 is silent on the conversion of electrical output to engineering units and their example calibrations are shown in engineering units.

Calibration is a process for establishing the accuracy and repeatability of the cone referred to as “measurement uncertainty” in ISO22476-1:2023, and hence the Cone Penetrometer Class. Calibration is done in a controlled laboratory process during which the cone is repeatedly loaded and unloaded to develop a plot of load versus measured output. The cone is loaded using a calibrated load cell or weights, at multiple load increments, usually to the full-scale range of the cone.

For the Sydney Harbour project, the contractor provided calibration factors (for q_c, in mV/MPa), The calibration data provided included the applied calibration load, output in millivolts (mV) and equivalent calculated applied load. The calibration process involved three loading and unloading cycles over the full-scale range of the cone using certified calibrated reference load cells with matching load capacities. The calibration factors were derived from the slope of the linear best fit line through the calibration points using the mean of the output values. The calibration factors were used to convert the measured voltages to equivalent calculated pressures for each load increment. This data was then used to perform the calibration assessment by calculating accuracy and repeatability errors.

4.1. Calibration Load Range

One of the objectives of the Sydney Harbour testing was to delineate the interface between the sediments and underlying rock which required pushing cones to “refusal”. For this reason, an initial phase of testing was carried out using cones with full-scale ranges of cone resistance of 0 MPa to 100 MPa or 0 MPa to 50 MPa, even in very soft soils. The maximum cone tip resistance recorded during the Sydney Harbour testing was 96 MPa.

Cones are typically recalibrated after testing if they are “overloaded” or if there is a significant difference in the reference values (zero readings). Table 1 shows the calibration factors derived pre- and post-testing for a 50 MPa rated cone used on the Sydney Harbour project.

Table 1. Example calibration factors for q_c: pre- and post-field testing (millivolts per MPa)

	Pre-testing	Post-testing	Low load range: post-testing
Calibration load range	5 – 50 MPa	5 – 50 MPa	0 – 1 MPa
Calibration factors (mv/MPa)	6.70	6.80	6.39

The derived calibration factors pre- and post-testing differ and this adds uncertainty to the results and potentially downgrades the Cone Penetrometer Class (and Test Category). There are several reasons for the differences, which could include shifts in sensor response because of the cone was loaded close to its load capacity.

In soft soils the measured cone tip resistance, q_c, is less than 500 kPa. This is only 5% of the applied load at the first calibration point for the 100 MPa cone used on the Sydney Harbour project (schematically shown in Figure 3), which was calibrated using a typical 10-equal increment loading and unloading sequence.

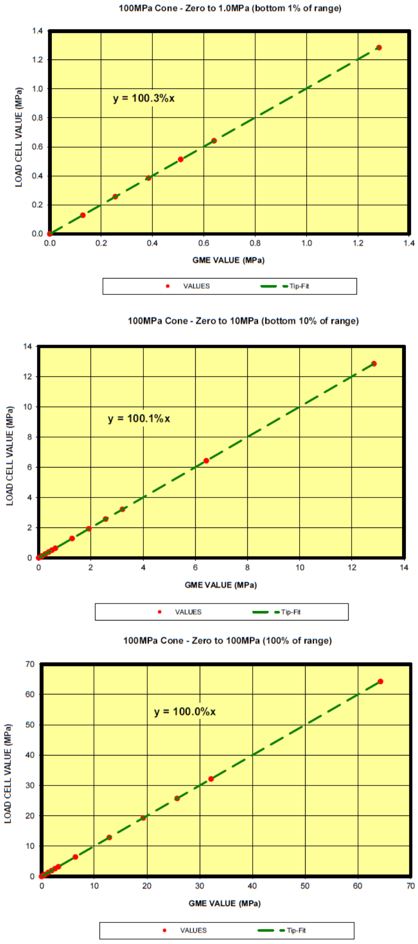
Table 2 shows the derived calibration factor for a 50 MPa rated cone used on the Sydney Harbour project recalibrated post-testing over the load range 0 MPa to 1 MPa. The low load range calibration factor (6.39 mV/MPa) is 6% lower than the full-scale range calibration factor (6.80 mV /MPa) and suggests possible non-linearity in the behaviour of the cone. Non-linearity means that the calibration factor is dependent on the load range and may not be uniform over the full-scale range.

As an example of the potential errors, in one test, soil at a depth of 2 m had a q_c value of 0.125 MPa calculated from the measured voltage output using the low load range calibration factor. If the calibration factor from the full-scale range had been used the calculated q_c value would have been 0.117 MPa. In the same test, soil at 15 m depth had a q_c value of 0.5 MPa, or 0.47 MPa if calculated using the full-scale range calibration factor, a difference of 30 kPa. These may seem like relatively small error margins, but may become significant when compounded with allowable Cone Penetrometer Class errors and reference value errors.

4.2. Method for Low Load Range Calibration

A certified calibrated 1 kN load cell using equal applied pressure increments of 0.1 MPa was used for the low load range calibration on the Sydney Harbour project. This was the first time that the contractor had calibrated cones at such low applied pressures. The specialist reported that smooth application of the load was challenging, particularly at the lowest load increment. Over time the calibration procedures were refined to "smooth" the initial load application. Another specialist in situ testing contractor in Australia (not involved in the testing discussed in this paper) has reported using calibrated weights at load increments of 0.03 kN (Pers. Comm).

It is possible that non-linearity could mean that the calibration factor adopted from the best fit of the calibration points over the full-scale range (100 MPa) is not the same as the calibration factor of the best fit line if the calibration had been carried out over a load range (matching the range of cone resistances in the soft soil). However, most good quality commercial cones today exhibit a high degree of linearity over large load ranges, as shown in the example calibration plot in Figure 4.



100MPa Cone - Zero to 1.0MPa (bottom 1% of range)

100MPa Cone - Zero to 10MPa (bottom 10% of range)

100MPa Cone - Zero to 100MPa (100% of range)

GME = calculated load (from calibration factor)

Figure 4. Calibrations of 100 MPa cone over different load ranges demonstrating good linearity (courtesy A. McConnell, IGS)

4.3. Calibration process in ISO22476-1:2023

ISO22476-1:2023 provides a "normative" methodology for calibration of cones (Appendix B.2) in which it is stated that "the measuring intervals for calibration of the sensors of the cone penetrometer should be selected to cover the measuring intervals of interest". The example calibration in Annex C of ISO22476-1:2023 shows a calibration load/ unload sequence that involves four load cycles and two unload cycles (compared to the three load and three unload cycles for the Sydney Harbour project). The load increments are not equal, with some smaller load increments at the lower load range of the cone (similar to the calibration loading intervals in the example in Figure 4). Whilst specialist in situ testing contractors may be aware of the requirements of the revised standard (ISO22476-1:2023) at least one has advised (Pers. Comm) that the calibration process is complicated and would be timely (and costly). Furthermore, the requirement in ISO22476-1:2023 is only for annual calibration of cones (unless testing suggests recalibration is warranted). This would appear to be a lower expectation than best practice, which would be to recalibrate before and after each project, and at intervals during longer projects or when significant differences in reference values are measured.

The contractor in Australia that provided the example calibration in Figure 4 compares calibrations carried out over the low (less than 1 kN), mid and full-scale range (less than 1 kN), even for cones with a much larger full-scale range (Pers. Comm).

5. Low load range cone tests

For the Sydney Harbour project, the measurement uncertainty for some of the tests in soft soils led to a subsequent phases of confirmatory testing at locations where significant thicknesses of soft soils had been identified. Some of the tests used cones with a full-scale range of 0 MPa to 10 MPa and the testing was contained within the sediments to limit the loads on the cone. Prior to testing, the cones were calibrated over the range 0 MPa to 1 MPa only, at 0.1 MPa load increments.

Derived calibration factors for one of the cones are shown in Table 3. The cone was manufactured and calibrated by a good quality manufacturer in the Netherlands. On arrival in Australia, the cone was separately calibrated by the specialist testing contractor at their facility using their certified calibrated reference load cells and the data acquisition system that was to be used for the field testing. After testing the cone was recalibrated.

Table 2. Example calibration factors (in millivolts per MPa) from low load range calibration

	Calibration Load Range (MPa)	Supplier: pre-dispatch	Contractor: pre-testing	Contractor: post-testing
q_c	0 – 1	1.271	1.253	1.252
q_c	0 -10	1.258	1.252	1.254
f_s	0 – 0.5	60.250	60.935	60.370
u	0 – 2	237.20	238.10	
a		0.81	0.78	

The pre- and post-testing difference in calibration factors for q_c are relatively small, as are the differences for the two ranges over which the cone was calibrated, less than 0.1%. This indicates good repeatability and linearity.

The reason for the difference in calibration factors pre-testing between the supplier and contractor is not known but could be due to the method used to pick the best fit slope between the calibration points and because the testing contractor used the actual acquisition system that was used for the field testing. Regardless the difference is less than 1%, equivalent to a cone resistance, q_c of less than 2 kPa for a soft soil with q_c of 125 kPa.

During testing the shift in the zero value (reference measurement) using the cone in Table 3 was close to zero. In accordance with the updated ISO22476-1:2023 and new terminology the cones would have met the requirements of Test Category B, resulting in a medium confidence level for soil deposits with q_c <1 MPa (refer to Figure 2 above).

The difference in the “a” value is likely because the supplier provided value is based on cone dimensions whereas the specialist contractor in Australia determined the “a” value from calibration in a pressure vessel, as specified in ISO22476-1.

6. Reference (or zero) values

ISO22476-1 calls for reference readings (zero load values) of q_c, f_s and u to be taken before and after each CPT test. The differences in reference readings, the “zero drifts”, are to be recorded with each set of data. The magnitude of the zero drift defines the test category (Table 2).

The measured zero drifts for q_c for several of the tests during the first phase of the Sydney Harbour testing was in excess of 100 kPa. Zero drift can occur for a variety of reasons including temperature differences, extreme loading (hard refusal), and soil ingress into the filter.

The user is left with the issue of how to allow for zero drift in the readings. Possible options could be:

- reporting the zero drift measurements with the results so that the users of the information can make their own allowances,
- adjusting the data in each CPT by linearly spreading the drift over the measurements as the depth increases.

In reality, the error cannot be reliably distributed because the zero error is unlikely to have accumulated linearly with depth. The Test Category (see Table 2) would need to be downgraded. The cone would need to be checked for damage and/or cleaned, recalibrated and the test repeated if the objective was to achieve a higher Test Category. For the Sydney Harbour project, some tests were repeated, as discussed earlier in the paper, partly because of the uncertainty in the test results meant that the specified Application Class 1 could not be achieved.

7. Conclusions

Without a high degree of rigour to the requirements of to the method of calibration of cones there is a risk of unacceptable uncertainty in CPT results. Zero drift error add to the uncertainty. The uncertainty has compounding impacts on the the interpretation of design strength profiles.

The newly updated ISO22476-1:2023 provides definitions of Cone Penetrometer Class and Test Category which the end user can adopt for specifying cone accuracy requirements and the expected test outcomes. Careful calibration is the first step towards achieving certainty in test results, but rigorous field procedures (not specifically the topic of this technical note) are also required. The actual level of certainty in the test results can only be known after the test has been completed and the zero drift errors are known.

In very low strength soils cone test results can be sensitive to the calibration factors used to calculate the cone parameters: cone tip resistance, qc, sleeve friction, fs and pore pressure, u; the method of calibration, the accuracy and repeatability of the cone and non-linearity. In these soils the reliability of the tests requires:

- careful selection of cones, preferably with a full-scale range matching that of the expected loading during testing,
- a high level of sophisticated calibration by experienced operators at loads that match the expected test loads and capture load /unload and zero load points,
- duplicate testing at the same location using cones with different full-scale ranges where there is the conflicting requirement to push to refusal and obtain reliable results in soft soils, or use of alternative tools suited to soft soil conditions, such as the ball penetrometer, T-bar or vane tests,

8. References

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