Does CPT reference value drift really inform CPT correctness?

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ABSTRACT

The two authors' company (IGS) is an in situ testing and sampling contractor. Approximately 40% of the company's business is cone penetration testing (CPT). The CPT cones they use are good quality commercial units supplied by the Dutch company Geomil, with q_c capacities ranging from 3MPa to 100MPa. Both compression-type and subtraction-type cones are used. IGS undertakes their own in-house calibrations on all cones, using externally calibrated load cells, and a combination of dead weights and hydraulic load application. Calibration and adjustment is undertaken on every cone on an unusually frequent basis, explained in the paper, far more frequently than current standards or manufacturer recommendations require. At each calibration, the reference readings (sometimes known as baseline readings) of each cone's tip q_c, sleeve f_s, and pore pressure U sensors are noted. And the slope of the applied-load/pressure-vs-cone-readout for each of these sensors (ie accuracy) is measured and adjusted to give as close as reasonably possible 100% accurate output. All of this is recorded for each cone. Thus the authors have a database of reference reading drift that can be compared to slope adjustments (ie calibration adjustments) that have been needed to achieve the desired cone accuracy. This paper graphically reports the data for tip and sleeve of eight typical CPT cones of the day-to-day types used by the company.

Keywords: CPT; reference readings; calibration.

1. Introduction

The CPT industry/profession has an interest in the issue of comparing various before-vs-after zero-load-offset values of CPT load and pressure sensors, as a method of determining/monitoring various things associated with CPT quality. These zero-load-offsets are defined in the two international standards as follows:

- in ISO 22476-1:2022 as reference readings (sometimes referred to as reference values);
- and in ASTM D5778 – 20 they are defined as baseline readings.

The industry/profession's interest lies in the change or drift in these reference readings or baseline readings:

- (a) from the time of last calibration until the present test time, defined in ISO 22476-1:2022 as "calibration drift";
- (b) from the time of the beginning of a specific test until the end of that specific test, ie across the test, defined in ISO 22476-1:2022 as "zero drift".

For convenience in this paper the authors use the ISO 22476-1:2022 terms as per (a) and (b) above throughout.

Also for convenience they have, from here on, abbreviated ISO 22476-1:2022 to ISO-22 and ASTM D5778 – 20 to ASTM-20.

1.1. Calibration Drift (a)

Calibration drift is deemed to be one indication of the on-going quality and condition of a cone itself; ie the device. The standards say that if there has been too much calibration drift since manufacture or since the last calibration then the cone must be repaired and/or re-calibrated. What the standards state:

- Under ISO-22, the limit before repair and/or recalibration is specified as 2% of FSO - full-scale output - (section 5.1.2).
- Under ASTM–20, the limit before repair and/or recalibration is specified as 5% of FSO - (section 10.1.2.1).

There is 250% difference in this parameter's action levels between these standards, but at least they are within the same order of magnitude.

In neither standard is there any explanation of the background to these numbers – they are simply specified.

It is noted that the manufacturer of CPT cones used by the authors' company recommends 5% of FSO for this limiting calibration drift parameter; and their data acquisition software issues an alarm if this is exceeded (Geomil 2018).

1.2. Zero Drift (b)

Zero drift is perceived to be one indication of the quality of a test that has been undertaken, ie the difference in reference readings or baseline readings before the test vs after; ie drift across the test.

The CPT data acquisition system used by the authors' company treats the reference readings of each sensor before a test starts as a kind of tare; the software records this data and deducts the tare values from all sensor readings at the start of the test and then for every reading taken throughout that test; this process starts at the moment that the Operator clicks the "start test" button.

The software also records the reference values for each sensor after the test is completed, ie at the moment that the Operator clicks the "finish test" button. So zero drift data, as defined by ISO-22, is recorded automatically; in engineering units – kPa, MPa, etc, inside the test's data file.

Zero drift is obviously construed by the creators of ISO-22 as one very important measure of the correct functioning of the equipment during the test. Under that standard, zero drift seems to be a "Holy Grail", and acceptability is very tightly defined. Expressed in kPa, it is one of only two parameters on which test quality (called test category in the standard) is determined. The other parameter is cone penetrometer class - not discussed here. See Fig 1 below.

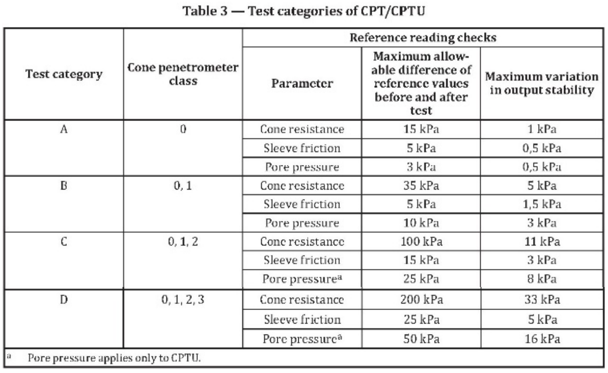


Table 3 — Test categories of CPT/CPTU

Test category	Cone penetrometer class	Reference reading checks		
		Parameter	Maximum allowable difference of reference values before and after test	Maximum variation in output stability
A	0	Cone resistance	15 kPa	1 kPa
		Sleeve friction	5 kPa	0,5 kPa
		Pore pressure	3 kPa	0,5 kPa
B	0, 1	Cone resistance	35 kPa	5 kPa
		Sleeve friction	5 kPa	1,5 kPa
		Pore pressure	10 kPa	3 kPa
C	0, 1, 2	Cone resistance	100 kPa	11 kPa
		Sleeve friction	15 kPa	3 kPa
		Pore pressure[a]	25 kPa	8 kPa
D	0, 1, 2, 3	Cone resistance	200 kPa	33 kPa
		Sleeve friction	25 kPa	5 kPa
		Pore pressure[a]	50 kPa	16 kPa

[a] Pore pressure applies only to CPTU.

Figure 1. – Table 3 from ISO 22476-1:2022
Test categories of CPT/CPTU

Focusing here, for convenience and brevity, on just cone resistance q_c:

- a test category A test (the highest quality) permits maximum 15kPa zero drift across that test;
- a test category B test permits maximum 35kPa zero drift across that test;
- a test category C test permits maximum 100kPa zero drift across that test;
- and a test category D test (the lowest quality) permits maximum 200kPa zero drift across that test.

Under ASTM-20 a completely different impression of the importance of zero drift evolves. Section 10.1.2.2 simply states that permitted zero drift (in ASTM-20's words – "change in initial and final baseline values) of 2% of FSO shall not be exceeded".

Thus, assuming for illustration, a 100MPa cone capacity; ASTM-20 permits 2,000kPa zero drift (apparently for any test) - compared to 15kPa to 200kPa for the carefully defined range of test categories under ISO-22.

That is, ASTM-20 permits 1,000% to 13,000% higher permissible baseline drift during a test than that specified for the full range of test categories by ISO-22.

It is noted that the manufacturer of CPT cones used by the authors' company recommends 0.5% of FSO for q_c zero shift and 1.0% of FSO for f_s and U; again the software issues an alarm if any of these values are exceeded (Geomil 2018).

2. Does CPT reference value drift really inform CPT correctness?

The authors admit some perplexity when deliberating on the huge differences between these two international standards' requirements, and at least one manufacturer's recommendation; and the authors wondered, "does CPT reference value drift really inform CPT correctness?" What does this all mean? – if anything?

As a consequence, their company started some time back collecting data that might help to shed light on the matter, and became more focused on this after perusal of the draft of ISO-22, first seen by them in 2021, where the Holy Grail designation of zero drift within that up-coming standard became apparent.

This paper neither comments on the wisdom or otherwise of any of this nor recommends values. Instead it reports some of that collected data from the company's records that might be of interest to those who wish to think more deeply about this matter.

Given the importance attached to all of this, the authors expected to see a firm connection of some sort between reference value or baseline value shift, and cone sensor accuracy.

3. Where has the reported data come from?

Within the authors' company, calibration and adjustment is undertaken on every CPT cone on an unusually frequent basis. It is done in-house because, as can be seen from the explanation below, it would be unworkable to contract it out. The process is as follows:

a) Every cone is calibrated before every job, then recalibrated after the job, each time using the cone's true dimensions, and focusing on each sensor's lower range of values. If any job runs more than one week or so, then the cones on that job are changed over with freshly calibrated cones on an approximate seven-day service cycle.
b) Before each cone's recalibration, the used cone's as-is accuracy is first checked and then compared to the data from its previous calibration, to cross-check for any significant changes; in which case action might be taken.
c) If a cone lies in store (ie it is not used for testing) for 90 days or more after its last calibration, it is recalibrated again before going to the field to be used.

All of this is recorded; and a reference-value-drift-performance-and-cone-accuracy type of history is developed for each cone.

A consequence of this practice is that calibration and adjustment is undertaken on every cone on an unusually frequent basis; far more frequently than current standards or manufacturers recommend/require. For example:

- ISO-22 Table B1 stipulates: Calibration shall be carried out at least every twelve months or when sensors are overloaded or show signs of malfunction or if reference readings before the start of the test show a drift larger than 2% of the full scale compared to the calibration zero load readings.

- ASTM-20 stipulates: For cones used regularly, periodic calibrations should be performed. The calibration period can be based on production footage, such as once every 3000m of soundings, or time period.

The authors' company's calibration laboratory, normally staffed by one technician, can calibrate (say) 3-4 CPT cones per day. To achieve this, the calibration process is kept relatively simple, using a combination of dead-weights and externally calibrated load cells and pressure sensors. And using a data acquisition device and cabling identical to those used on the company's CPT rigs. A typical calibration report is shown in Figure 7.

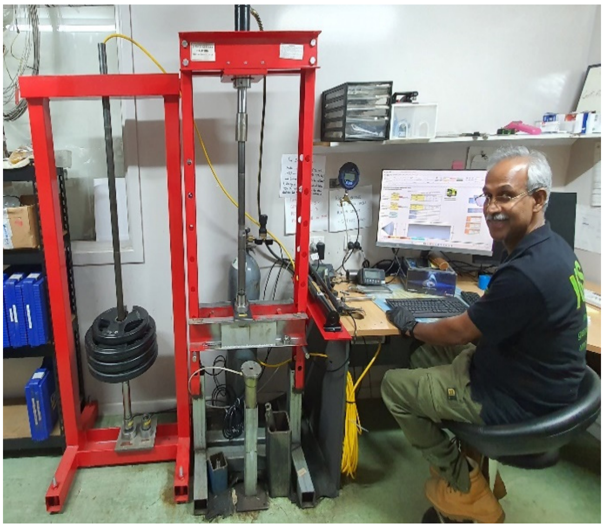


Figure 2. – The IGS calibration laboratory

Note that the same procedure is used by the company for both compression cones and subtraction cones. See Fig 3 and the following discussion for an explanation of the differences between these cone types.

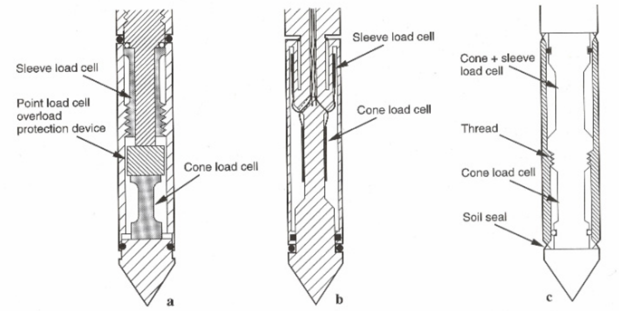


Figure 3. Design of Cone Penetrometers (Lunne et al 1997) (a) compression cone – (c) subtraction cone

The relevant difference between a compression cone and a subtraction cone is that:

- A compression cone has independent load cells for the tip and the sleeve. Hence these load cells can be sized for the purpose; typically a larger load cell for the tip and a smaller one for the sleeve.
- A subtraction cone has two load cells that must both be of the larger variety. Typically they would be identical or nearly identical. One of these, that just behind the tip, measures the tip load only and the other, above the screwed on connection to the sleeve, measures the combined tip-plus-sleeve load. Software subtracts one value from the other to determine sleeve friction.

In the past, all cones were subtraction cones. Compression cones were developed later, ostensibly to improve a CPT's ability to measure sleeve friction (Robertson et al 2015 – page 21).

Some recent developments however have up-ended this situation; by design and manufacture of super-sensitive 3MPa and 10MPa subtraction cones that have been shown to better measure extremely low sleeve frictions (McConnell et al 2022). These super-sensitive 3MPa and 10MPa subtraction cones are not included in the data presented in this paper or discussed further herein.

4. The data and the plots (Figures 5 and 6)

The authors' company operates approximately 80 CPT cones. Sequential calibration records from eight of these cones, taken over a two year period, were interrogated and have been compiled and plotted. The eight CPT cones chosen were as follows:

- Two off 10MPa compression cones.
- Two off 25MPa compression cones
- Two off 100MPa compression cones.
- Two off 100MPa subtraction cones.

These were chosen simply to cover the range of cones that the company operates on a more-or-less day-to-day basis. For simplicity, the data plotted was of cone resistance q_c and sleeve friction f_s.

For each of these sensors and for between six to 20 sequential calibrations each, totalling 84 calibrations, the following has been plotted/reported:

a) Change (ie drift) in reference/baseline q_c and f_s readings since the cone's previous calibration, expressed in both percent of FSO (rounded to one decimal point) and in kPa.

b) The slope adjustment, (expressed as percent of FSO) needed to adjust the q_c and f_s sensors to achieve best possible accuracy (typically to achieve better than 99% accuracy over the bottom 1% of FSO).

An example calibration report sheet for one of the 100MPa cones is shown as Figure 7.

There is a lot of data presented in the plots in Figures 5 & 6. To assist with perusal of this the figures have been colour coded and a numbering system has been adopted that permits ready finding of any individual set of plotted calibration data.

The individual graphs in Figures 5 & 6 are designated A to P and each calibration is numbered sequentially - A-1 to P-14.

5. Level of confidence in this data

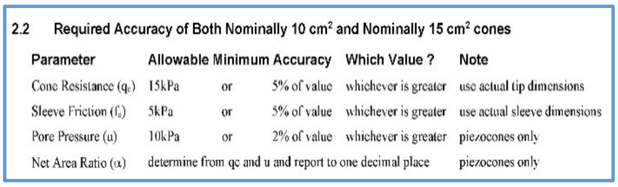
5.1. The calibration process

As mentioned in Section 3 the company's calibration process is kept relatively simple. For q_c and f_s covered here, using a combination of dead-weights and externally calibrated load cells. The process is described below:

a) (i) Cone tip and sleeve dimensions are carefully measured using a good quality, annually calibrated, vernier calliper; (ii) loads are applied to each sensor separately, using either calibrated dead weights and/or a hydraulic press with the annually calibrated load cells; and (iii) the q_c and f_s readouts from the data acquisition system are recorded and tabulated in engineering units.

b) Each calibration cycle, ie process (a) above, is undertaken once to establish as-is conditions, called a pre-cal, and the cone's sensor constants are then adjusted to compensate for any identified error.

c) Calibration cycle (a) is then repeated again with the now adjusted constants for q_c and f_s, to check that the adjusted cone now meets the company's required minimum calibration criteria (see Figure 4 below). Sometimes this is repeated in an iterative manner to achieve the best outcome.



2.2 Required Accuracy of Both Nominally 10 cm^2 and Nominally 15 cm^2 cones

Parameter	Allowable Minimum Accuracy			Which Value ?	Note
Cone Resistance (q_c)	15kPa	or	5% of value	whichever is greater	use actual tip dimensions
Sleeve Friction (f_s)	5kPa	or	5% of value	whichever is greater	use actual sleeve dimensions
Pore Pressure (u)	10kPa	or	2% of value	whichever is greater	piezocones only
Net Area Ratio (α)	determine from qc and u and report to one decimal place				piezocones only

Figure 4 – The company's cone calibration criteria (Insitu Geotech Services – 2020)

Note that for the super-sensitive 3MPa and 10MPa subtraction cones mentioned in Section 3 but not discussed within this paper, much tighter criteria are adopted.

5.2. Repeatability of calibration outcomes

Referring back to Section 3, numbered paragraph (c), if a cone lies in store (ie it is not used for testing) for 90 days or more after its last calibration, it is recalibrated again before going to the field to be used.

This provides an opportunity to cross-check the calibration outcomes for repeatability. If the cone has not been used for testing then its calibration should reasonably be expected to remain stable if the calibration process is valid.

Referring to Figures 5 and 6, calibrations A-2, A-8, A-9, B-2, B-8, B-9, H-5 and L-5 fall into this category. Repeatability can be observed in these examples.

5.3. Conclusion re data confidence

The authors have confidence in the data presented in Figures 5 and 6, and discussed below.

6. Perusal of the data plots (Figures 5 & 6)

6.1. A note on the maintained quality of these cones

It is important to note that none of the recalibrations represented in Figures 5 and 6 were made because of suspicions about the cones' quality or accuracy. The recalibrations were simply a result of the company's quality-control processes. And in no case did the recalibrations indicate significant malfunction:

- Expressed as percent of FSO, reference value drift never reached 1% and mostly this was much lower.
- Expressed as percent of FSO, accuracy drift never reached 5% and mostly this was much lower.

And none of these drifts occurred over the duration of a single CPT test. These drifts occurred over typically many more than one test – they were observed calibration-to-recalibration.

6.2. Some interesting observations

As stated in Section 2:

- Given the importance given to all of this (ie reference value drift), the authors expected to see a firm connection of some sort between reference value or baseline value shift, and cone q_c or f_s sensor accuracy.

The authors however could see no such firm connection. In fact the data presented shows some examples of the opposite – notable of which are summarised here:

- C-5, C-7, C-10, E-7, E-8, H-3, H-6, M-3 and N-19 showed some of the higher reference value drifts expressed as percent FSO, yet none of these had impacts of any note on cone accuracy – in all of these instances tip or sleeve accuracy correction was zero, or effectively zero.
- The three highest accuracy drifts (still only 4.1%-4.7% of FSO) D-8, J-6, M-9 and N-9, were associated with negligible reference value shifts.

7. References

ASTM D5778 – 20 *Standard test method for electronic friction cone and piezocone penetration testing of soils*. 2020.

Geomil *Troubleshooting 18-001_rev_0* June 2018

Insitu Geotech Services *20-05-22(f) IGS Specification for CPT Calibration*. May 2020

ISO 22476-1 *Geotechnical investigation and testing-Field testing-Part 1: Electrical cone and piezocone penetration test.* Second edition 2011-12.

Lunne, T., P.K Robertson & J.J.M Powell (1997). *Cone Penetration Testing In Geotechnical Practice.*

McConnell, A.J & E.J.C Wassenaar (2022) *An innovative new 3MPa CPT – to detect and measure very small fs values.*

Robertson P. K. & K.L. Cabal (2015) *6th Edition Guide to Cone Penetration Testing for Geotechnical Engineering.*

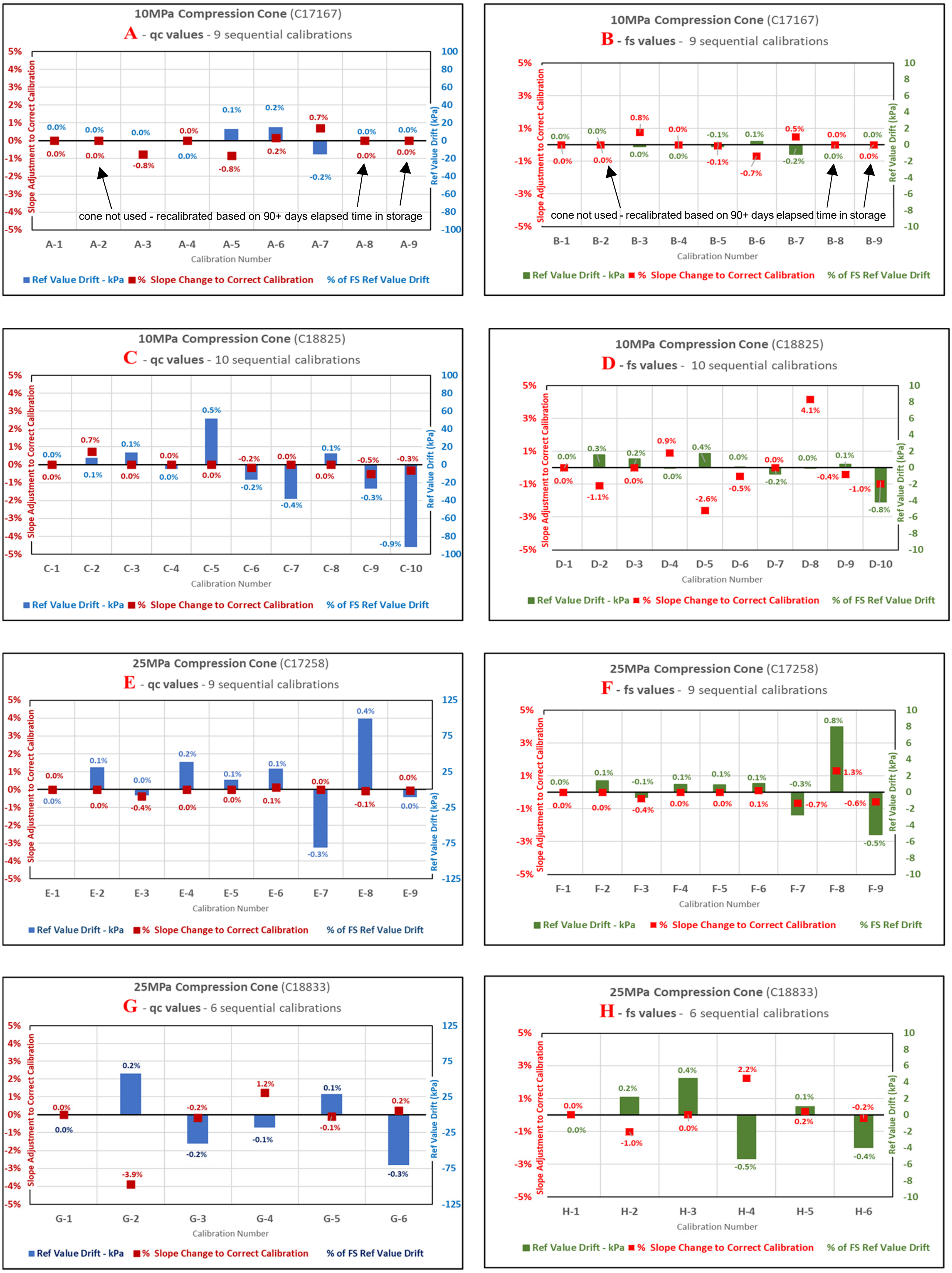


Figure 5 – Graphs A to H

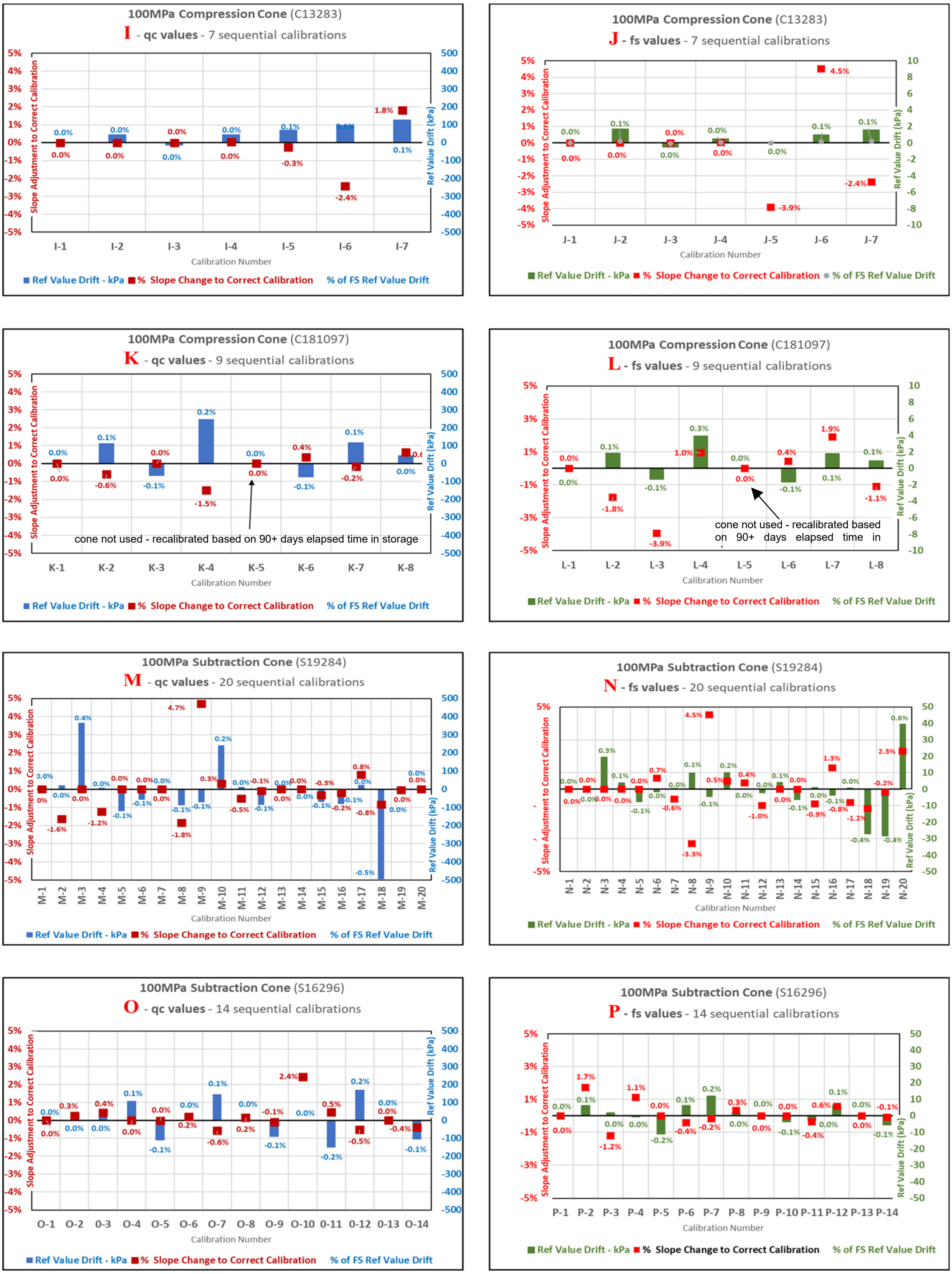
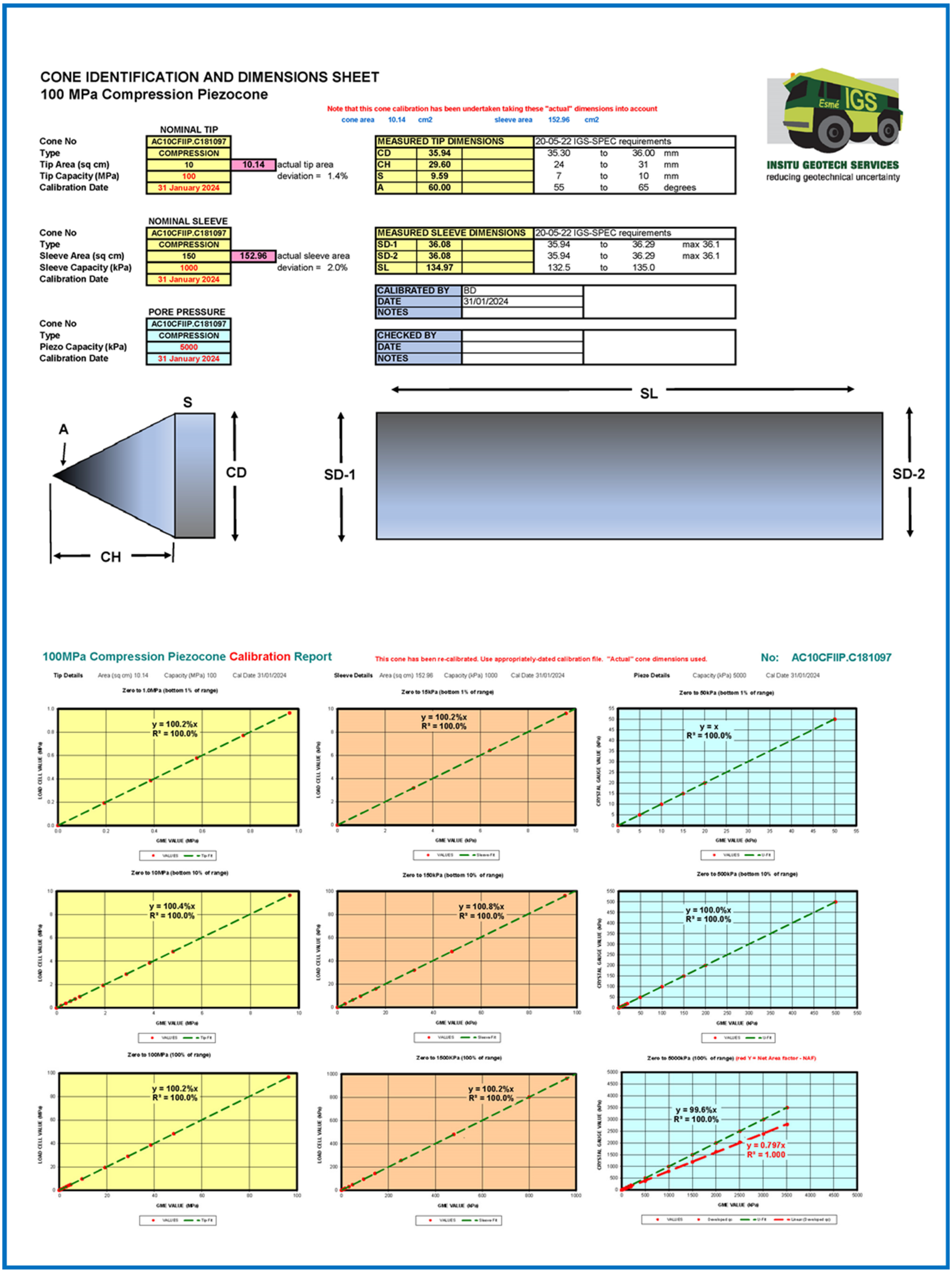


Figure 6 – Graphs I to P



CONE IDENTIFICATION AND DIMENSIONS SHEET

100 MPa Compression Piezocone

Note that this cone calibration has been undertaken taking these "actual" dimensions into account

cone area 10.14 cm2 sleeve area 152.96 cm2

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	NOMINAL TIP		
Cone No	AC10CFIIP.C181097		
Type	COMPRESSION		
Tip Area (sq cm)	10	10.14	actual tip area
Tip Capacity (MPa)	100		deviation = 1.4%
Calibration Date	31 January 2024		

MEASURED TIP DIMENSIONS			20-05-22 IGS-SPEC requirements			
CD	35.94		35.30	to	36.00	mm
CH	29.60		24	to	31	mm
S	9.59		7	to	10	mm
A	60.00		55	to	65	degrees

	NOMINAL SLEEVE		
Cone No	AC10CFIIP.C181097		
Type	COMPRESSION		
Sleeve Area (sq cm)	150	152.96	actual sleeve area
Sleeve Capacity (kPa)	1000		deviation = 2.0%
Calibration Date	31 January 2024		

MEASURED SLEEVE DIMENSIONS			20-05-22 IGS-SPEC requirements			
SD-1	36.08		35.94	to	36.29	max 36.1
SD-2	36.08		35.94	to	36.29	max 36.1
SL	134.97		132.5	to	135.0	

CALIBRATED BY	BD
DATE	31/01/2024
NOTES	

	PORE PRESSURE
Cone No	AC10CFIIP.C181097
Type	COMPRESSION
Piezo Capacity (kPa)	5000
Calibration Date	31 January 2024

CHECKED BY	
DATE	
NOTES	

100MPa Compression Piezocone Calibration Report

This cone has been re-calibrated. Use appropriately-dated calibration file. "Actual" cone dimensions used.

No: AC10CFIIP.C181097

Tip Details Area (sq cm) 10.14 Capacity (MPa) 100 Cal Date 31/01/2024

Sleeve Details Area (sq cm) 152.96 Capacity (kPa) 1000 Cal Date 31/01/2024

Piezo Details Capacity (kPa) 5000 Cal Date 31/01/2024

Figure 7 – A typical calibration – Cone Number C181097