A paradigm shift in CPTu testing of extremely soft tailings

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ABSTRACT

CPTu (piezocone) testing is routinely used as part of modern site investigations in tailings storage facilities. The test is well-established and is celebrated as a convenient and rapid means to establish parameters used to analyse stability, settlement, potential for liquefaction, etc. The test was developed originally for natural soils. Many correlations exist for determining the various parameters, based on the three fundamental test outputs: cone resistance (q_c or q_t); sleeve friction (f_s); and pore pressure (u). An inconvenient truth however is that in extremely soft or very loose (ooze-like) materials, typical in many tailings situations, even the best quality conventional CPTu equipment cannot reliably or repeatably measure and report extremely small values of f_s. There are reasons for this, related to the physical design of CPTu sleeve systems, almost guaranteeing that this problem will exist. The in situ testing industry to some extent deals with this inconvenient truth as an 'elephant in the room'; a topic not talked about much, if at all, but rather agonisingly hanging around in the shadows in the background of CPT testing. Of course treating it this way means that parameters determined from the well-established correlations, and other parameters that might be directly measured, are compromised. In 2021 two of the authors, a testing practitioner and an equipment manufacturer, developed a new CPTu cone that has been proven to overcome this problem. This required a significant design paradigm shift that has evolved into a new innovative design that works. The new CPTu cone was described by the authors at the CPT'22 Conference in Bologna in 2022. Now it has been in use for more than a year and some meaningful comparative tailings testing data is available that demonstrates the efficacy of the new device, provided (100%) that it is maintained and calibrated carefully. The new CPT cone is commercially available to all; it is not a secret in-house tool.

1 INTRODUCTION

1.1 This paper expands on a paper at CPT'22 and repeats some material

In June 2022 the authors published and presented a paper at the conference CPT'22 in Bologna, titled '*An innovative new 3 MPa CPT – to detect and measure very small f_s values'* (McConnell 2022). That paper introduced the background and some design aspects of a 3 MPa special cone developed by the authors to detect and measure very small f_s values that could not (and still cannot) be detected and measured using conventional CPT compression cones – ie using the industry paradigm for high quality testing.

As that conference was a targeted CPT conference, and as a clear understanding of the new cone is essential to an appreciation of this current paper, the authors have deliberately repeated here some of the CPT'22 paper, for an element of greater completeness. The CPT'22 paper referred in places to the then-current international standard ISO 22476-1-2012, and where relevant those references are repeated here. It also referred to what was at that time a draft update of ISO 22476-1. This draft has now very recently evolved into the current international standard BS EN ISO 22476-1-2023. Where relevant, material from the new standard is referred to, and in some places this will be a little different to that from the draft previously referenced.

1.2 The CPT'22 introduction (repeated here)

Insitu Geotech Services (IGS) undertakes much CPT testing in soils and sediments that can be described in everyday terms as "extremely soft", or even as "ooze"; for clients who are seeking data that permits them to make confident designs.

As a consequence they are almost every day working in an arena where one would aspire to better than Application Class 1 testing quality, if being described according to (the past) ISO 22476-1-2012.

To achieve the highest quality that they can in testing these conditions and in satisfying clients they:

- Use known good quality CPT cones. In soft soils these have been previously usually of 25 MPa or 10 MPa tip capacity.

- Maintain/manage all CPTs meticulously.

- Undertake in-house calibration-checking-recalibration under a very stringent program, as described below.

The IGS calibration program is run in-house because, as you can see from the explanation below, it would be unworkable to contract it out:

a) Every cone is calibrated before every job, then recalibrated after the job, each time using the cone's actual dimensions, not nominal values. If the job runs more than one week, then the cones are changed over with freshly calibrated cones on an approximate 7-day service cycle. All of this is carefully recorded and a calibration-drift-performance type of history is developed for each cone.

b) Recalibration data is then always compared to the data from the previous calibration, to cross-check for any significant change.

c) And, before-vs-after zero-load-drift comparisons (called "reference values' in the new standard), are taken as part of each test's management.

d) It's rigorous, it works, and it's business as usual, built into the company culture and cost structures.

Following the above approach IGS has been successful in regard to the ability to defensibly and repeatably measure very low q_c values, and to be as good as reasonably achievable at measuring f_s values.

2 LIMITATION RE MEASURING VERY SMALL SLEEVE FRICTIONS

In regard to f_s though, they have run up against the 'industry normal' limitation in measuring very small sleeve frictions; a limitation that is associated with the design of normal Compression Cones. To help discussion of this, refer to Figure 1 below.

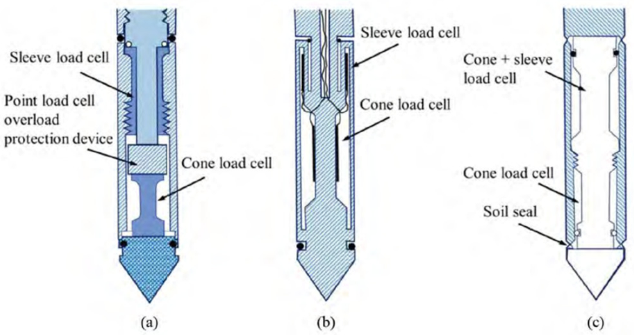


Figure 1 Design of Cone Penetrometers (modified in Robertson 2022 from Lunne et al 1997)

In this paper type (a) is designated as a compression cone and type (c) as a subtraction cone.

For this discussion, the relevant difference between a compression cone and a subtraction cone is that:

- A compression cone has separate 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 load cell 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 load cell value from the other to determine the sleeve friction. Hence a relatively big number is subtracted from another relatively big number to get a smaller number. If calibration of either or both load cells is not precise, or they drift differently during a test or after calibration, one can reasonably expect significant errors in the sleeve friction values determined this way.

Compression cones (these authors perceive) were developed in the first instance ostensibly to improve a CPT's ability to measure sleeve friction.

3 THE CURRENT PARADIGM

So this is the current industry-wide paradigm:

- If you want to most accurately measure sleeve friction, you must use a compression cone.

In support of this statement that this is the current paradigm, refer Robertson et al (2022), as follows:

- (Page 22). *For accurate sleeve resistance measurements in soft sediments, it is recommended that cones have separate (compression) load cells*.

And in support of something that follows in this paper, quoting from the same document as above, the following paragraph, referring now to compression cones:

- (Page 23*). f_s measurements, in general, will be less accurate than tip resistance, q_c, in most soft fine-grained soils*.

The problem is that, in extremely soft or ooze-like soils, this 'in general expected lower accuracy' in f_s typically ends up meaning no f_s measurement at all, or something too low to be credible.

4 EXPLANATION – WHY VERY SMALL SLEEVE FRICTIONS ARE ELUSIVE

4.1 A simple explanation – referring to Figure 1

- In a compression cone, the sleeve has to move slightly to permit it to apply load to the friction sleeve load cell.

- Dirt seals behind the friction sleeve resist this slight movement and use up some of the force applied by soil friction to the friction sleeve.

- Hence not all or any of the soil friction force ‘gets to’ the friction sleeve load cell. A significant error occurs if this applied soil friction force is very low (as it will be in extremely soft materials).

If one is testing stronger materials then it’s not a significant issue at all, but if one is testing extremely soft material it becomes a problem.

Until recently this limitation was typically handled as an ‘elephant in the room’, not talked about much, but rather agonisingly hanging around in the shadows in the background of CPT testing.

But it’s become a pretty big deal for organisations like IGS that nowadays do much testing in extremely soft or ooze-like soils; and for their clients.

4.2 References to this problem by others

This issue was discussed at CPT’14 in a paper (Santos et al 2014) where the authors correctly ascribed the problem to the friction in sleeve seals and presented an example sleeve calibration showing the difference in load cell readings compared to applied load (Fig 2a) without friction sleeve seals, and (Fig 2b) with seals.

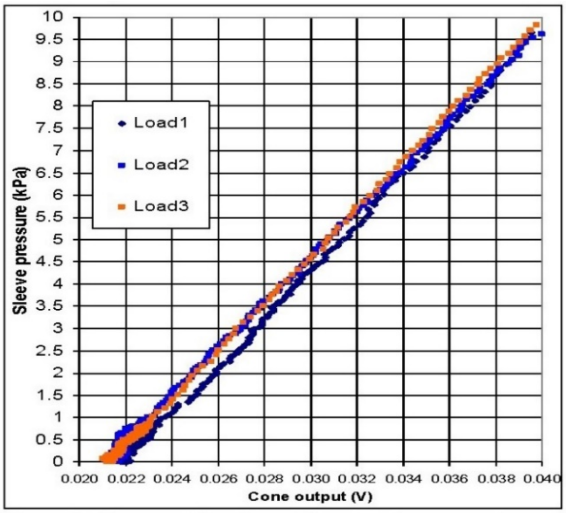


Figure 2(a) Sleeve calibration with no seals

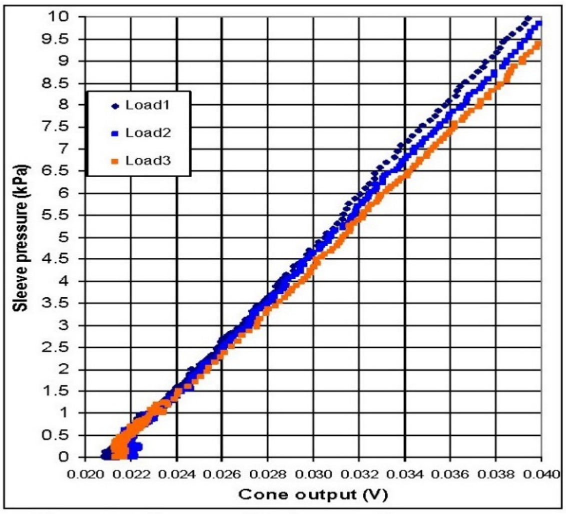


Figure 2(b) Sleeve calibration with seals

Those authors discussed a novel spring-loaded (preloaded) sleeve seal design to attempt to solve the problem. This has/had been taken up by A.P. van den Berg for their cone design.

The issue was again mentioned in a paper at the 2021 Mine Waste and Tailings Conference, (Entezari et al 2021). In that paper, the authors were discussing limitations in the use of CPT data to determine the fines content of extremely soft oil sands tailings.

In that paper, for the analysis they were undertaking, many data points were ‘*screened out in order to remove data where the soil-sleeve friction was less than internal o-ring (sic) friction’.*

This meant discarding a lot of their data.

5 IGS WANTED A SOLUTION – NOT ANOTHER COMPROMISE

IGS wanted a solution, so talked at length to their supplier/partner Geomil as to what this might entail. They then jointly conceived and funded an atypical design as a trial.

The conversation and thinking went as follows:

a) As described in Sections 3 & 4, compression cones have friction sleeves that must move a small amount to be able to register an f_s reading.

b) The sleeves of subtraction cones do not have to move more than a miniscule amount to register friction load. But they have the historically-deemed problem of having to subtract one big number from another big number to get a small one, as discussed in Section 3.

c) As a solution, would it be possible to develop a subtraction cone with unusually high quality and sensitive load cells, and to calibrate these very rigorously to help overcome the problem in subtracting a big number from a big number?

d) And would it be possible to design for much lower cone capacity overall, hence making the two big numbers smaller, further reducing the problem?

e) And would it be possible to make the load cells more responsive than normal, by adopting different construction materials for the elastic bases on which the load cells' strain gauges would be fixed?

Of course this would all comprise a significant paradigm shift, compared to the existing one. Reiterating that paradigm here: *If you want to most accurately measure sleeve friction, you must use a compression cone.*

Some heart was taken in the knowledge that Fugro's very sensitive Fibre Optic Cone, announced at the prototype stage via a paper (Looijen et al 2018) at CPT'18 in Delft, also designed for testing soft materials, is a subtraction cone with unusually sensitive load cells; in principle the same idea.

So IGS and Geomil talked more and eventually Geomil made a first small run of special cones to the agreed design. In accord with (c) and (d) above, they opted for a cone size of 15 cm^2 and an extremely low tip capacity of only 3 MPa; this being adequate for the testing of extremely soft materials that were/are the target.

And, in accordance with (e) above they opted for a special alloy base for the load cells, giving a physical strain gauge response approximately 300% greater than it would be for a conventional steel base.

Of course, also in accordance with (c) above, IGS has adopted the same calibration regime discussed in Section 1, with the enhancement of using dead weights for the application of load to the tip and sleeve.

6 HIGH HOPES AND EXPECTATIONS

Because of high hopes for these cones, IGS had set a policy in place that, to the extent possible, they will calibrate these cones to achieve the accuracy outcomes proposed by the (then) draft international standard ISO/DIS 22476-1 criteria for Class 1+ cones. Now that draft has become a standard, IGS has re-aimed to target, to the extent possible, the prescription described in the finalised standard, not the draft. The new standard BS EN ISO 22476-1-2023 has no Class 1+ but has changed the designation to Class 0.

To date that objective is looking good. A full IGS calibration for one of these cones is shown on the last page of this paper.

In other words, these cones, under these rigorous calibration processes, are pretty remarkable by current measures.

Of course calibration is just one aspect of a CPT. How have these cones behaved in the field?

7 FIELD TRIALS

IGS has had several 3 MPa cones in operation now for about 18 months, in some places testing very soft natural soils but in more places testing ooze-like tailings sediments. The results are satisfying, demonstrating:

a) Ability to repeatably detect, measure and record very low q_c values – say 10kPa and even below.

b) Ability to repeatably detect, measure and record very low f_s values that make sense when compared to the q_c values being measured – say 1 kPa and even below.

Figure 3 below, shows the improved response to sleeve friction compared to what was previously possible, using a figure from the CPT'22 paper.

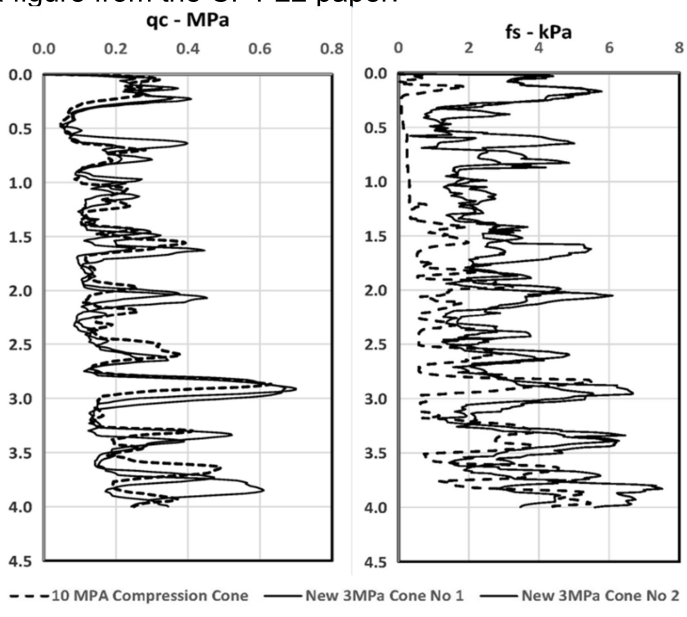


Figure 3 q_c & f_s plots – new 3 MPa cone vs 10 MPa compression cone.

This is just a single illustrative example. All tests undertaken with these new cones have shown the ability to measure very low q_c and a much improved response in regard to extremely low sleeve friction f_s values.

8 REAL EXPERIENCE - WHAT'S THE BENEFIT FOR A TAILINGS INVESTIGATOR?

In pursuit of a method to answer this question in a clear and easily contrasted manner, data from a number of real project tests have been processed using the computer software CPeT-IT v.3.0 – CPT Interpretation Software (Ioannides 2007) to plot CPT-based Soil Behaviour Type using the (Robertson 2016) Soil Behaviour Type Index I_B, that Robertson (2022) states *'capture(s) the SBT boundaries better than the original circular Ic'.*

Four examples are shown in the following as Figures 4c to 4d; three tailings dams tests and one from a natural soil site. These clearly show that the Index I_B increases when testing was done using the new 3 MPa cone compared to side-by-side (or nearly so) tests using a conventional compression cone. It should be noted that all cones were in very good calibration during all of these tests. It should also be noted that higher I_B values indicate more dilative soil behaviour than lower values.

8.1 A coal tailings dam in the Bowen Basin

(25 MPa compression cone vs new 3 MPa cone – q_t mainly 0-100 kPa)

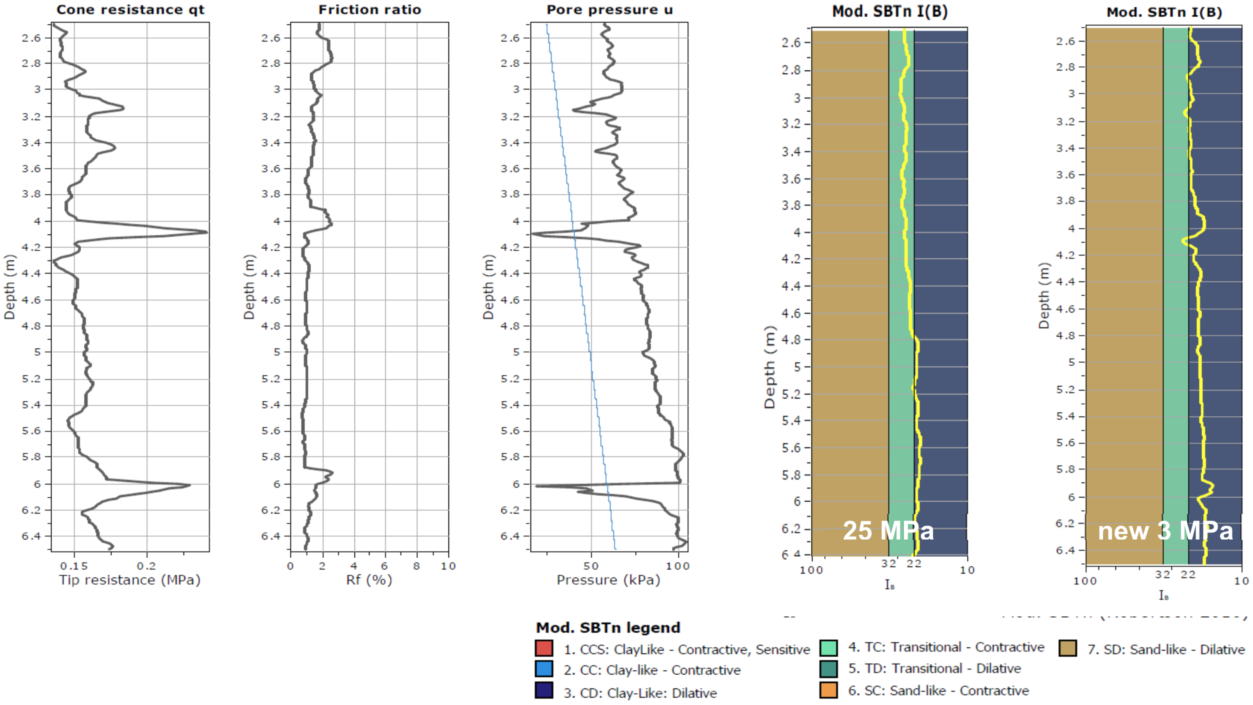


Figure 4a: q_t, R_f, u and I_B plots for a coal tailings dam in The Bowen Basin

8.2 A coal tailings dam in the Hunter Valley

(10 MPa compression cone vs new 3 MPa cone – q_t mainly 0-500 kPa)

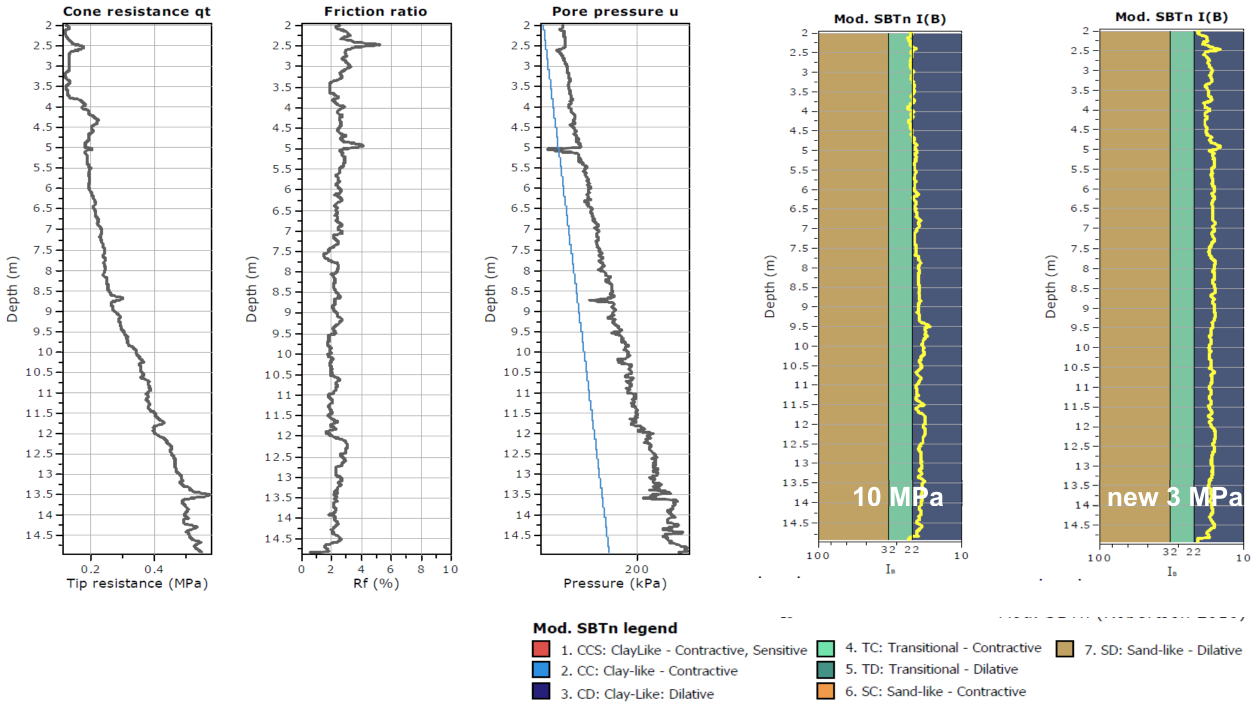


Figure 4b: q_t, R_f, u and I_B plots for a coal tailings dam in The Hunter Valley

8.3 A metalliferous tailings dam in northern Australia

(10 MPa compression cone vs new 3 MPa cone – q_t mainly 0-120 kPa)

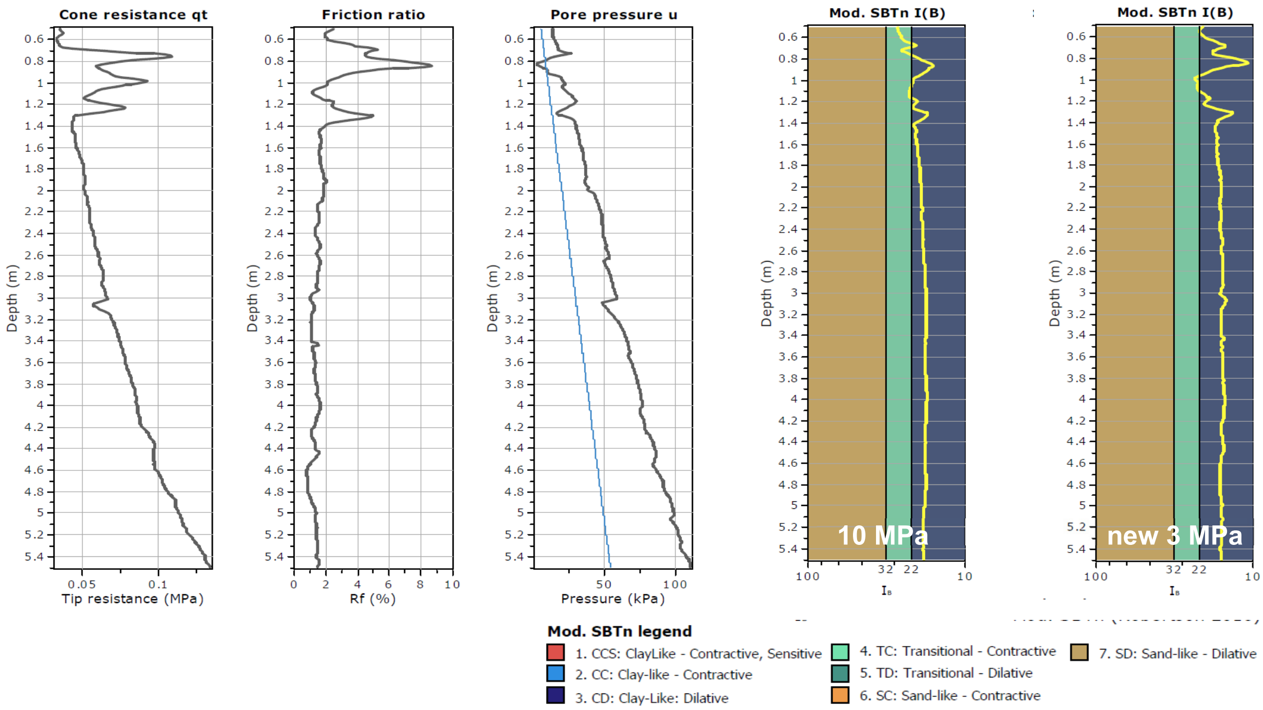


Figure 4c: q_t, R_f, u and I_B plots for a metalliferous tailings dam in northern Australia

8.4 A natural very soft clay site in Tasmania

(100 MPa compression cone vs new 3 MPa cone – q_t mainly 0-100 kPa)

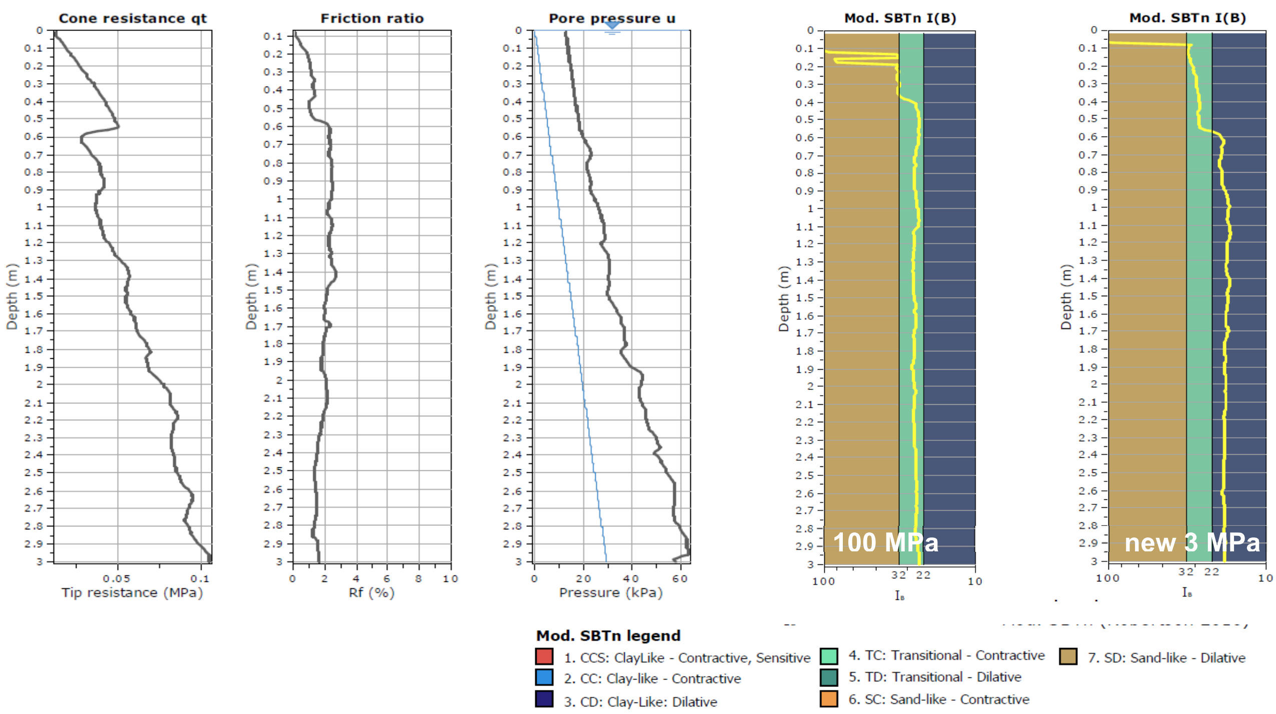


Figure 4d: q_t, R_f, u and I_B plots for a natural very soft clay site in Tasmania

9 FIELD TRIALS – REFERENCE VALUES

The CPT industry/profession is passionate on the issue of comparing “before-vs-after” zero-load-offset values (ie reference values shift) as a method of determining/monitoring:

- the quality and actual condition of a cone itself, and
- the quality of a test that has been undertaken.

IGS’s cone history recording system will one day allow a report on the reliability of this dependence on reference value shift; a quantified study to support the passion (or otherwise).

In the meantime however the authors acknowledge that this is an industry-accepted field indicator of the quality of a test undertaken, so monitoring and recording these zero-load-offsets is part of IGS’s every-test practice.

The new standard BS EN ISO 22476-1-2023 relies heavily on this parameter in determining test quality, called ‘Test Category’, with different categories/qualities numbered A to D; A being the highest quality.

Under the new standard (Table 3), one decides the Test Category by:

a) the Class of cone used and

b) the drift/difference in the before-vs-after reference values.

In the standard, deployment of a Class 0 cone and a before-vs-after drift/difference of less than 15 kPa for the tip, combined with less than 5 kPa drift/difference for the sleeve, categorises the test as Category A, the highest test quality category.

This typically involves measuring the after-test-offsets once the cone has been cleaned and reassembled after testing. It cannot be a value extracted from the completed test’s data file, as this immediately-after value is likely to be influenced by dirt in seals and gaps after cone extraction.

Figures 5(a) and 5(b) below show sets of before-vs-after drift/difference data from a randomly chosen 21 CPT tests using the new 3 MPa cone, The shaded parts represent the BS EN ISO 22476-1-2023 ‘Maximum allowable difference of reference values before and after test’ for Test Category A (the standard’s highest test category) Table 3.

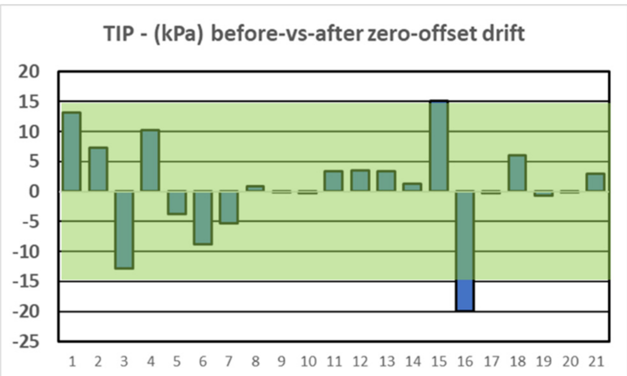


Figure 5(a) before-vs-after tip reference values

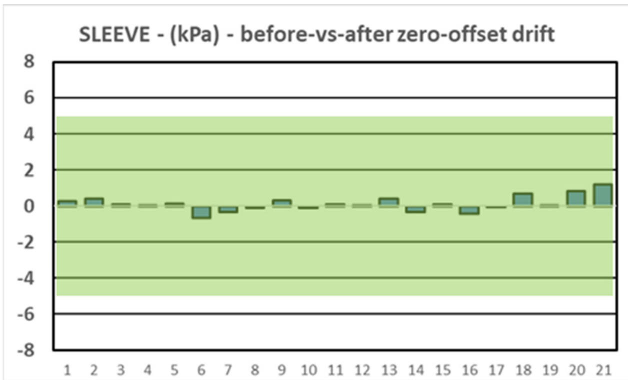


Figure 5(b) before-vs-after sleeve reference values

10 TRANSIENT TEMPERATURE EFFECTS

Transient temperature effect, arguably the least understood potential error in any CPT testing, is a matter that IGS takes seriously in all of their testing. Their default testing procedures do what is reasonably possible to minimise these effects during all stages of a test; including 'cool down or warm-up' pauses in testing in some profiles and circumatsnces.

The work that has been done on this aspect to-date in relation to the new 3 MPa cone has been essentially comparisons of the new cone against conventional cones that have been used for the same type of testing, and for which the management procedures have been proven with time. This is to judge whether the current management procedure to manage this issue can apply to the new cones.

The plot below demonstrates that the new 3 MPa cone is very similar to other cones as described above.

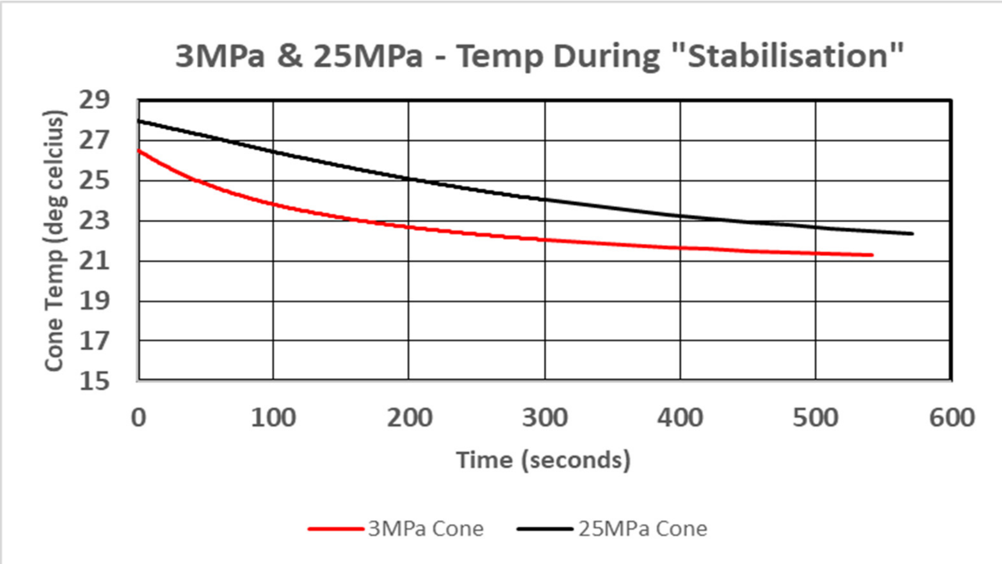


Figure 6: Comparison of transient temperature stabilisation of the new 3 MPa cone vs a 25 MPa compression cone

11 SUMMARY AND CONCLUSIONS

Accurate and repeatable detection and measurement of extremely low sleeve friction (f_s) values during CPT testing is an industry-wide problem, often treated as an 'elephant in the room'.

This paper describes the development of an innovative new CPT cone that the authors believe has solved this problem.

The paper goes on to demonstrate the difference in SBT determined by using this new cone in very soft tailings materials and natural soils. In essence, this difference is that higher I_B values (Robertson 2016), which indicate more contractive soil behaviour than lower values, can be expected if using this cone.

The authors labour to reiterate here that the whole premise of this paper is that all cones will be properly calibrated, and that the new 3 MPa cone absolutely requires good calibration if to be useful in the way described here.

12 REFERENCES

Entezari, I., T. Boulter, S. McGregor, & J. Sharp (2021). Machine Learning to Estimate Fines Content of Tailings Using Gamma Cone Penetration Test*. Australia: Proc AusIMM Mine Waste And Tailings Conference.*

Ioannides, (2007) CPeT-IT CPeT-IT v.3.0 – CPT Interpretation Software. (Online). Available: http://*geologismiki.gr/products/cpet-it*

Looijen, P., N. Parasie, D. Karabacak & J. Peuchen (2018) Fibre optic cone penetrometer. *The Netherlands: Proc CPT'18.*

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

McConnell, A., Wassenaar, E. 2022. An innovative new 3MPa CPT – to detect and measure very small f_s values. *5th International Symposium on Cone Penetration Testing (CPT'22), Bologna, Italy, 8-10 June 2022.*

Robertson P. K. & K.L. Cabal (2022) 7th *Edition Guide to Cone Penetration Testing for Geotechnical Engineering.*

Robertson P. K. (2016) Cone penetration test (CPT)-based soil behaviour type (SBT) classification system – an update. *Canadian Geotechnical Journal / Volume 53, Number 12, December 2016.*

Santos R.S., A. Barwise & M. Alexander (2014). Improved CPT sleeve friction sensitivity in soft soils. *Las Vegas, USA, 3rd International Symposium on Cone Penetration Testing.*

CONE IDENTIFICATION AND DIMENSIONS SHEET

3 MPa Special Purpose Piezocone

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

cone area 15.22 cm2 sleeve area 228.91 cm2

	NOMINAL TIP		
Cone No	AS15CFIIPT.S21003		
Type	SPECIAL PURPOSE		
Tip Area (sq cm)	15	15.22	actual tip area
Tip Capacity (MPa)	3		deviation = 1.4%
Calibration Date	15 October 2021		

MEASURED TIP DIMENSIONS			ISO 22476-1-2012 requirements			
CD	44.02	critical	43.20	to	44.10	mm
CH	36.50		29	to	38	mm
S	11.74		9	to	12	mm
A	60.00		55	to	65	degrees

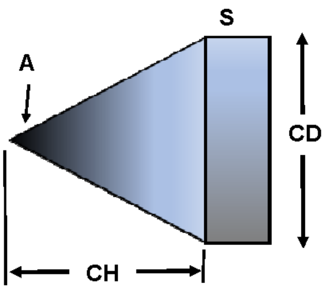
	NOMINAL SLEEVE		
Cone No	AS15CFIIPT.S21003		
Type	SPECIAL PURPOSE		
Sleeve Area (sq cm)	225	228.91	actual sleeve area
Sleeve Capacity (kPa)	200		deviation = 1.7%
Calibration Date	15 October 2021		

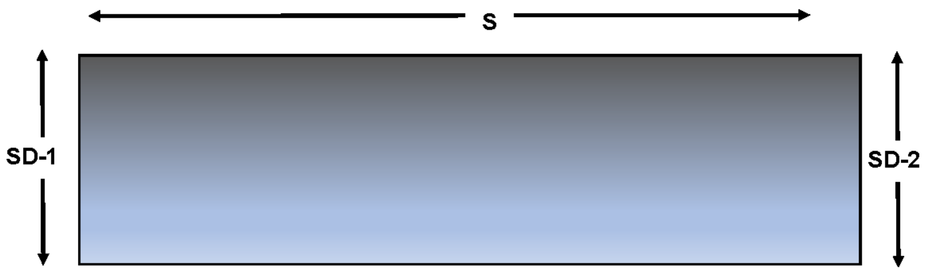
MEASURED SLEEVE DIMENSIONS			ISO 22476-1-2012 requirements			
SD-1	44.11	critical	44.02	to	44.37	max 44.2
SD-2	44.11	critical	44.02	to	44.37	max 44.2
SL	165.19		162.3	to	165.3	

CALIBRATED BY	AS
DATE	15/10/2021
NOTES	

	PORE PRESSURE
Cone No	AS15CFIIPT.S21003
Type	SPECIAL PURPOSE
Piezo Capacity (kPa)	2000
Calibration Date	15 October 2021

CHECKED BY	
DATE	
NOTES	





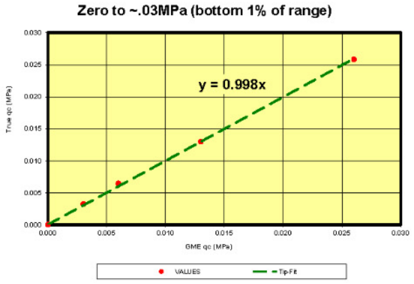
3MPa Special Purpose Piezocone Calibration

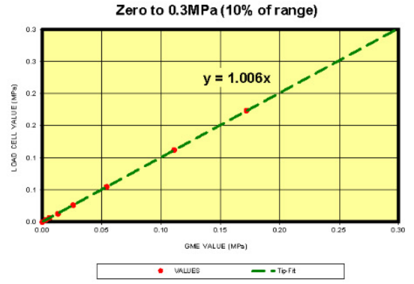
This cone has been re-calibrated. Use appropriately-dated calibration file. "Actual" cone dimensions used.

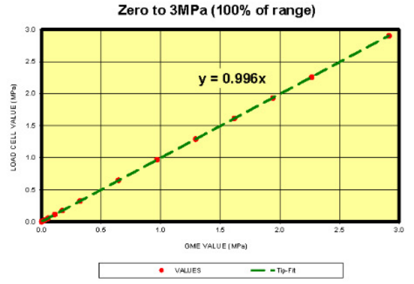
No: AS15CFIIPT.S21003

Tip Details Area (sq cm) 15.22 Capacity (MPa) 3 Cal Date 15/10/2021 **Sleeve Details** Area (sq cm) 228.91 Capacity (kPa) 200 Cal Date 15/10/2021 **Piezo Details** Capacity (kPa) 2000 15/10/2021

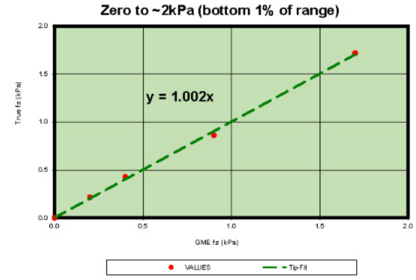
Cone Resistance qc

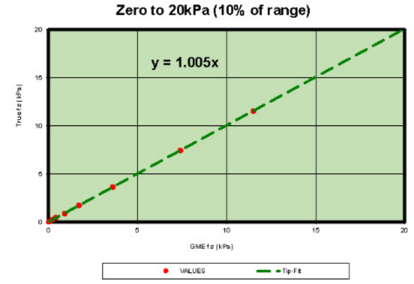


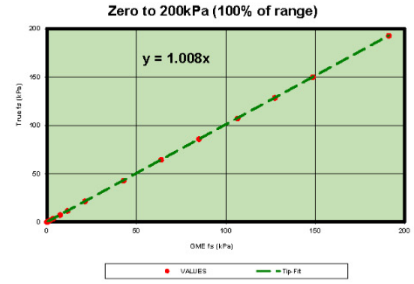




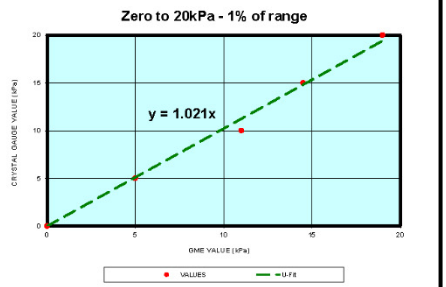
Sleeve Friction fs

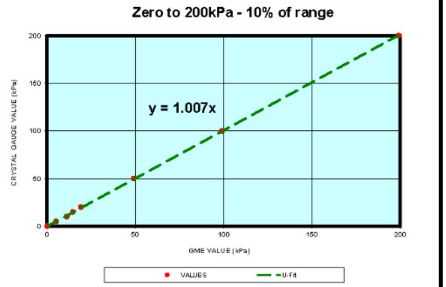


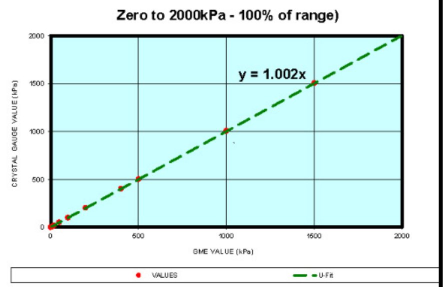




Pore Pressure u







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