Estimating in situ state of tailings using Panda Dynamic Cone Penetrometer

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ABSTRACT

Identifying tailings layers susceptible to static liquefaction, particularly for contractive soils, is a fundamental question considered by geotechnical engineers involved with the design, construction and operations of tailings storage facilities (TSFs). To determine the likelihood of static liquefaction for any given TSF, usually, geotechnical engineers aim to understand the *in situ* state of the tailings using empirical correlations and/or critical state soil mechanics. The state parameter approach has been recognised as an efficient tool to assess the liquefaction potential of tailings. Cone penetration testing (CPT) has been demonstrated to play an essential role in determining the *in situ* state parameter. However, the size and weight of the CPT rigs may limit their access to soft tailings surfaces. Furthermore, the logistical requirements to mobilise a CPT rig can be cumbersome in remote areas. The Panda dynamic cone penetrometer (Panda DCP) is a lightweight variable energy tool that has been used throughout Europe, particularly in France, for compaction control of engineered fills. Panda DCP applications have also been reported in Chile for compaction control of upstream construction of TSFs. The Panda DCP can rapidly be deployed for testing, is quick to carry out a test, can be undertaken by one person and can access areas inaccessible by low-pressure CPT rigs. The paper presents the results of a trial program that aimed to estimate state characteristics of tailings using the Panda DCP. The trial program was undertaken at a TSF in Queensland, Australia. Firstly, this study compared Panda DCP dynamic cone resistance, q_d against CPT cone tip resistance, q_c. Secondly, this study estimated *in situ* state of the tailings with the Panda DCP. This was done using two methods referred to in this paper as Method-1 and Method-2, with the results compared with CPT-based approach for determining *in situ* state of tailings. The results in this paper indicate that the Panda DCP could become an interesting alternative to screen and estimate the state of contractive and dense tailings.

INTRODUCTION

Mine tailings are hydraulically placed material of predominantly sand, silt or clay-sized particles resulting from mining and mineral processing after the mineral has been extracted or the unwanted material separated, eg shale and clays from coal, clayey fines from iron ore or bauxite (Fell *et al*, 2018). For coal and bauxite, the ore will not be ground, and the process is one of separation of the other rock particles from coal or finer clays and silts from bauxite gravel by washing and separation (Fell *et al*, 2018). Most tailings storage facilities (TSF) consist of tailings of sandy, silty, and clay grain-sized soil particles. There are many forms of tailings disposal, including tailings water slurry, thickened discharge, co-disposal and filtered paste technology. Conventional tailings are thickened in high water content slurry and either pumped or gravity feed to a TSF where tailings are discharged from single, several discharge points or spigots. Deposition of tailings slurry from the spigot encourages the segregation of material particles. Tailings can be discharged into TSF via subaqueous (deposited underwater) or subaerial deposition (deposited above water over the beach) methods. Subaqueous deposition tailings densities are dictated by particle density and settlement of fines which usually results in low densities and low shear strength. Subaerial depositions allow for drying, bleeding and desiccation during deposition cycling, which increases *in situ* densities.

Particle size is important to geotechnical engineers as sand, silt and clay size particles exhibit different material behaviours at different void ratios under the same effective stress conditions. During the deposition of tailings slurry, the sand and finer silt and clay-sized particles are segregated. Experience on sites with subaerial deposition of high-water content tailings slurry (30 per cent to 40 per cent solids content) has shown that heavier sand and coarse silt particles segregate and drop out closer to the spigot/embankment, and the smaller silt and clay size fractions travel further down the tailings beach away from the spigot.

When a TSF is nearing maximum design storage capacity, plans are usually underway to increase storage levels within the dam by raising the dam walls. Three standard methods can extend the storage capacity: upstream raise, centreline raise or downstream raise. Upstream raise embankment construction begins with starter embankment, and the free draining tailings beach close to the embankment becomes the foundation for embankment wall raise.

A common challenge for geotechnical engineers involved in upstream TSF dam raise design and construction is characterising the *in situ* states of the tailings foundation and determining whether the tailings are susceptible to static or seismic liquefaction. Static liquefaction usually occurs when contractive materials are loaded to a state of shear stress ratio such that contractive undrained shearing may occur with a small trigger. Been (2016) states that static liquefaction has been identified as one of the most damaging failure modes for tailings facilities, including TVA Kingston tailings dam, Mt Polley tailings dam and Fundao tailings dam. The TVA Kingston failure was attributed to the undrained static failure of fine-grained fly ash and caused significant environmental contamination (Been and Jefferies, 2016); Mt Polley tailings dam failure was attributed to the rapid foundation yielding resulting in a dam breach and static liquefaction event, causing one of the biggest environmental disasters in modern Canadian history (Independent Expert Engineering Investigation and Review Panel (IEEIRP), 2015); and Fundao tailings dam failure was attributed to static liquefaction with at least 17 dead and estimated damages of billions of dollars (Morgenstern, Vick and Watts, 2016).

Characterising mine tailings and their foundation and understanding strength behaviour is at the forefront of geotechnical engineers, mainly when undertaking stability assessment of upstream TSF dam raise design in accordance with governing guidelines and standards like the Global Industry Standard on Tailings Management (GISTM, Global Tailings Review, 2020) and ANCOLD Guidelines on Tailings Dams (ANCOLD, 2019).

This paper studied a TSF in Queensland, Australia, which has been designed and constructed using the upstream raise construction method. During the geotechnical investigation phase of the feasibility design, Panda dynamic cone penetrometer (Panda DCP) was undertaken adjacent to Cone penetrometer test (CPTu) locations on the existing tailings surface. The objective was to determine whether the Panda DCP dynamic cone tip resistance, q_d, correlated with CPTu static cone tip resistance, q_c, and whether the Panda DCP correlations may be used to determine whether the tailings foundation is in a dilative or contractive state. Estimating the *in situ* state of tailings was done using two alternative methods referred to in this paper as Method-1 and Method-2, with the results compared with the CPT-based approach for determining *in situ* state of tailings.

The Panda DCP is a lightweight device (20 kg), portable and easily transported by one person. The Panda DCP can rapidly be deployed for testing, is quick to perform a test, can be undertaken by one person, and access areas inaccessible by low-pressure CPTu rigs, making Panda DCP a favourable tool for screening *in situ* state of tailings. The Panda DCP with a larger cone tip size (4 cm^2 and 10 cm^2) is capable of testing to depths of up to 6.0 m but limited with possible inclination and damping of hammer energy transfer to the cone tip due to rod flex. The Panda DCP, with a smaller cone tip size (2 cm^2), has a maximum recommended testing depth of 1.5 m as skin friction of the rods may overestimate cone tip resistance. This is seen as a limitation by some practitioners. The Panda DCP is a variable energy tool used throughout Europe for compaction control of engineered fills and in Chile for compaction control of upstream construction of TSFs. A drawback of the Panda DCP is that there are no local Australian standards for Panda DCP equipment and that the user will need to adopt foreign (eg French or Chilean) standards and industry best practices. This study aims to address a data gap existing in the tailings industry with a particular application to the Australian market. The Panda DCP may also serve as suitable testing equipment for tailings operation quality control to ensure tailings foundations is progressively in a dilative state in preparation for upstream raise construction.

In Australia, ground improvement of slurry deposited tailings material by low-ground pressure swamp dozers is usually called mud farming. Mud farming promotes dilative tailings state by compaction and then drying thanks to environmental action. Mud farming also provides surface drainage paths towards the decant. A long beach and central decant structure usually characterise upstream raises. Adequate water management mitigates the risk of static liquefaction of foundation materials. Historically, mud farming quality control for the studied dam comprises field *in situ* dry density (ie nuclear density guage) and conventional Dynamic Cone Penetration (DCP) test. Nuclear density guage are only limited to testing a maximum depth of 0.3 m and DCP test results with low blow count in soft tailings are difficult (and not recommended) to correlate to *in situ* state. Some correlations with relative density exist. The Panda DCP is a useful tool for quality control of mud-farmed tailings and provides useful information to designers and operators to plan and prepare for future upstream raise loads. As the tailings rate of rise is only limited to a maximum of 0.5 m per deposition cycle, the depth limitation of the Panda DCP is often not an issue.

TAILINGS *IN SITU* DENSITY THROUGH STATE PARAMETER

Relative density is a measure of the state of the soil (or tailings). The critical state and state parameter concept, ψ, is often used as a quantitative measure to assess liquefaction potential. State parameter, ψ, is the difference between the current void ratio, *e* and the void ratio at the critical state, e_{cs}, at the same mean effective stress (Robertson, 2010).

$$\psi = e - e_{cs} \tag{1}$$

The critical state locus (CSL), varies with mean effective stress, and in this study, has been observed to vary with the fines content. ψ is introduced as a measure of deviation from the critical state. The use of the critical state and state parameters is argued to be more useful for understanding soil behaviour and properties than simply using relative density or void ratio (Robertson, 2010).

Currently, in the mining industry, the *in situ* state of the tailings is commonly assessed by *in situ* testing, eg CPTu and triaxial testing correlation to ψ (Jefferies and Been, 2016). Triaxial testing is a laboratory technique that allows determining the location of the CSL, and it is a cost-effective alternative; however, it does not inform the *in situ* state of the tailings on-site unless the tailings samples were in a true undisturbed state at the time of testing. The disadvantage of CPTu, is the cost and availability of low-track pressure rigs in Australia capable of accessing mine tailings (Fourie *et al,* 2013). The high demand for CPTu rigs and triaxial testing is currently experienced throughout the industry since the implementation of GISTM requirements. While CPTu testing can be more onerous than a laboratory campaign, it indirectly measures the state of tailings on its *in situ* condition. A combination of both techniques, laboratory testing and CPTu testing, is considered a recommended option for tailings characterisation.

Despite the advantages of laboratory and field techniques, each presents drawbacks. As mentioned, CPTu testing can cost considerably more than a laboratory testing program. When dealing with soft surfaces some site investigation, alternatives include the construction of fingerpads to ease access. A finger pad often results in tailings disturbance underneath the testing pad making the CPTu results lose representativity. Amphibious CPTu rigs have become common in recent years. Securing an available amphibious CPTu rig can be problematic due to the significant backlog of work seen during the last three years due to the implementation of GISTM requirements. Furthermore, undertaking a CPTu survey during the deposition of tailings can conflict with operations and pose risks to operating personnel.

CPTu test results allow evaluation of existing site conditions. In contrast, a laboratory program is useful to assess present and future stress conditions. However, laboratory testing also presents some limitations. For example, the most common undisturbed sampling method in Australia for soft soils is the open sample (Shelby tube 50 mm to 75 mm). It has been demonstrated that mechanical parameters obtained from laboratory tests on samples recovered from Shelby tubes do not always represent *in situ* conditions (Pineda *et al,* 2018). Another common undisturbed sampling practice in Australia is the fixed-piston sampler. Pineda *et al* (2018) have reported that the quality of the retrieved fixed-piston tube sample is highly influenced by the skills of the driller. Research has shown undisturbed samples of soft clays, sand, or silt undergo disturbance and void ratio change during sampling, waxing, transportation, handling, extrusion, trimming and consolidation in the laboratory. Despite the limitations, laboratory testing allows for assessing the behaviour under various stress paths, including current and future conditions.

Due to the likelihood of sample disturbance during sample transportation resulting in changes to its *in situ* state, geotechnical practitioners are more inclined to gather data via *in situ* testing methods to provide *in situ* state information. The information is used at a later stage to inform reconstituting sample procedures in the laboratory. Laboratory testing is necessary for determining the CSL of particular tailings. Key questions for geotechnical practitioners designing TSF upstream wall raises are:

- What is the state parameter of tailings? Do the tailings being studied exist in a contractive state?
- At what state do the tailings exhibit contractive behaviours, and how would tailings perform under future loads?

By understanding these questions, geotechnical practitioners may develop solutions to future potential problems, especially if it means a high risk of impact on people and the environment.

One challenge to operators and designers of a mud-farmed TSF is achieving design tailings density during deposition before the next cycle of tailings deposition. Quality control of mud-farmed tailings usually includes the measurement of field dry density testing with a nuclear density guage, which is limited to a maximum 300 mm test depth. Information regarding the *in situ* state of deeper tailings is unknown without the use of CPTu equipment. The Panda DCP is proposed here to provide a quick source of information regarding the *in situ* state of the tailings during operating conditions, especially in areas not accessible by CPT rigs. It also facilitates taking corrective actions through quality control procedures when *in situ* state does not meet design conditions.

SOILS CHARACTERISATION THROUGH CONE INDENTERS

Pieter Barentsen developed the Dutch cone penetrometer around 1930 in the Netherlands to measure the resistance of soil resistance on the conical tip. The original purpose of penetration testing was to characterise hydraulic fills' thickness and bearing capacity. The first Dutch cone tip had an area of 10 cm^2 (diameter 37.5 mm) with a 60° apex angle.

The conventional Dynamic cone penetrometer (DCP) was invented in Australia (Scala, 1956). The DCP is a simple and rapid device which was first used in Australia for the characterisation of subgrade soils for pavements. The make-up of the DCP consisted of a 9 kg mass dropping 508 mm onto an anvil and rod with a 30° apex cone tip. The South African variant of the DCP was introduced in 1970 with an 8 kg mass dropping 575 mm onto an anvil and rod with a 60° apex cone tip.

Sol Solutions developed the Panda DCP in France as a lightweight DCP capable of soil strength testing and compaction control. The Panda continually measures a dynamic cone resistance, q_d (MPa) with depth as the Panda DCP hammer drives the probe into the ground. q_d is derived using the modified Dutch formula (Cassan, 1988) given in Equation 2.

$$q_d = \frac{1}{A} \cdot \frac{\frac{1}{2} \times mv^2}{1+\frac{P}{m}} \cdot \frac{1}{x_{90^\circ}} \tag{2}$$

where:

A	Area of Cone
V	Speed of Impact (of the hammer)
m	the weight of the striking mass
P	the weight of the struck mass
X_{90°	Penetration due to one blow (90° cone apex).

The work described herein used cone tips with the following cross-sectional areas: 2 cm^2, 4 cm^2, and 10 cm^2. All the cone tips had a cone apex angle of 90°. The Panda DCP equipment is compliant with French Standard NF P 94–105-April 2012 (French Standards Association (AFNOR), 2012). The testing described in this paper was undertaken in accordance with Chilean Standard NCh3261–2012 (Instituto Nacional de Narmalizacion (INN), 2012).

The Panda DCP testing for this geotechnical investigation was carried out by striking a 5 kg weight onto an accelerometer on the head of a tool which measures the velocity of the impact, and the control panel microprocessor records the penetration depth with each blow on the tool. Based on laboratory calibration chamber experiments for different materials at different *in situ* dry densities and water contents, Laurent (1999) demonstrated the relationship between q_d, dry density, γ_d and water content, w, was supported by Equation 3. Regression coefficients A, B and C are introduced.

$$\gamma_d = A(w) + Bln(q_d) + C \quad (3)$$

Benz-Navarrete *et al* (2019) simplified the dry density estimation correlation based on tip resistance to be:

$$\gamma_d = 1.06 \cdot ln(q_d) + 15.82 \quad (4)$$

Benz-Navarrete *et al* (2019) established that bulk density may be estimated from (Robertson, 2022):

$$\gamma/\gamma_w = 0.36 \log\left(\frac{q_d}{p_a}\right) + 1.43 \quad (5)$$

Where γ_w is the unit weight of water and p_a is the atmospheric pressure. Using Equation 6 and the existing empirical Panda correlation in Equation 4, the void ratio, *e* can be estimated:

$$e = \left(\frac{G_s \gamma_w}{\gamma_d}\right) - 1 \quad (6)$$

Where G_s refer to the specific gravity of a given soil particle.

For each void ratio estimate, the mean effective stress, p'_0 can be estimated if we assume that the vertical stress, σ_{v0} acting at depth, z is $\gamma'.z$, where bulk density can be estimated using Equation 5. The approach requires knowledge of the piezometric surface. Mean effective stress, p'_0 can be estimated using Equation 7:

$$p'_0 = \gamma' z\,(1 + 2K_0)/3 \quad (7)$$

where the earth pressure coefficient at rest, K_0 may be derived from measured values using self-boring pressuremeter testing or estimated based on existing soil correlations.

The piezometric water level at the studied site is known to be significantly lower than the tailings beach surface level (>5.0 mbgl). The piezometric surface was established from VWP readings in the tailings and decant water levels. Therefore in this paper, using this information, soil unit weight, γ', used in Equation 7 is equal to the bulk density calculated in Equation 5.

TAILINGS CHARACTERISATION

To understand and characterise the tailings, a geotechnical investigation campaign was undertaken. Tailings surface samples were taken at 10 m, 100 m, 150 m, 200 m and 250 m away from the spigot at two locations on the TSF being studied. Twenty-three Specific Gravity (G_s) tests found the tailings material to range between 2.51 and 2.71, with 2.51 being the closest to the spigot and 2.71 being the furthest away from the spigot. Ten Particle size distribution (PSD) tests were undertaken on tailings samples gathered at set distances from the spigot. The testing aimed to classify tailings particle size with distance from the spigot location down the tailings beach and determine whether particle segregation had occurred. G_s of the tailings material were found to be dependent on fine content percentage. The results of surface sampling at the locations studied are depicted in Figure 1. The figure shows a decrease in sand content percentage and an increase in fines content percentage with distance away from the spigot location.

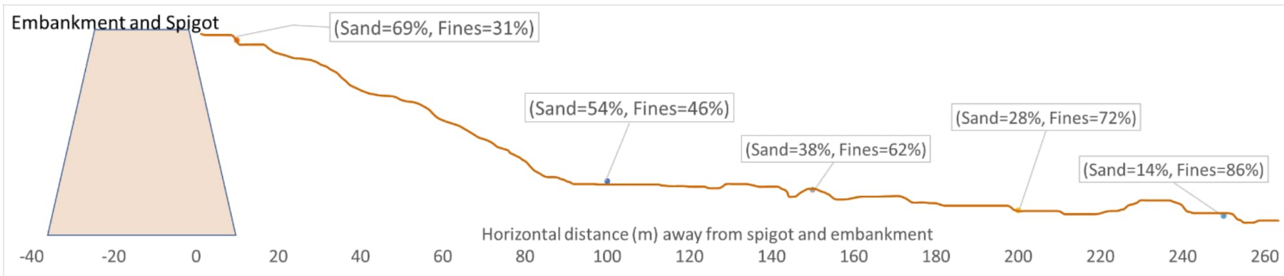

FIG 1 – Typical segregation of tailings particles at TSF study.

Based on the PSD analysis in Figure 1, the 10 m and 100 m tailings samples are of 70 per cent to 55 per cent sand size particles which supports the notion that the heavier sand particles drop out closer to the spigot and the lighter, smaller silt and clay size fractions travel further down the tailings beach away from the spigot. Based on on-site experience, the tailings particle size content at a given location away from the embankment and spigot is subject to change depending on the following:

- Spigot location and tailing beach angle.
- Deposition strategy.
- Mud farming process.
- Washing out of fines during rain events or pipe flushing, which washes the lighter fines further down the tailings beach profile.

A recent wall raise quality control construction data was assessed whereby 436 Atterberg limits and compaction tests were undertaken on tailings borrow material gathered between the spigot location and 150 m distance from the spigot location. The tested tailings borrow material was found to be predominantly of low to intermediate plasticity fines. The results were observed to plot above the A-line in the Casagrande plasticity chart with some outliers below the A-line. A review of the quality control standard compaction results showed that when field dry density is between 1.55 t/m^3 and 1.72 t/m^3, the standard density ratio was found to be greater than 99 per cent resulting in a dilative embankment.

In situ testing of tailings comprised nine CPTu locations utilising 100 MPa Geomil compression cones. To evaluate the Panda DCP suitability for mine tailings characterisation, ten Panda DCP tests were undertaken adjacent to the existing CPTu, approximately within 1.0 m distance from the CPTu location. CPTu testing was undertaken between 20 m and 100 m distance from the spigot location. PANDA testing was driven to a depth between 1.0 m and 4.7 m below existing tailings surface levels. The Panda DCP location and tip sizes used for this study are summarised in Table 1.

Disturbed samples were recovered and taken for laboratory testing to determine the CSL. The location of the CSL is necessary because the methods proposed herein rely on determining the state of tailings, not the state parameter directly. Testing was undertaken on the tailings for various fine contents. This was done to represent the segregation of tailings down the tailings beach and G_s being affected by fines content. The CSL results obtained from the laboratory study are presented in this work because the information is required to demonstrate the method. More details about the CSL test results will be provided in subsequent publications. Samples were prepared at state parameters of between 0.09 and 0.11 (loose of critical). The summary of CSL parameters is shown in Table 2. A remarkably similar CSL slope in the compressibility plane was noted. This was attributed to very similar mineralogy. Fines content was observed to influence the CSL intercept in the compressibility plot.

TABLE 1

Regression analysis of q_d, and q_c at the same depth.

Location	Distance from spigot (m)	Cone tip area (cm^2)	Test depth (m)	No. of readings	q_d range (MPa)	q_c range (MPa)	q_c/q_d	R^2
02	100	2	4.62	150	0.16–13.31	0.34–8.16	0.62	0.82
02	100	4	4.34	200	0.25–12.23	0.25–8.16	0.83	0.88
02	100	10	1.01	88	1.06–8.24	1.95–8.16	1.1	0.84
04	30	2	3.01	126	2.53–20.76	0.49–6.6	0.48	0.78(1)
04	30	4	2.41	140	1.31–6.68	0.49–6.60	1.13	0.89
05	20	4	3.6	455	1.49–18.34	2.69–14.67	1.26	0.94
08	20	2	4.69	125	0.5–11.71	0.38–12.21	1.17	0.89
09	20	2	3.11	86	0.97–11.93	1.3–15.58	1.27	0.82
11	100	2	3.04	125	0.65–14.73	0.82–21.18	0.82	0.82(2)
11	100	4	4.66	204	0.05–13.17	0.08–21.18	0.97	0.83(2)

Note (1): natural material was encountered at 1.4 m and therefore, regression analysis was undertaken to 1.4 m depth.
(2): Regression analysis of the dry crust between 0.0 m and 0.7 m ignored.

TABLE 2

Summary of Critical state testing.

CSL parameter	Fines content 6%	20%	40%	80%
λ_{10}	0.161	0.161	0.161	0.161
λ_e	0.069	0.069	0.069	0.069
Γ	1.049	0.999	0.990	1.065
G_s	2.60	2.63	2.67	2.72
LL	32	36	35	50
PL	25	23	24	21
IP	7	13	11	29
LL*G_s	0.83	0.95	0.93	1.36

REGRESSION ANALYSIS OF CPT AND PANDA DCP SOUNDING

To determine whether a correlation existed between the Panda q_d and CPTu q_c, linear regression analysis was undertaken for pair data of q_d and q_c at the same depths. The q_d readings were staggered and non-consistent when compared with the CPTu, which records q_c reading every 10 mm. The data was filtered to compare and correlate the measured q_d and q_c at the same depths. The result of the linear regression analysis, R^2, is provided in Table 1, with q_c and q_d plots detailed in Figure 2. Based on the plots in Figure 2 and other Panda DCP data not shown in this paper for brevity, it was determined that the Panda DCP cone tip resistance shows a good correlation with CPTu cone tip resistance. Three Panda cone tips with cross-sectional areas of 2 cm^2, 4 cm^2 and 10 cm^2 were trialled at location 2, showing good correlation with each other and with CPTu results, although the 10 cm^2 was seen to penetrate down to approximately 1.0 m depth. Panda cone tips with cross-sectional areas of 2 cm^2 and 4 cm^2 were trialled at locations 4 and 11. A Panda cone tip with a cross-section area of 4 cm^2 was trialled at location 5. A Panda cone tip with a cross-section area of 2 cm^2 was trialled at locations 8 and 9. The 4 cm^2 cone tip was observed to have the highest R^2 on average – 0.89. The 2 cm^2 cone tip was observed to have the lowest R^2 on average – 0.83. A single 10 cm^2 cone R^2 calculated for location 2 resulted in 0.83.

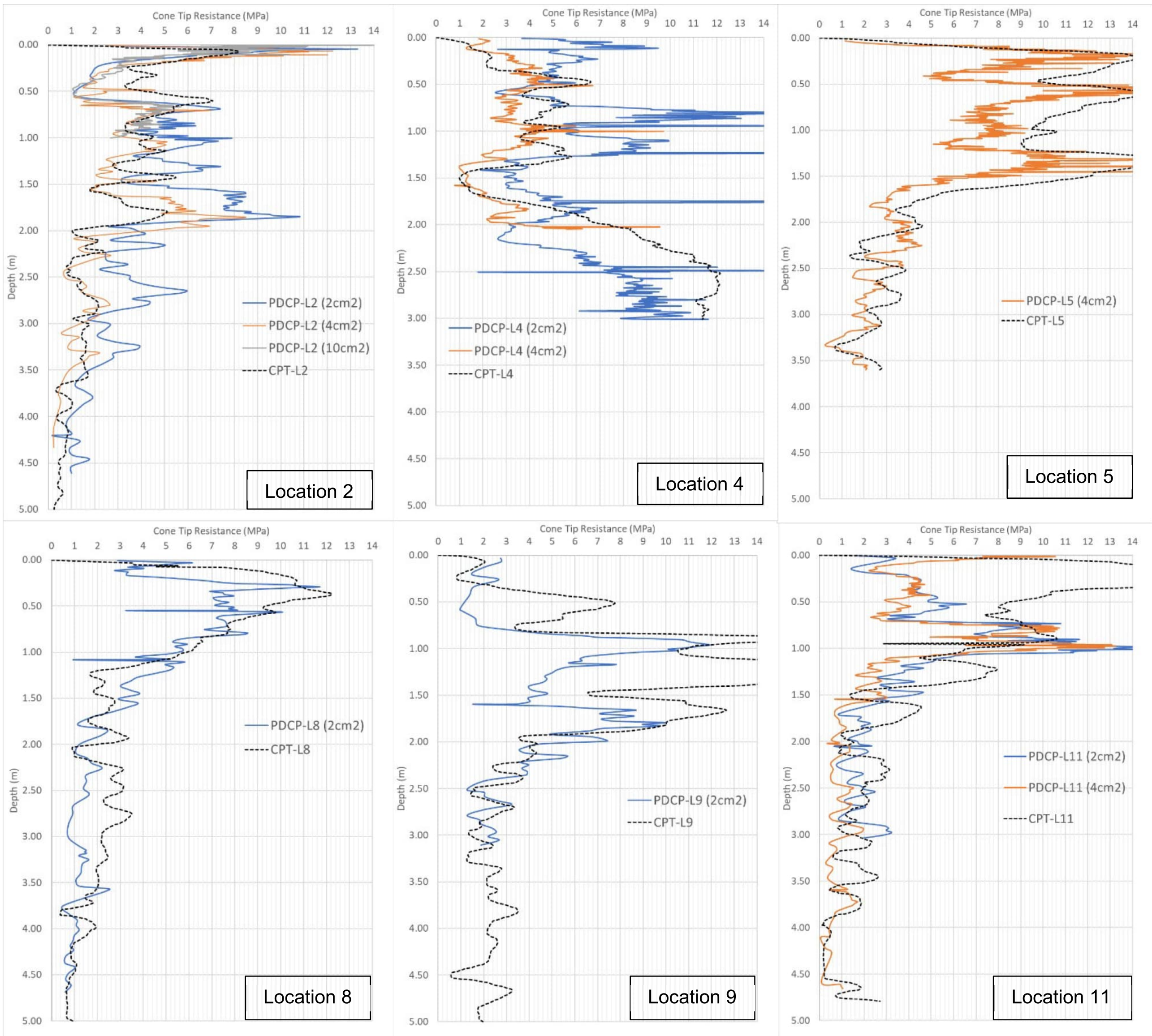

FIG 2 – CPTu, q_c and Panda DCP, q_d cone tip plots.

Experience using the different cone tip sizes on-site has shown that the bigger the cone tip area, the higher the resistance, resulting in higher operator hammer force and repetition to advance the Panda DCP tip to depth. The 2 cm^2 and 4 cm^2 were favoured by the Panda DCP operators as they required the least force and hammering repetition in mud-farmed tailings when compared to 10 cm^2. The 10 cm^2 tip size was the preferred cone tip size for soft tailings (<1 MPa) if encountered near the surface. This was why the 10 cm^2 was only trialled in one location as higher operator hammer force and higher repetition were required to advance Panda DCP to depth.

The following points below are a summary of linear regression analysis, R^2 in Table 1, for each cone size:

- 2 cm^2 cone tip q_d vs q_c relationship range between q_c=0.48 to 1.27 × q_d (R^2=0.78 to 0.89), for locations 2, 4, 9 and 11.
- 4 cm^2 cone tip q_d vs q_c relationship range between q_c=0.83 to 1.26 × q_d (R^2=0.83 to 0.94), for locations 2, 4, 5 and 11.
- 10 cm^2 cone tip q_d vs q_c relationship range between q_c=1.1 × q_d (R^2=0.83), for location 2.

Location 4, 2 cm^2 cone result (refer Figure 2) showed large spikes in tip resistance, which resulted in R^2=0.78 but 4 cm^2 cone faired better. Based on the summary above, q_d for the cone sizes can be within ±20 per cent of q_c results with similar trend. The difference in cone tip resistance is explained due to moisture and dry density conditions at the time of test, energy transfer loss and driving mechanism.

EVALUATION OF CRITICAL STATE LOCUS CPTU AND PANDA PLOTS

To estimate the *in situ* state of the tailings using the Panda data, two methods are referred to in this section which are Method-1 (M1) and Method-2 (M2). M1 and M2 are described in Tables 3 and 4, respectively.

TABLE 3

State parameter assessment using Panda DCP Method-1 (M1).

Parameter	Panda DCP (M1)
γ_d – dry density	Equation 4 – $\gamma_d = 1.06 \cdot ln(q_d) + 15.82$
e – Void Ratio	Equation 6 – $e = \left(\frac{G_s \gamma_w}{\gamma_d}\right) - 1$ where G_s estimated from laboratory testing, see Table 2 based on distance from the spigot and estimate fines content
p'₀ – Mean effective stress at depth	Equation 6 – $p'_0 = \gamma' z\,(1 + 2K_0)/3$ where bulk unit, γ weight can be estimated using Equation 5 and K_0 for demonstration of this paper we have adopted a value of 0.3

TABLE 4

State parameter assessment using Panda DCP Method-2 (M2) and CPTu (Been and Jefferies, 2016).

Parameter	Panda DCP (M2)	CPTu (Been and Jefferies, 2016)
Q – normalised cone resistance	$Q_p = \frac{q_d - p}{p'}$ (Been *et al,* 1986) where $p' = \gamma' z\,(1 + 2K_0)/3$ and q_d replacing q_c from Been *et al,* 1986)	$Q_p = \frac{q_t - p}{p'}$ (Been *et al,* 2016) where $p' = \gamma' z\,(1 + 2K_0)/3$
ψ – state parameter	$\psi = {-\ln[Q_p\ /k']}/{m'}$ (Been *et al,* 1986, 2016) where k' and m' estimated based on the conventional CPTu interpretation	$\psi = {[-\ln[Q_p(1 - B_q)\ /k']}/{m'}$ (Been *et al,* 1986) where k' and m' estimated based on the conventional CPTu interpretation and B_q is pore pressure ratio
e_c – critical void ratio	$e_c = \Gamma - \lambda_{10} \log (p'_0)$ (Been and Jefferies, 2016) where Γ and λ_{10} are provided in Table 1	$e_c = \Gamma - \lambda_{10} \log (p'_0)$ (Been and Jefferies, 2016) where Γ and λ_{10} are provided in Table 1
e – Void Ratio	Equation 1 – $e = \psi + e_c$	Equation 1 – $e = \psi + e_c$

A few extrapolations were considered for the study as follows:

- Equation 4 (M1) was originally derived for natural soils by the Panda manufacturers. Conventional site dry density testing at the surface and to depths of max 0.3 m was undertaken and compared against the estimates presented herein. Results compared remarkably well and are detailed in Figure 3.
- m' and k' (M2) were estimated based on the conventional CPTu interpretation. Improved m' and k' estimates will be considered in future studies.
- K_0=0.3 was adopted for demonstration of this paper.

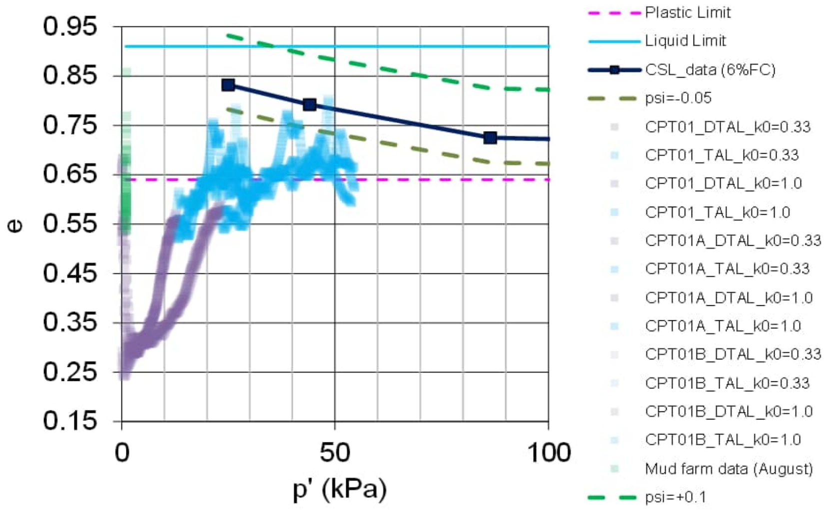

FIG 3 – Comparison between field dry density data (green data points at p'~0 at 0.3 m) measured using a nuclear densitometer and state parameter and CSL estimates.

The Panda method was compared to CPTu data critical state analysis using Been and Jefferies (2016) method to determine whether there is a basis for the method proposed herein. Been *et al* (1986) first demonstrated the relationship between ψ and q_c in a calibration chamber for sand in fully drained conditions. This was also demonstrated by Abedin and Hettiaratchi (2002). The CPTu state parameter assessment methodology (Been and Jefferies, 2016) is summarised in Table 4. Figure 3 shows that Been and Jefferies (2016) state parameter estimates at very low confinement stress agree remarkably well with the void ratio calculated from nuclear density guage field data in the vicinity of the CPT. Future studies will include the measurement of tailings density at depth using a mini-block sampler.

Using the Panda DCP and CPTu data in Table 1, critical state assessment may be derived from the Method-1 and Method-2 mentioned in Tables 3 and 4. The results were plotted on critical state plots, detailed in Figure 4. The CPTu-derived results are presented in broken black lines. Panda-interpreted results are plotted in blue lines (designated 2 cm^2 cone area), orange lines (designted 4 cm^2 cone area) and grey lines (designted 10 cm^2 cone area). Critical state lines corresponding to the fines content at each location are also included in each plot. The results show a generally good agreement when comparing the CPTu-borne results with Panda-borne results. Regions of largely dilative mud-farmed tailings were successfully characterised using both methods. Furthermore, a contractive layer underlying the mud-farmed tailings was identified in locations 2, 5, 8, 9 and 11, which are related to a region below about 3 m having q_c and q_d values below 1 MPa. Locations 2, 5, 9, and 11 show that both methods indicate the presence of potentially contractive tailings. The aforementioned contractive layer was found to lie at mean effective stresses of 30 kPa and above. Based on the data plotted in Figure 4, the CPTu and Panda methods show general agreement with similar trends in estimating *in situ* state of tailings.

The last two steps shown in Table 4 effectively derive the void ratio to facilitate plotting the CSL in a compressibility plot, see Figure 4. The authors recommend the procedure because the horizontal distance between each data point and the CSL can be used to estimate the stress required for that point to transition from dilative to a contractive state.

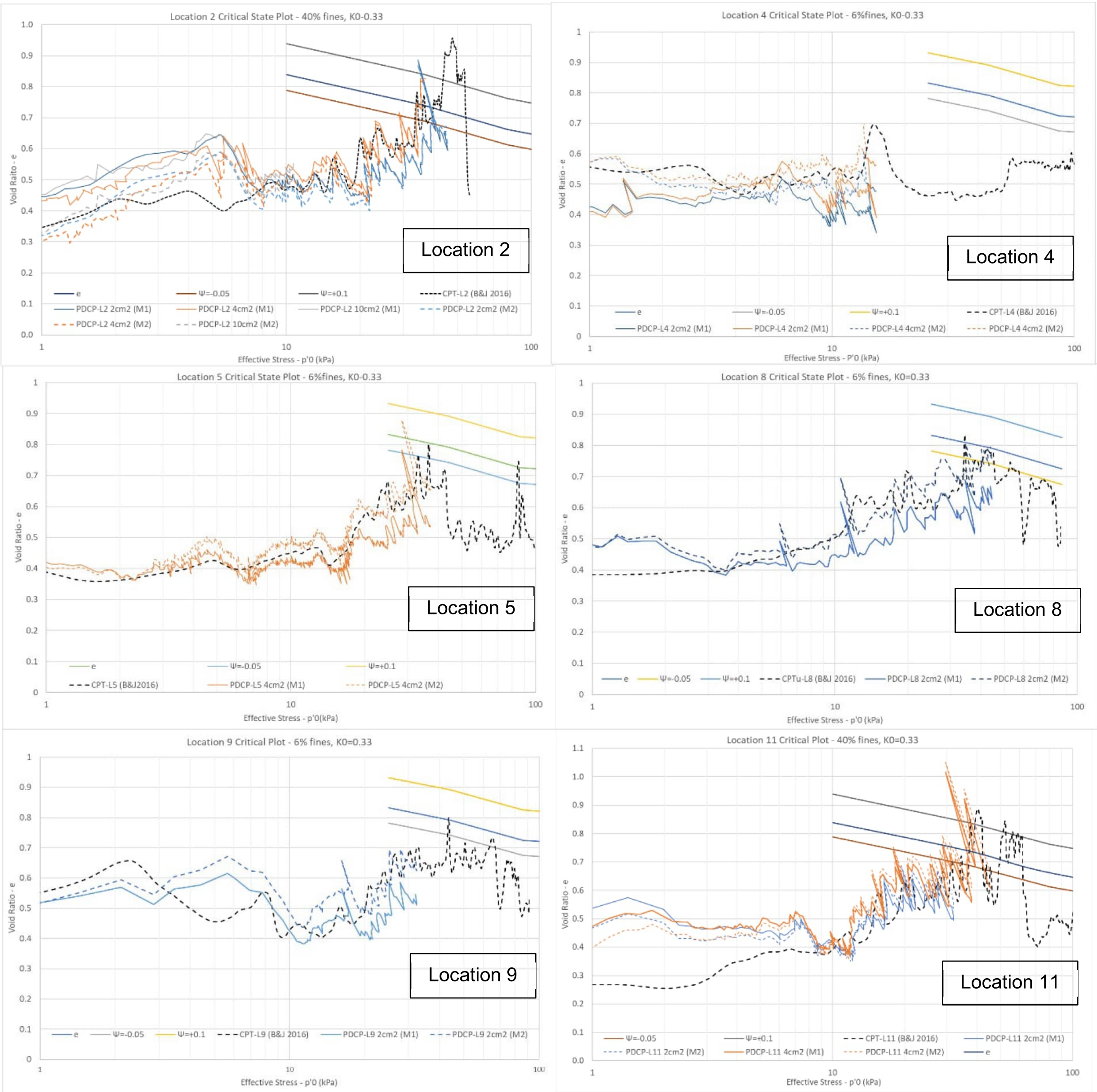

FIG 4 – Critical state plots (Effective stress *versus* void ratio) for Panda DCP Method-1 (M1) and Method-2 (M2) and CPTu (Been and Jefferies, 2016) data.

CONCLUSION

This paper has demonstrated how q_d shows good correlations with the widely accepted q_c for a TSF in Queensland, Australia. The method was trialled in sandy tailings and clayey tailings material. The Panda DCP-derived results for estimating *in situ* state are in general agreement and show a remarkably similar trend to Been and Jefferies (2016) results for determining *in situ* state. The following comments regarding the findings in this paper are as follows:

- Further studies need to be conducted on TSF of different mine ore origins and climates. The study should be replicated in controlled laboratory conditions using a calibration chamber. Tailings type and fines content dictate soil critical state behaviour.
- Measurement of K_0 parameter will provide a better estimation of *in situ* state. A sensitivity analysis of this parameter is recommended in the absence of such results. A sensitivity analysis is underway and will be presented in the future.
- Although useful, the method presented herein requires some extrapolations and is recommended when CSL laboratory data is available.

- The methods described herein are useful techniques for Quality Control during mud farming and targeting potential CPTu locations for more advanced geotechnical investigation. Because the method is recommended for Quality Control, the maximum depth achievable is not seen as a significant drawback.

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