CHARACTERISATION OF INTERMEDIATE MINE TAILINGS USING THE MEDUSA FLAT PLATE DILATOMETER

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ABSTRACT

Recently, a new fully automated flat plate dilatometer, Medusa DMT, has been introduced to field investigation works. Along with the capability to conduct high-quality and repeatable DMT tests, this device provided an opportunity for a new series of in situ tests designed to estimate in situ horizontal stress. These extensions to the capability of the DMT are particularly valuable in materials with intermediate behaviour, such as mine tailings, where partial drainage effects can significantly impact test outcomes. This paper introduces the new methods available with the Medusa DMT, namely DMT-Whilst Penetrating (DMT-WP) and DMT-Repeated A (DMT-RA), describes a method for screening for intermediate material behaviour and discusses the process used to reduce the partial drainage effects by testing to measure drained or undrained behaviours. The results from the DMT-WP and DMT-RA tests are analysed alongside adjacent CPTu and Vane Shear Tests (VSTs). The findings demonstrate the value of the new Medusa DMT tests in characterising intermediate mine tailings materials, assessing the drainage effects and providing insight in estimation of coefficient of earth pressure at rest, K_0.

1 INTRODUCTION

Investigating tailing materials typically involves using the Cone Penetration Test with Pore Pressure measurements (CPTu), in situ Vane Shear Testing (VST) and collecting disturbed and undisturbed samples for laboratory testing. The Flat Plate Dilatometer (DMT) test, whilst common in traditional civil and building site investigations, is not as commonly used for tailings investigations. The DMT test provides information about important material characteristics such as strength, stiffness and state. The importance of the Coefficient of Earth Pressure at Rest, K_0, in tailings has been discussed in recent studies by Jefferies and Been (2006), Wang and Ismail (2022), and Reid et al. (2021) where the static liquefaction assessments are heavily relying on the initial state of the tailings.

Unfortunately, there is some reluctance to use the DMT, which stems from partial drainage effects observed in tailing and intermediate materials (niche silts). Schnaid et al. (2015) discussed these impacts extensively in a study using DMT with a pore pressure sensor to monitor the decay of pore pressure during the test.

Advances in DMT tooling in the last five years have led to greater testing capability, understanding of the test and the soil response to the test, particularly in partially drained materials (Marchetti et al., 2019; Schnaid et al., 2021; Marchetti Danziger et al., 2024). The new Medusa DMT allows for drainage to be readily assessed, and new test methods have been developed to overcome these effects.

This paper discusses these new DMT test methods conducted with the Medusa DMT and reviews the impact on material characteristics derived from the tests.

2 DMT TESTING

2.1 FLAT PLATE DILATOMETER TESTING

The flat plate dilatometer is comprised of a 0.2 to 0.3mm thick circular aluminium diaphragm mounted on a flat stainless-steel blade. It has a sensing disk beneath it to detect electrical contact during insertion and target inflation of 1.1mm. The dilatometer is typically pushed into the ground using equipment like a CPT rig or SPT hammer, with measurements taken at 0.2 to 0.5-meter vertical intervals (Marchetti, 1980).

Once at the target depth, pneumatic pressure is immediately applied to the diaphragm via a surface control box and nitrogen gas bottle, causing the diaphragm to inflate to the A position in 15 seconds and the B position in another 15 seconds. Additionally, a C reading can be collected during the deflation process. (Marchetti, S. 2001).

The definitions of the three reading parameters are as follows (Marchetti, 2001):

- A reading: lift-off pressure, required to start the membrane expansion against the soil
- B reading: pressure for 1.1 mm membrane expansion at the centre

- C reading: membrane closing pressure, measured immediately after the B reading by slowly deflating the membrane

A schematic figure of the DMT blade is presented in Figure 1.

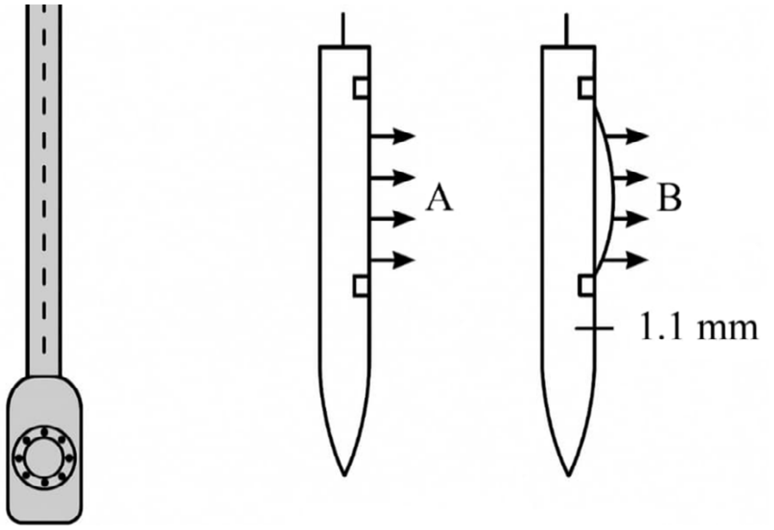


Figure 1: Schematic of DMT blade and pressure readings

2.2 IMPACT OF PARTIAL DRAINAGE

The standard DMT test is typically performed under drained conditions for sands and undrained conditions for clays. However, partial drainage can occur in intermediate soils, like natural silts and mine tailings, making distinguishing between drained and undrained conditions difficult, leading to unreliable data (Monaco et al., 2020). The DMT measures total horizontal stress in the soil but does not differentiate between pore water pressure and effective stress. In intermediate soils, excess pore pressure generated during penetration can dissipate over time, causing parameters like constrained modulus, over consolidation ratio, undrained shear strength, and K_0 to be underestimated.

In gold tailings, Schnaid & Obebrecht (2015) observed that A readings decayed along with excess pore pressure dissipation, resulting in readings that did not fully align with drained or undrained conditions. They recommended taking initial readings within 1-3 seconds of penetration, but this is difficult to achieve with standard DMT equipment, requiring expert operation.

The challenge of the partial drainage effect in tailings has been observed through various field testing methods other than DMT, such as CPTu and VST. Various research studies consistently emphasise the importance of conducting tests at rates that maintain truly undrained conditions to ensure accurate interpretation of soil behaviour. (DeJong et al., 2012; Reid et al., 2023).

2.3 MEDUSA DMT

The Medusa DMT is an advanced version of the traditional mechanical DMT, incorporating hydraulic automation and a pressure measuring system for autonomous testing. It includes a motorised syringe, electronic board, pressure transducer, and a hydraulically operated flat dilatometer blade. The Medusa DMT applies hydraulic pressure to the diaphragm, unlike the original compressed gas system. A pressure transducer monitors the pressure during inflation to A, B and C readings. The device connects to a laptop on the surface, allowing technicians to control parameters like inflation rate, test duration, and penetration rate.

The Medusa DMT's high level of inflation control enables two new test procedures, which are discussed in more detail below.

2.4 DMT-WHILST PENETRATING

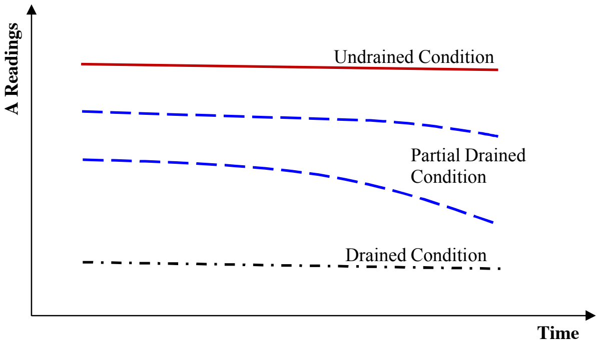
The Medusa DMT diaphragm is inflated to and ‘held’ in the A position by small adjustments to the diaphragm position. The DMT blade is then advanced into the soil at the nominated penetration rate by the CPT Pusher with a 1m stroke. The DMT pressure and positions measurements are collected at a high frequency whilst the blade is advanced, subject to soil consistency, creating a near continuous vertical profile of DMT A readings. A, B and C readings are also collected at 1m vertical intervals as additional rods are added and the pusher reset. Initial tests conducted using this approach have shown remarkable repeatability in young clay-type materials discussed in Marchetti et al. (2021).

This research conducted the DMT-Whilst Penetrating (DMT-WP) tests using the DMT Repeated A (DMT-RA) module within the acquisition software. The tests were conducted over a fixed penetration distance of 1.0m at a fixed velocity. The data collected is then adjusted from pressure versus time readings to pressure versus depth readings.

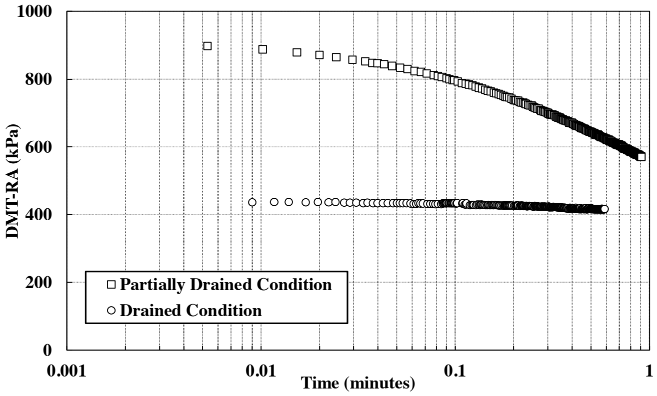
2.5 DMT-REPEATED A

In the DMT RA test, the blade is advanced into the soil and at the target depth, the membrane is inflated to the A position. The Medusa system makes minor adjustments to the plunger position and pressure to maintain the membrane at the A position, compensating for the decay in the excess pressure. The test measures the decay in total horizontal stress. If no change in horizontal stress occurs during the A reading, it indicates either drained or undrained conditions over the period of the test. A stress drop suggests partial drainage, meaning the conditions are neither fully drained nor undrained. An example of this behaviour is conceptually shown in Figure 2(a), for A readings measured over 15 seconds. Figure 2(b) also presents example data measured in the current study on tailings under drained and partially drained conditions. Empirical correlations used to estimate undrained shear strength and K_0 from DMT results are derived for undrained conditions. To maintain consistency with these assumptions, materials exhibiting partial drainage behaviour should be tested over shorter time periods to minimise excess pore pressure dissipation during the test.

DMT-RA with Medusa DMT provides an opportunity to improve on the standard DMT test with A readings taken continuously for 15 seconds followed by a 15-second inflation to B, allowing for monitoring of excess pore pressure dissipation and screening for partial drainage (Marchetti and Totani, 1986 and Totani et al., 1998).



(a) Conceptual A reading response in different drainage conditions



(b) Sample data demonstrating drainage influence on A-Reading
Figure 2: Variation in A-Reading response under different drainage conditions

3 SITE CONDITION AND TESTING PROGRAM

The DMT tests were performed on the tailings of an operational upstream Tailings Storage Facility (TSF) in Australia. The tailings in the TSF typically consist of varying thicknesses of coarse (sandy silt and silty sand) and fine tailings (silts). The fines contents of tailings vary from 10% to 100%. Due to the deposition methodology through the years, interbedded layers of coarse and fine tailings are encountered in the TSF. The fine portion of tailings is predominantly made of low to medium plasticity, with a plasticity limit ranging from 7 to 40%. The tailings have an average bulk density of 20 kN/m^3, with a specific gravity of 3 to 3.3. The fine portion of tailings is predominantly contractive, while the coarser layers are mainly dense with a dilative response during penetration.

The testing was conducted in a TSF constructed using an upstream method. The dam geometry comprised a starter embankment followed by a series of upstream raises. Testing was carried out along a single cross-section at two different clusters. Cluster 1 was positioned on the upstream side, situated on the tailings beach and away from the starter embankment, with a maximum penetration depth of 40 m. In contrast, Cluster 2 was located closer to the starter embankment and reached a total penetration depth of approximately 25 m. The phreatic level was inferred to be at 5.3 m in Cluster 1 and at 3.15 m in Cluster 2.

Two CPTu tests were performed in each cluster at penetration rates of 20 mm/sec and 100 mm/sec. A total of 19 dissipation tests were conducted across both clusters to assess drainage conditions. Thirty-eight VSTs were conducted in Cluster 1 and four in Cluster 2 using a down-the-hole vane shear device to calibrate the CPTu-derived shear strength results. Both DMT-RA and DMT-WP tests were also performed in each cluster. The DMT tests were carried out at a penetration rate of 20 mm/sec.

4 RESULTS AND DISCUSSIONS

4.1 DISSIPATION TESTS

Pore water pressure dissipation testing was conducted during the CPTu to assess the site's drainage condition. The horizontal coefficient of consolidation, c_h, was derived using the procedure outlined by DeJong and Randolph (2012). The rigidity index was estimated using the shear wave velocity data and Method B proposed by Krage et al. (2014).

The estimated c_h values in Figure 3 suggest the tailings are prone to partial drainage conditions with the t_{50} (time to 50% pore pressure dissipation) of less than 30 seconds in all cases (Robertson et al., 1992). Although attempts were made to assess the drainage condition further using the normalised velocity concept developed by DeJong et al. (2012), the limitations were mainly related to the estimation of the anisotropic consolidation ratio for tailings with different properties and layer thicknesses.

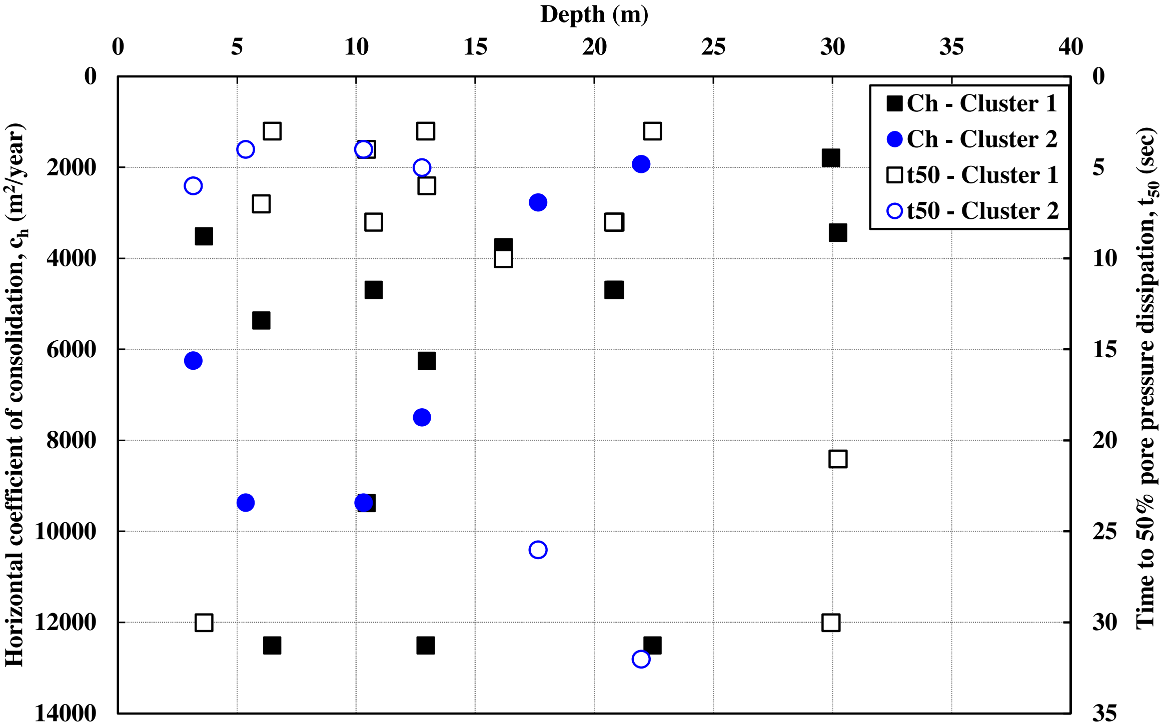
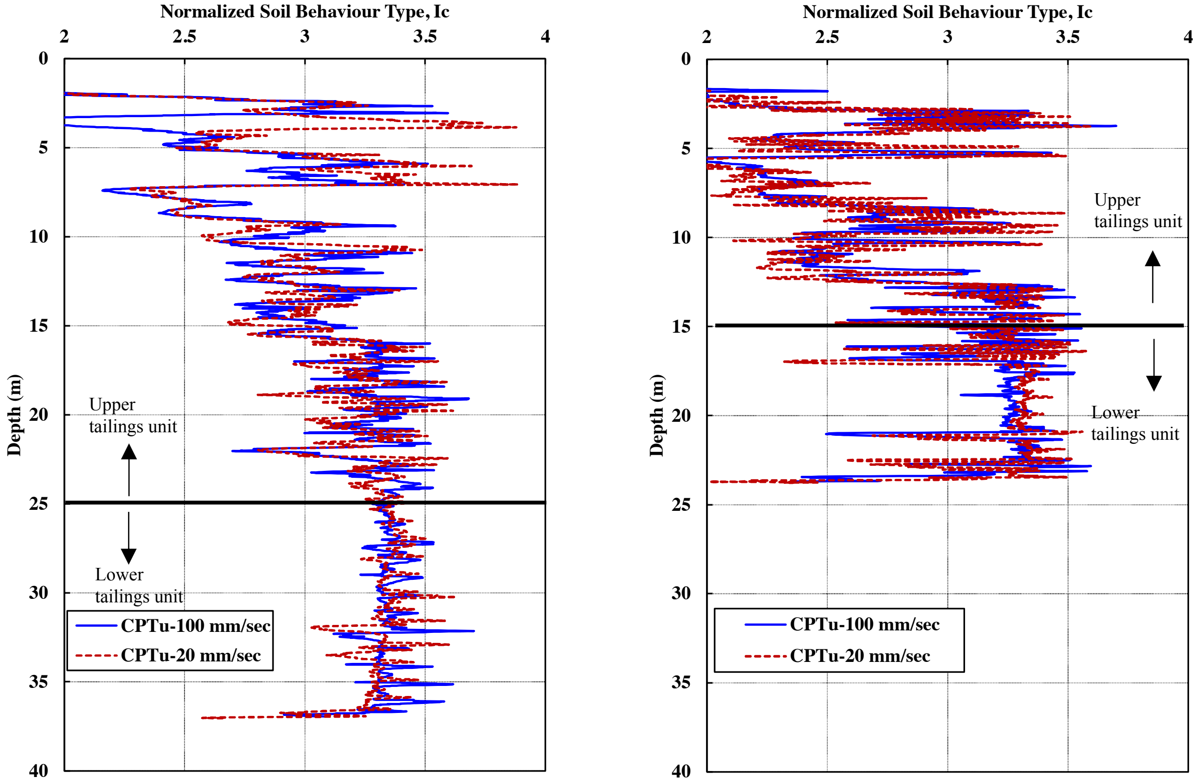


Figure 3: Dissipation test results: C_h and t_{50} versus depth

4.2 CPTU RESULTS

The results of the CPTu investigation profiles are presented in Figures 4 to 6 with both penetration rates of 20 and 100 mm/sec. In both clusters, the Normalized CPT Soil Behaviour Type (I_c) indicates interbedded coarse and fine tailings layers in the upper section, as shown in Figure 4. However, the tailings exhibit a uniformly clay-like behaviour at depths of more than 25m in Cluster 1. In Cluster 2, a clay-like response is also observed beyond 15 m depth, although some layers of coarser tailings are present within this interval. For the purposes of this study, these deeper, clay-like zones are classified as the lower tailings unit, while the overlying materials are referred to as the upper tailings unit. Although, in theory, a faster penetration rate should affect the I_c estimation due to changes in cone resistance and sleeve friction in partially drained material, the difference in estimated I_c between the two penetration rates is not significant enough to indicate a different material type behaviour at any given depth.



(a) Cluster 1 **(b) Cluster 2**

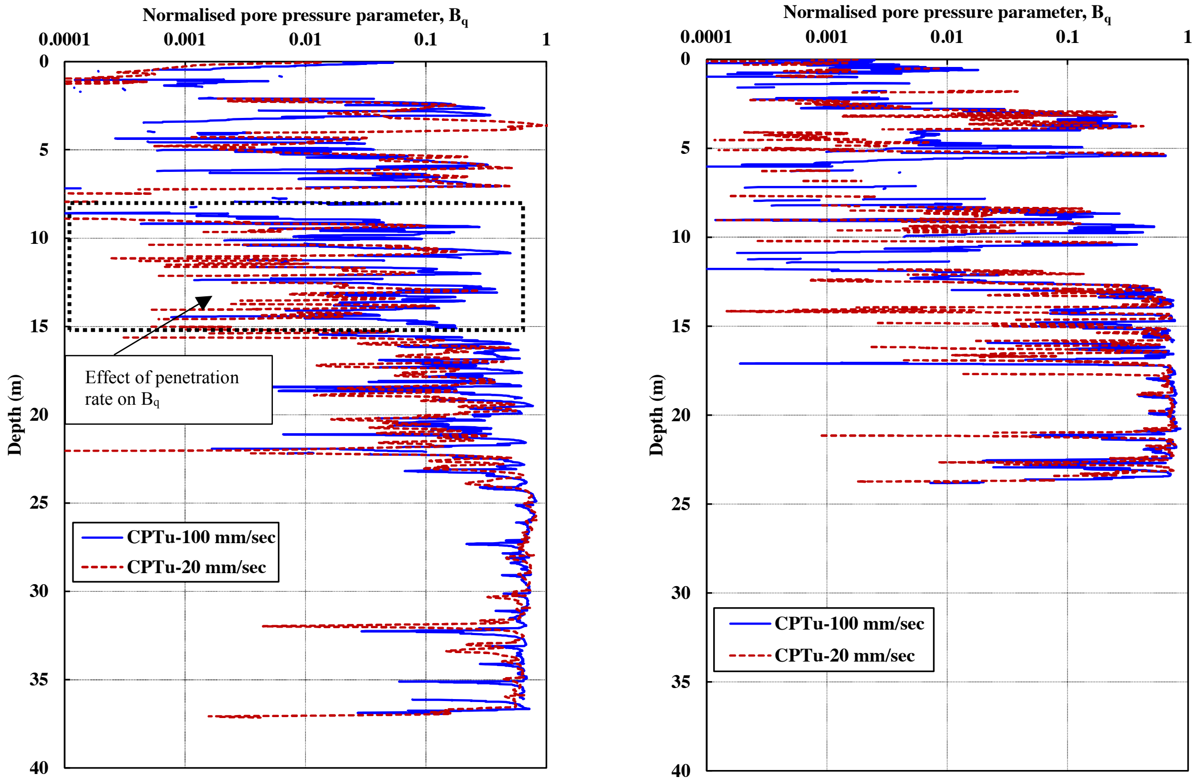
Figure 4: Normalized CPT Soil Behaviour Type, I_c versus depth

The normalised pore pressure parameter, B_q, was calculated for both clusters and shown in Figure 5 to assess the drainage condition. Generally, the faster the penetration, the higher the pore pressure induced in fine tailings, especially the fine tailings in the upper tailings unit. An example of this is highlighted in the Cluster 1 data (Figure 5a), within the depth range of 8 to 15 m, where the 100 mm/sec penetration rate results in significantly higher B_q values compared to the other dataset. This emphasises the possibility of partial drainage at lower penetration rates. For the lower tailings units, the difference in B_q of two penetration rates is marginal, potentially indicating "undrained" penetration condition. These layers have a uniform I_c of more than 2.95.

To assess the shear strength response, the following equation was used:

$$S_u = \frac{q_t - \sigma_v}{N_{kt}} \tag{1}$$

where q_t is corrected tip cone penetration, σ_v is total vertical stress, and N_{kt} is an empirical parameter.



(a) Cluster 1 **(b) Cluster 2**

Figure 5: Normalised pore pressure parameter, B$_q$ versus depth

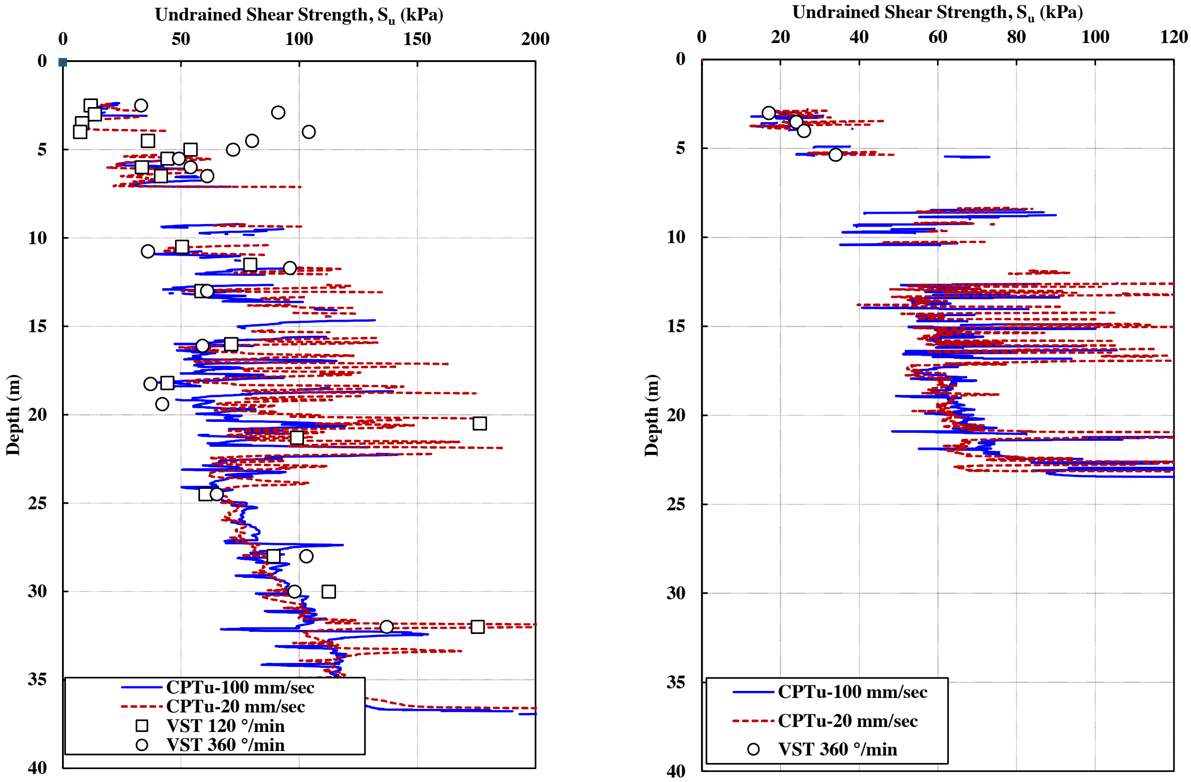
Mayne and Peuchen, (2018) proposed the following correlation for estimation of N$_{kt}$:

$$N_{kt} = 10.5 - 4.6\ln\left(B_q + 0.1\right) \tag{2}$$

Equation (2) was used as a preliminary estimate of N$_{kt}$. Two important limitations of this equation in the context of the current investigation are: (a) it was primarily developed for natural clay materials, and (b) B$_q$, as shown in Figure 5, can be influenced by the penetration rate. Therefore, the estimated S$_u$ was compared against field VST data, with the results shown in Figure 6. The S$_u$ was only estimated for layers with B$_q$ greater than 0.02 and I$_c$ greater than 2.95. Although this is not an entirely robust criterion for distinguishing undrained from drained penetration, it provides a reasonable level of data filtering.

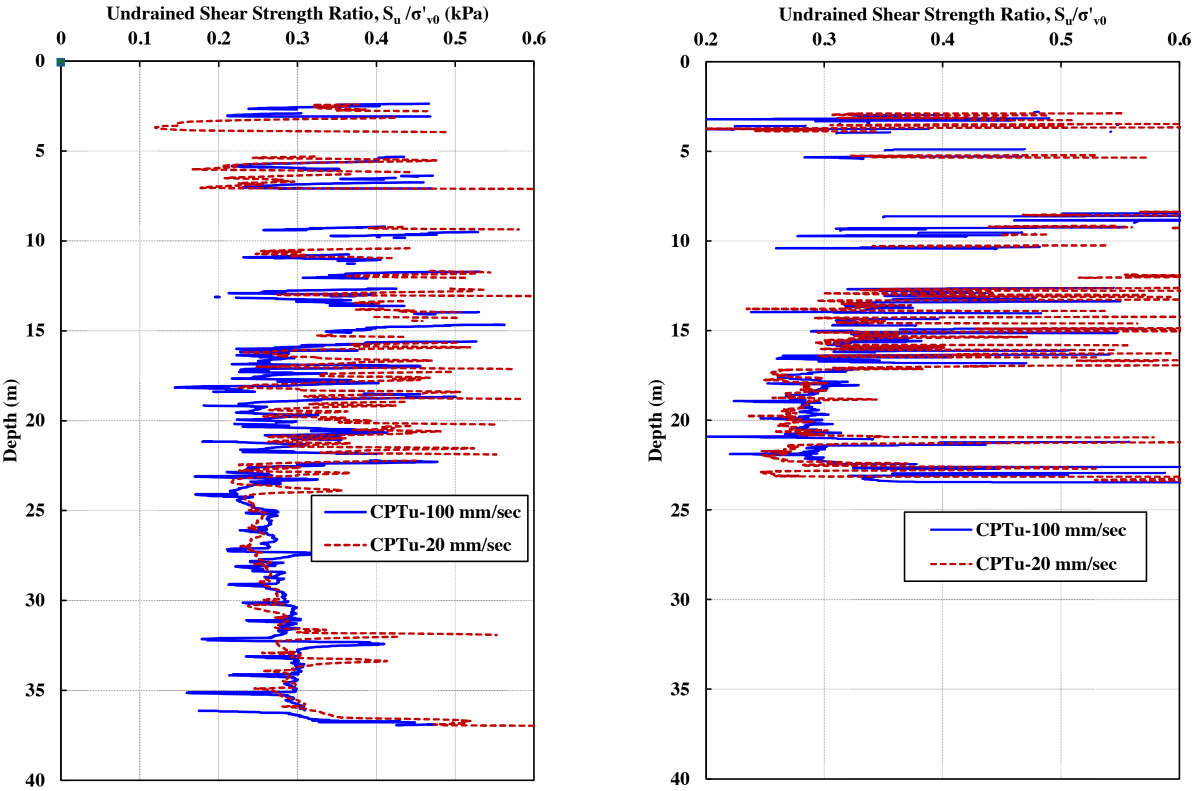
The VSTs were conducted at two rotation rates: 120 and 360 degrees per minute in Cluster 1, while all four tests in Cluster 2 were performed at 360 degrees per minute. According to the criteria proposed by Chandler (1988), none of the tests conducted at 120 degrees per minute could be classified as undrained. In contrast, the tests performed at 360 degrees per minute in both clusters either satisfied the undrained condition or are close to the dimensionless time factor T of 0.05, as defined by Chandler (1988).

For Cluster 1, a broad range of VST data is available at various depths to validate Equation (2). As the CPTu data matches reasonably well with the measured VST data, the same methodology was applied to Cluster 2. The results show that the two CPTu penetration rates yield relatively similar S$_u$ estimates in the lower tailings unit, particularly in Cluster 1 supporting the trends observed in the B$_q$ data. It should be noted that using Equation (2), an approximate N$_{kt}$ of 12 was derived for the lower tailings unit. The estimated undrained shear strength ratio (S$_u$/σ'$_{v0}$) is shown in Figure 7. Between the two clusters, and within the lower tailings unit, a marginal difference in S$_u$/σ'$_{v0}$ is observed, with higher values determined in Cluster 2.



(a) Cluster 1 (b) Cluster 2

Figure 6: CPTu estimated S_u



(a) Cluster 1 (b) Cluster 2

Figure 7: CPTu estimated S_u/σ'_{v0}

4.3 DMT RESULTS

Figure 8 provides the DMT-WP initial Readings. The A readings were collected at a depth interval ranging between 5-30 mm, while the B readings are only performed after every 1m penetration interval. Therefore, parameter B was linearly interpolated between each two points. Given the interbedded nature of the tailings in this investigation, the one metre interval of B readings may have missed important responses in both coarse and fine tailings. However, the continuous and accurate A readings carry significantly more weight in the estimation of parameters such as K_0, particularly through the application of Equations (3–8) presented below.

The initial readings in Figure 8 can be used to estimate the following corrected readings (Marchetti, S. 2001):

$$P_0 = 1.05(\mathrm{A} + \Delta A) - 0.05(\mathrm{B} + \Delta B) \tag{3}$$

$$P_1 = (\mathrm{B} + \Delta B) \tag{4}$$

where ΔA and ΔB are membrane calibration values, P_0 is the corrected lift-off pressure, and P_1 is the corrected second reading. The parameter P_0, which is predominantly derived from A readings with minimal influence from B readings, can be used to estimate several intermediate parameters, as outlined below (Marchetti, S., 2001):

$$I_D = (P_1 - P_0)/(P_0 - U_0) \tag{5}$$

$$K_D = (P_0 - U_0)/\sigma_{v0}' \tag{6}$$

where I_D is a material index, K_D is the Horizontal Stress Index, U_0 is the equilibrium water pressure and σ'_{v0} is the effective vertical stress. The parameter I_D provides an indication of material type and penetration condition (drained or undrained), while parameter K_D is used to estimate the interpretation parameters such as K_0 and undrained shear strength (Marchetti, S. 2001):

$$K_0 = (K_D/1.5)^{0.47} - 0.6 \tag{7}$$

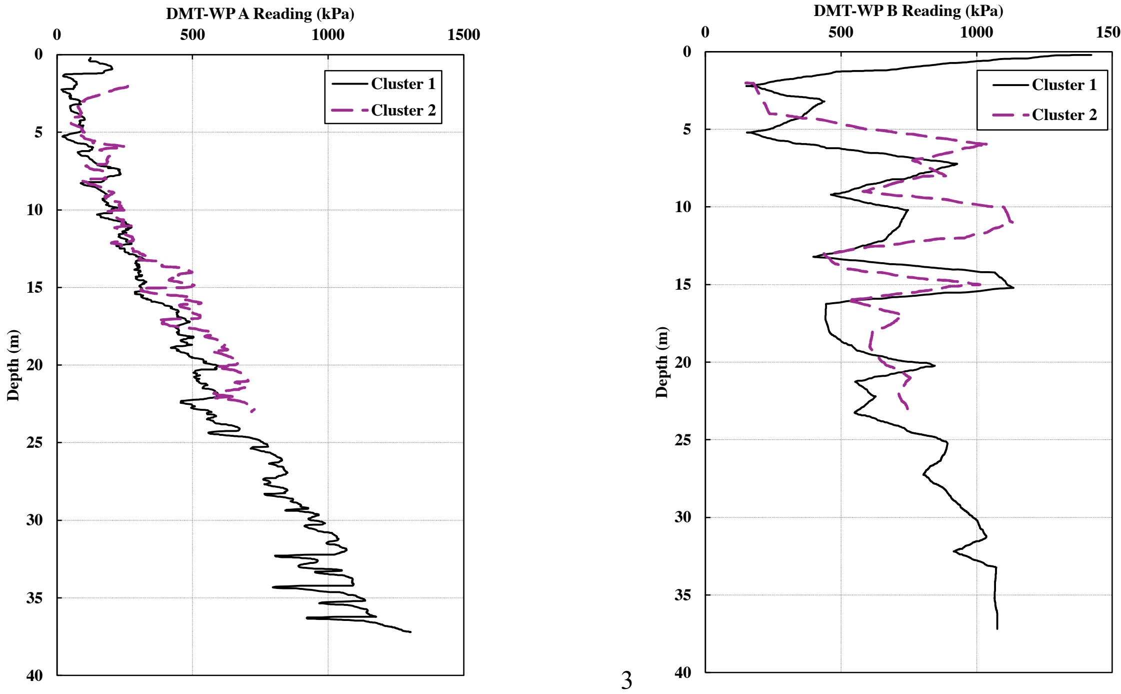
$$S_u = \alpha\, \sigma_{v0}'(0.5K_D)^{1.25} \tag{8}$$

where parameter α is an empirical factor to estimate undrained shear strength. The α of 0.22 was suggested based on the discussions of Mesri (1975) for normally consolidated soft clays (Marchetti 1980) and it is mainly used in DMT test results evaluations (Marchetti, 2001). For the lower tailings unit in this study, the 50th percentile undrained shear strength ratio is approximately 0.27 (Figure 7), and this value was adopted in Equation (8). The median was selected for this unit because the data shows relatively low variability compared to the upper tailings unit. In contrast, a lower-bound value corresponding to the 20th percentile ($S_u/\sigma'_{v0} = 0.3$) was used for the upper tailings unit, due to the greater variability in the data caused by the presence of interbedded coarse and fine tailings.

Equations (6) and (7) were proposed for I_D less than 1.2, classifying as clay and silt materials (Marchetti, S. 2001). However, partially drained materials such as tailings can also yield an I_D less than 1.2, while undrained penetration remains in question.

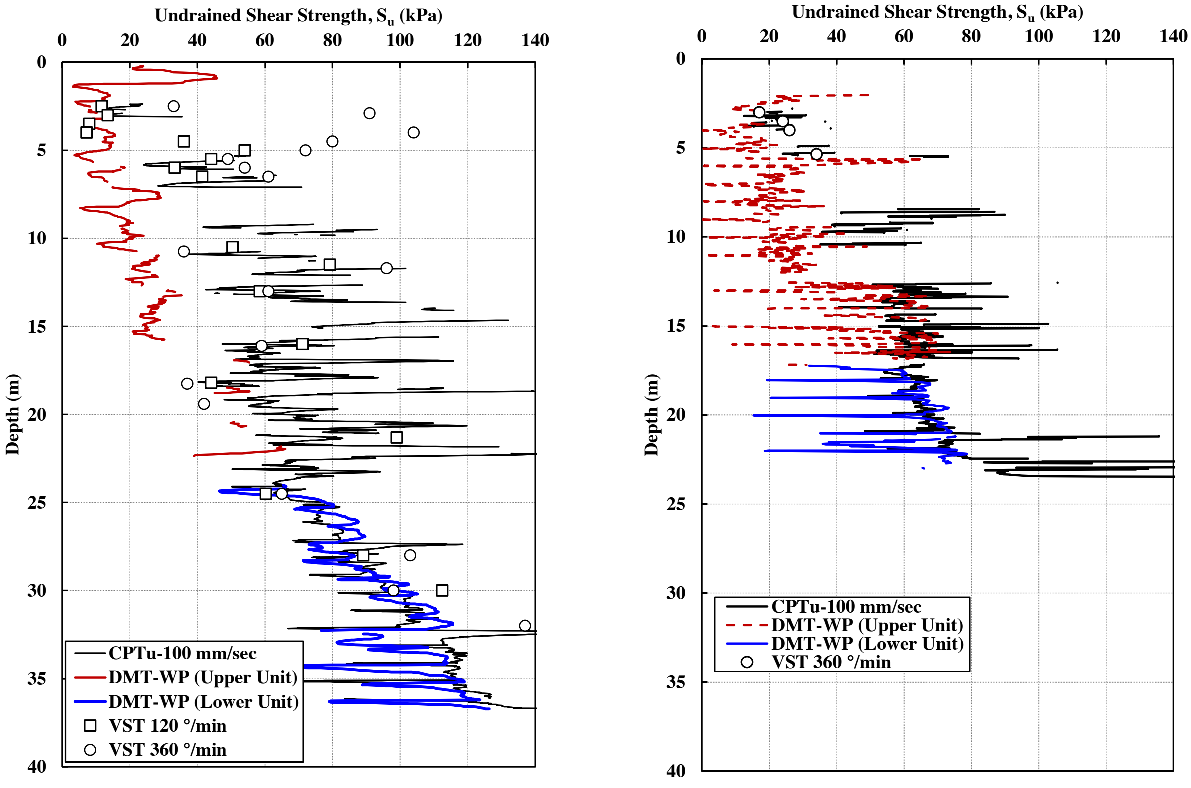
Equations (7) and (8) were originally derived from studies on natural clays and silty materials (Marchetti, 1980), primarily under undrained conditions. While the tailings in this study contain low to medium plasticity fines, their behaviour may deviate from the assumptions underlying these empirical correlations, particularly given the potential for partially drained condition. In the absence of site-specific calibration data, these equations are applied for initial estimates of S_u and K_0, with recognition of the associated uncertainty. Future work incorporating laboratory testing or direct in-situ stress measurements K_0 would help validate and refine the applicability of these correlations to tailings materials.

The resulting undrained shear strength from DMT-WP is shown in Figure 9. The comparison is made using CPTu data with a 100 mm/s penetration rate, as the effects of partial drainage are less pronounced at higher penetration rates. The results are presented for lower and upper tailings units in different colours. Good agreement is observed between DMT-WP and CPTu/VST data for the lower tailings units in Cluster 1. In Cluster 2, VST data are not available for the lower tailings unit; however, given the similarity of the material to Cluster 1, comparison between DMT and CPTu data is considered appropriate. This suggests that a potential undrained condition could be met at a lower depth where uniform layers of fine tailings are present. Spikes in the DMT results are mainly linked to the start of penetration at each 1 m interval, where undrained conditions were not properly achieved. The primary cause is the pore pressure decay that happens when penetration is stopped to perform the B reading. For the upper tailings unit, the undrained shear strength cannot be estimated accurately due to partial drainage



(a) Cluster 1 **(b) Cluster 2**

Figure 8: DMT-WP A and B readings

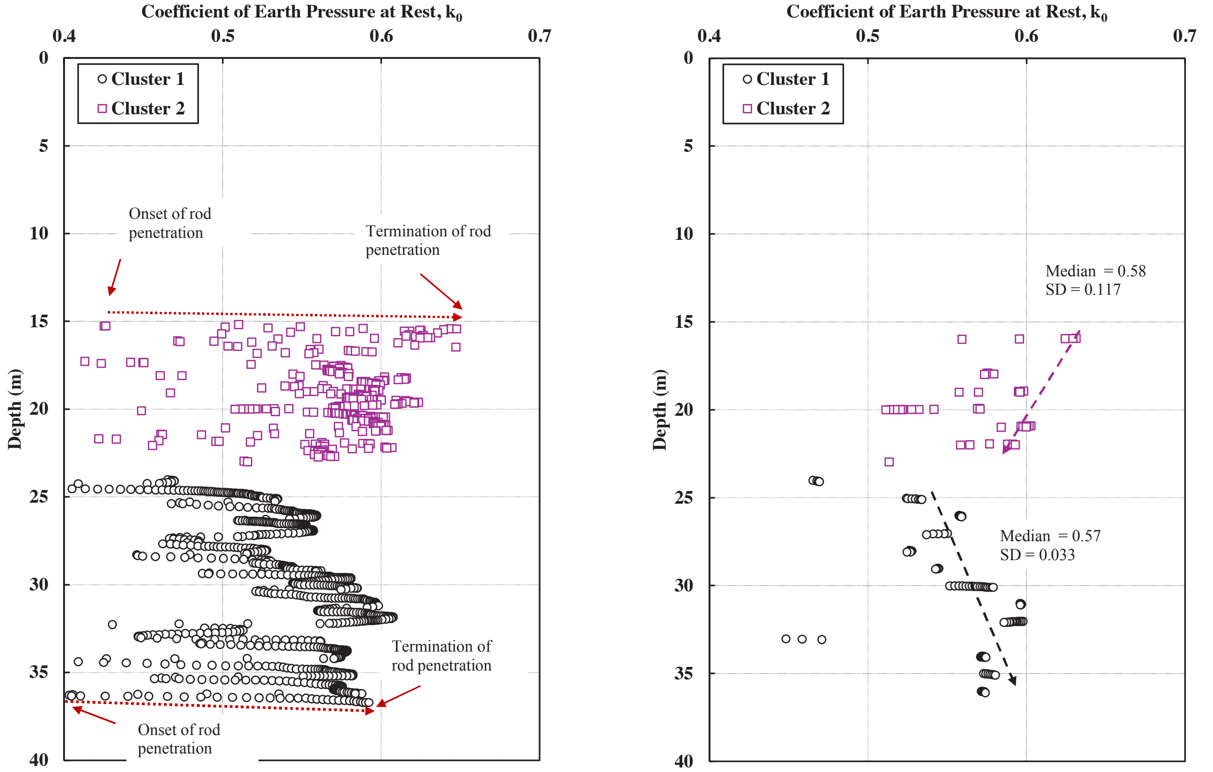


(a) Cluster 1 **(b) Cluster 2**

Figure 9: DMT-WP estimated Su against the CPTu data.

The parameters K_0 and S_u are derived directly from P_0 readings, with no influence of P_1 readings. Since the DMT-WP provided reasonable shear strength results for the lower tailings unit, the parameter K_0 was only determined for the same depth and is presented in Figure 10(a). The data predominantly ranged between 0.5 and 0.6 in Cluster 1 and 0.5 to 0.65 in Cluster 2. This is appropriate given that Cluster 2 data are closer to the starter embankment and early stages of upstream raises, tolerating some level of bias, which results in higher K_0 than Cluster 1.

As shown in Figure 10(a), the onset of rod penetration consistently corresponds to the lowest estimated K_0 value within each penetration interval. This is likely due to the B reading being taken prior to rod advancement, allowing some pore pressure dissipation and resulting lower A (and consequently P_0) readings. Upon resuming rod penetration, the A reading increased until stabilising at a relatively constant value within each interval. This stabilisation is evident in the final 10 cm of rod penetration for each interval in Cluster 1 data, as illustrated in Figure 10(b). In Cluster 1, most of the data points in the last 10 cm penetration are confined to a narrow K_0 range (less than 0.3), except for one data set around the 33 m depth. In contrast, Cluster 2 exhibits more scatter, likely due to the presence of interbedded coarse tailings observed beyond 15 m depth, as shown in Figure 4(b).

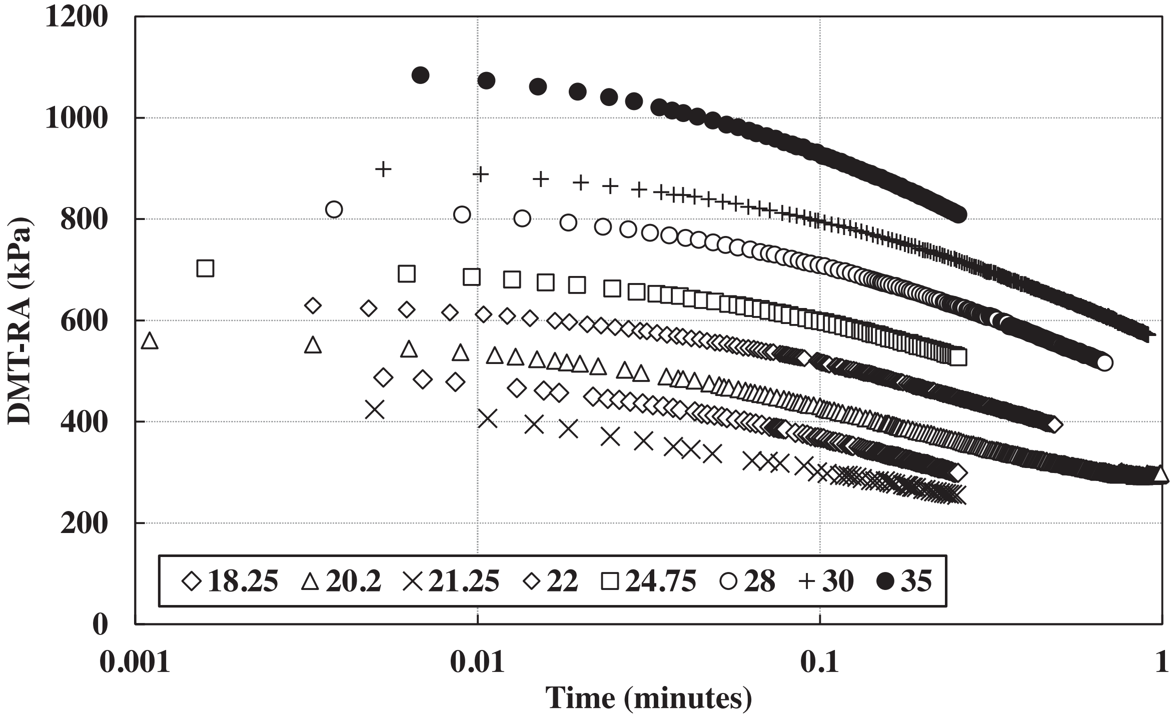


(a) All data in lower tailings unit

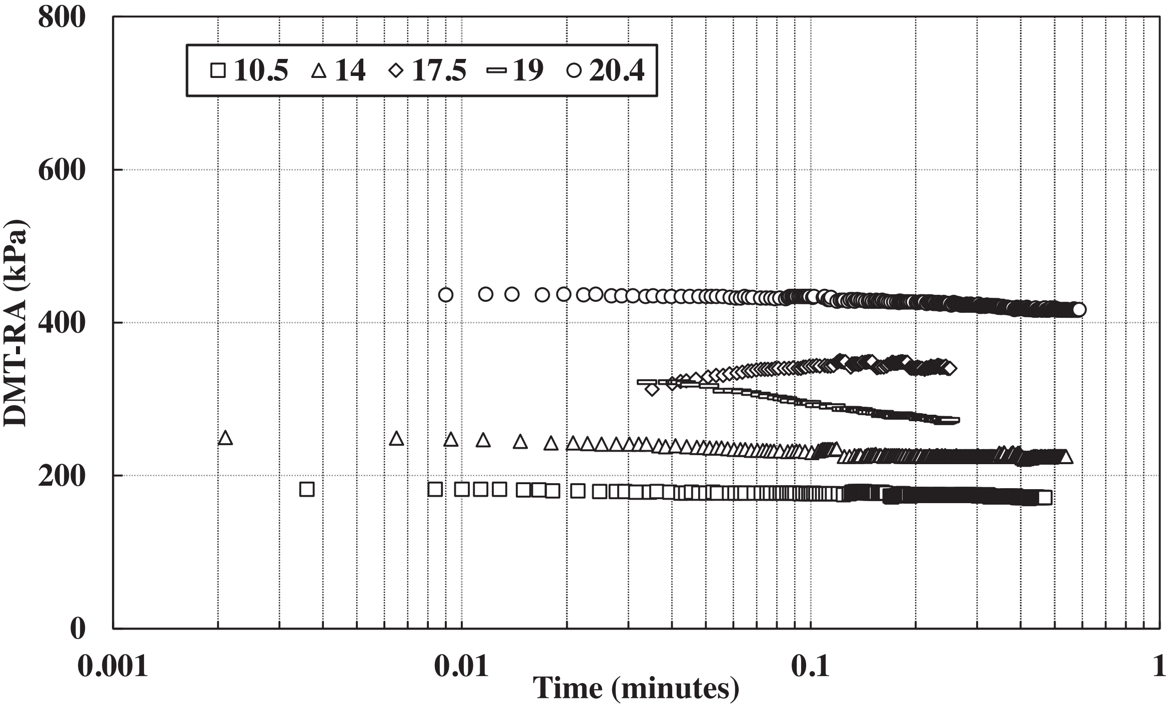
(b) Last 20cm penetration of each rod interval

Figure 10: DMT-WP estimated K_0 versus depth

The significant drop in A readings over a short time span and its impact on K_0 can be further assessed with DMT-RA testing. DMT-RA tests were performed, not in the same clusters but in proximity with similar tailings profiles. The resulting A decay with time is shown in Figure 11 for the upper and lower tailings units. For the lower tailings unit, the decay in A readings occur immediately after the penetration is stopped to collect reading, while for the upper units, the penetration is either in a drained condition or the decay in excess pore pressure has occurred before the start of A readings.



(a) Lower tailings unit



(b) Upper tailings unit

Figure 11: Variation of DMT-RA readings with time

To emphasise the rate effect on DMT test results in intermediate materials, a comparison in estimated P_0 is shown between the standard DMT, Corrected DMT-RA and DMT-WP in Figure 12 for Cluster 1 data. It can be observed that the standard DMT significantly underestimates the P_0 using the A readings at 15 seconds. The normal DMT results can be corrected by using the A readings at the time ~ 0-1 seconds, and the results of calculated P_0 are closer to the DMT-WP, although still on the lower bound. These results indicate that the A readings should occur as quickly as possible in intermediate materials, prior to drainage occurring which directly results in an underestimate of P_0.

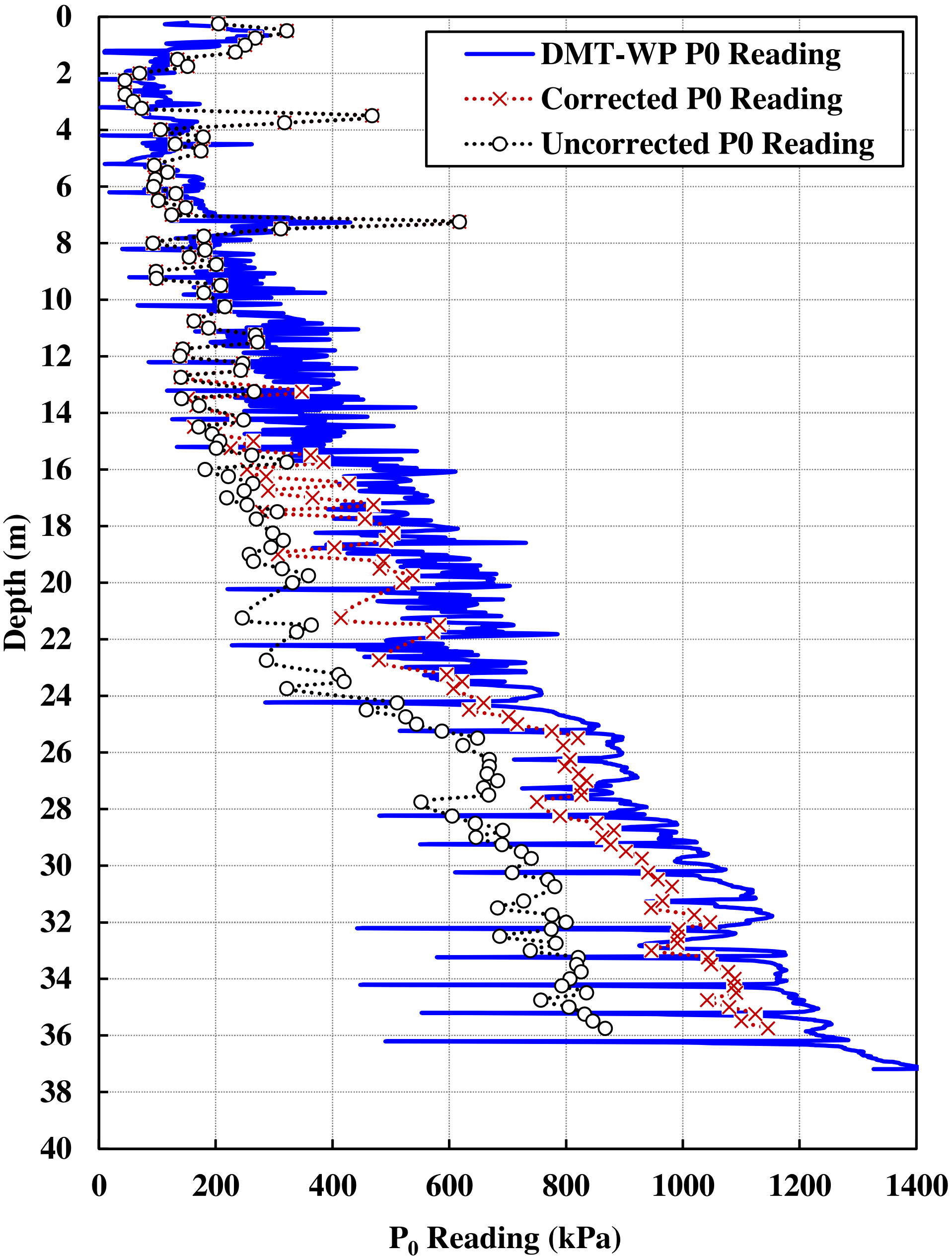


Figure 12: P_0 readings in DMT-WP and corrected and uncorrected Normal DMT

5 LIMITATIONS

The following limitations are highlighted as part of the current study:

- The DMT tests are generally performed at a penetration rate of 20 mm/sec. Given the significant A decay with time observed in this study, employing higher penetration rates could enhance the accuracy of parameter estimations by reducing pore pressure dissipation during testing.
- The empirical correlations used to derive parameters such as S_u and K_0 from DMT data were primarily developed for natural clays. Their direct application to tailings and low-plasticity silts may introduce uncertainties, highlighting the need for further calibration specific to these materials.

6 CONCLUSIONS

A series of in-situ test were performed on tailings, including CPTu, VST and DMT testing. The tailings range from coarse to fine, with varied plasticity and fines content. The dissipation test results suggested that the materials are prone to partial drainage, where penetration rate and testing speed can influence the results. The CPTu data illustrated that the upper tailing units consist of a combination of interlayered coarse and fine tailings, while the lower unit were predominantly uniform clay-like behaving material.

The CPTu test results suggested differences in upper unit under different penetration rates, the lower units were less affected, showing similar results. There was a noticeable difference in the P_0 readings in the lower unit between the three different DMT test methodologies, with the DMT-WP results less or unaffected.

The values from the DMT-WP test were used to estimate the undrained shear strength for lower units, which matched well with CPTu and VST results. This alignment supported the assessment of the other P_0 derived parameters, K_0 and S_u in lower tailings units. The field-testing procedure adopted in this work provides valuable information in the interpretation of the DMT test results.

DMT-RA tests were conducted at regular intervals as part of a standard DMT profile to access the drainage during the test. This test method provides helpful information regarding the drainage condition of the material and assessment of A reading decay with time. It is envisaged that this test procedure will become standard practice with every DMT test, particularly in tailings.

These new DMT test methodologies are only possible with the new Medusa DMT which enables high-quality operator-independent tests. The high-speed readings and adjustments to the diaphragm position enable new tests that can assess and manage partial drainage effects. In intermediate materials the DMT test should be performed in the fastest practical way to estimate the parameters related to the undrained condition, such as undrained shear strength and K_0.

CRediT authorship contribution statement

Mahdi Naeini: Data curation, Formal analysis, Writing - original draft. **Mark Chapman:** Methodology, Data curation, Writing – review & editing. **Arun Muhunthan:** Conceptualisation, Supervision, Writing – review & editing. **Marty Viney:** Project administration. **Pamela Soto:** Funding acquisition.

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