INVESTIGATION INTO THE IMPACTS OF MECHANICAL IMPROVEMENT OF TAILINGS WITHIN THE CRITICAL STATE SOIL FRAMEWORK

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ABSTRACT

A geotechnical investigation was undertaken in tailings and subsequently analysed within the critical state soil mechanics (CSSM) framework. The geotechnical investigation included cone penetration testing with porewater pressure measurement (CPTu) and laboratory testing. The laboratory testing was inclusive of triaxial compression testing in addition to classification and oedometer testing. The tailings samples were retrieved using the mini-block sampling (MBS) technique to minimise disturbance, though the triaxial testing included both reconstituted and testing in MBS recovered samples. The tailings material was split into four groups related to the deposition methodology used. This included mechanically improved tailings, sub-aerially deposited tailings and two types of sub-aqueous deposited tailings.

Using the triaxial test results, four critical state lines (CSLs) were defined based on fines content of 6%, 40%, 50% and 80%. Each CSL has a varying slope and intercept observing to follow a well-documented trend leading towards an Omega Point. These four CSLs were used to define a CSL region within which there is an independent CSL based on fines content, i.e., a tailings with 5% fines content have a different CSL to one of 55% based on the developed functions. The soil behaviour index (Ic) was then used to estimate the fines content of the CPTu results using three methods; Boulanger and Idriss (2014), Agaiby and Mayne (2020) and a site-specific calibration.

The CPTu results were plotted against the modelled CSL region. The results were used to predict the potential of the tailings to behave either contractive or dilative. The results of this assessment clearly demonstrate that whether the tailings material will behave in a contractive or dilative manner is related to placement strategy. Most relevantly, the assessment allowed estimation of the stress progression and at which point the dilative tailings will transition to contractive behaviour upon subsequent upstream loading. The methods used in this paper provide a robust rational framework to demonstrate the effect of various tailings management practices on design outcomes, able to be applied by practitioners for increased understanding of their tailings and hopefully leading to more informed decision making.

1 INTRODUCTION

Tailings Storage Facilities (TSF) are some of the largest man-made structures and are used to store millions of tonnes of waste materials produced by mining operations. These facilities are anticipated to only grow larger in the future as rising public demand for commodities supports the increasing mine production and associated tailings production rates (Morrison, 2021). Because of the sheer size of the facilities, the failure of a TSF is often devastating for all involved with thousands of deaths being linked to TSF failure (Hudson et al., 2024). The community, surrounding environment and company all suffer in varying degrees when a TSF failure occurs. Furthermore, TSFs are different to traditional water storage facilities (WSF) in that they are raised, often regularly, after being built, where WSFs are often built and may only be raised once or twice in their lifecycle. Raising TSFs throughout the mining process enables operations to capture economical efficiencies. The resources industry is volatile so raising a TSF for the predicted life of the mine commits what may be unnecessary capital (Williams, 2021). Raising a TSF periodically allows the procedure of an upstream raise, where the TSF is raised on top of the tailings previously deposited. An upstream raise substantially minimises costs due to the reduced requirements of earthworks. However, one of the drawbacks is that the TSF is now being raised on tailings which may exhibit reduced strengths and have the potential to behave in a contractive manner (a predisposition to volume reduction with increased pore pressure) or brittle (a predisposition to volume and strength reduction volume with increase pore pressure). The reduced strength and potential for contractive behaviour has led to larger failure rates and failure flow events occurring in upstream raised TSFs when compared to other construction methods (Halabi et al., 2022). Accurately assessing the strength and potential of tailings to behave contractively is essential to ensuring a safe and sustainable facility and is an area of ongoing research.

The risk of tailings liquefying is linked to the saturated and loose deposition methods, as tailings are typically pumped into the storage facility due to the reduced costs associated with this mode of transport in comparison to other methods such as conveyor or truck (Williams, 2021). The placement of tailings via hydraulic filling involves the tailings settling out onto the tailings beach. The results of this are that the tailings are exceptionally loose, far looser in situ than can often be achieved in the laboratory (Reid and Fanni, 2022). Furthermore, this deposition method results in segregation of the tailings along the beach according to particle size with the coarser particles typically settling shorter distances from the spigot (Figueroa et al., 2015). An assessment of tailings behaviour based on the deposition method was undertaken within the critical state soil mechanics (CSSM) framework. A brief description of the CSSM framework will be provided, following with the site and tailings details and subsequent analysis. Both mini-block samples (MBS) and reconstituted samples were tested to determine their critical state line (CSL) with four different CSLs created based on varying fines content. To compare the laboratory results and in-situ results a site-specific fines content calibration was created. This enabled comparison of the cone penetration with porewater pressure measurement (CPTu) to the four CSLs. Lastly, the implications of the tailings deposition method will be discussed before closing on outcomes and recommendations for practitioners.

2 THEORY

When discussing the stability of a TSF it is necessary to understand the principles of liquefaction and CSSM as this influences the potential behaviour of the TSF. Liquefaction is a phenomenon in which soil loses much of its strength, generally associated with loose saturated soils, and occurs due to an increase in pore pressure reducing the effective stress state. This increase in pressure results from an undrained or partially drained condition which can be triggered by any number of mechanisms (e.g., seismic event, rapid loading, change in stress state). The case of determining a trigger has significant difficulties and recent recommendations are that for High or Extreme consequence facilities a trigger should be assumed and consequence mitigation measures prioritised when brittle material are present (ICOLD, 2023). The strength loss has the potential to reach residual strength that could be more dramatic than traditionally understood in CSSM of clay deposits. CSSM is a framework within established plasticity theory developed to deal with the behaviour of soils that exist across a range of states (i.e. void ratio or density). The critical state is the state of a soil where, were to be deformed (sheared) continuously, it would exhibit no further volume change. To assess a soils density relationship to the CSL, or the critical state, the State Parameter, ψ is used. The definition of ψ (Figure 1) is the distance between the current void ratio (i.e. density) of soil/ to the CSL void ratio. Dense soils have a negative ψ and loose soils have a positive ψ.

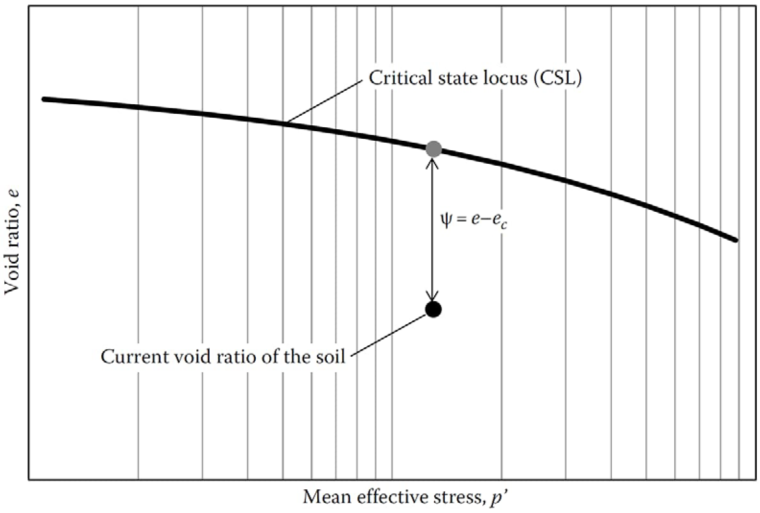

Figure 1: Definition of the state parameter for a dilative soil (Jefferies and Been, 2015)

A complication when determining a CSL is that it varies based on fines content (FC). Previous research has indicated that the CSL moves downwards to a threshold value of around 40% to 50% FC and then backwards (Papadopoulou et al., 2008; Nguyen et al., 2014). One of the aims for practitioners to determine is the in situ state of the soil and the potential for the in situ state to change based on changing conditions. This is done through in situ testing and laboratory testing of the soil. One of the more common testing procedures, and the one used throughout this case study, is the Cone Penetration Test with pore-water pressure measurement (CPTu). Laboratory testing is used to assess additional parameters of tailings, particularly when MBS can be obtained. For this case study the MBS technique was used, which has consistently shown much better-quality samples then alternative methods such as tube samples (Emdal, 2016; Amundsen et al., 2021; Lines et al., 2023). While tailings frequently comprise ground rock with or without clay minerals and have been subject to chemical processing and sometimes heated processing, indications are that they tend to follow the principles of geotechnics as applied to natural soils. This indicates that CSSM can be applied to tailings with the caveat that during mining and processing of the ore that has become tailings there may be deviances from common soil behaviour that need to be considered.

3 SITE BACKGROUND

The TSF is in Australia with the location having a tropical monsoonal climate and experiences about two metres of rainfall each year, mostly between the months of December and March. Constructed in 2018 it is a relatively young TSF having only undergone a few wall raises. It is about 1000 Ha in area and is separated into two cells, with one cell being raised each year. The design life of the TSF is approximately 25 years, with a series of 12 to 13 upstream raises anticipated, reaching a final height of about 20 m. A total of 9-10 million dry tonnes per year of tailings are deposited into the TSF.

3.1 PIEZOCONE AND CLASSIFICATION TEST RESULTS

During the start-up phase of the TSF the entirety of the TSF was not available for deposition due to mining operations within one of the cells. This resulted in suboptimal drying time after each deposition cycle. Moreover, the tailings were deposited sub-aqueously due to the accumulation of supernatant water on the operating cell. Following this start-up phase as more of the TSF became available for deposition, the tailings were deposited sub-aerially. In 2022 there was a decision to begin mechanical improvement of the tailings to increase densities near the embankment. Subsequent geotechnical investigations have led to the classification of the tailings into four distinct groups based on the CPTu profile and geotechnical parameters with each group relating to the deposition processes, this includes:

1. Mechanically improved sub-aerially deposited tailings referred to as DTAL
2. Sub-aerially deposited tailings without mechanical improvement referred to as TAL.
3. Sub-aqueously deposited tailings referred to as STAL.
4. Sensitive sub-aqueously deposited tailings referred to as SSTAL.

Two example CPTu profiles displaying the cone tip resistance and pore pressure with depth are shown in Figure 2. Of the tailings, the DTAL tailings has the highest cone tip resistance typically > 5 MPa and while the strength is a good indicator, the DTAL can be cross-referenced with the timing and location of mechanical improvement. The TAL tailings have a much lower cone tip resistance at around 2 MPa and the STAL and SSTAL tailings display < 1 MPa with the sensitive having consistently minimal cone tip resistance as low as 0.2 MPa. The dynamic pore pressure was greatest in the SSTAL, but was typically present in the other tailings, though there were instances of negative pore pressure and zero pore pressure at the surface. The second example shows an occasion where the DTAL is not at the surface but interbedded, mechanical improvement is not a continuous activity and it is often ceased for periods of time, such as during significant weather events. Sensitivity refers to the ratio of peak to residual undrained strengths. The SSTAL had a sensitivity of up to 8 when calculated with the in-situ vane shear testing (VST) results, combined with increased presence within the corresponding CCS region using the Robertson (2016) SBTn chart, resulted in designation of the 'sensitive' to differentiate that layer. Based on the CPTu profiles it can already be seen that the deposition technique has a significant impact on the outcome of the tailings strength.

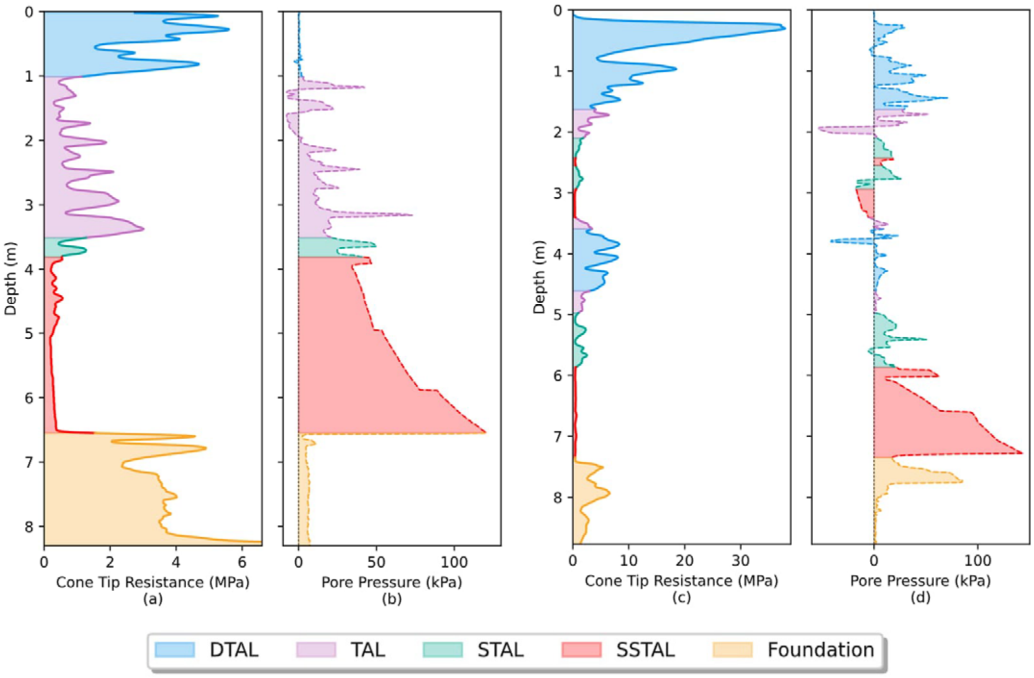

Figure 2: Example CPTu profiles displaying cone tip resistance of tailings and pore pressure. (a) and (b) form the first example and (c) and (d) form the second example

Figure 3 and Figure 4 display the particle size distribution (PSD) and the Atterberg Limits (AL) of the various tailings categories. The main takeaway from this information is that the sensitive sub-aqueous (SSTAL) tailings display an increased fines content over the other tailings categories. The high water volume on the TSF surface during deposition is the mechanism that results in the increased amount of fines present since when the tailings stream enters the supernatant pond the coarse fraction settles out rapidly leaving the fines to flow on towards the decant point. This is a well-known phenomenon in the industry.

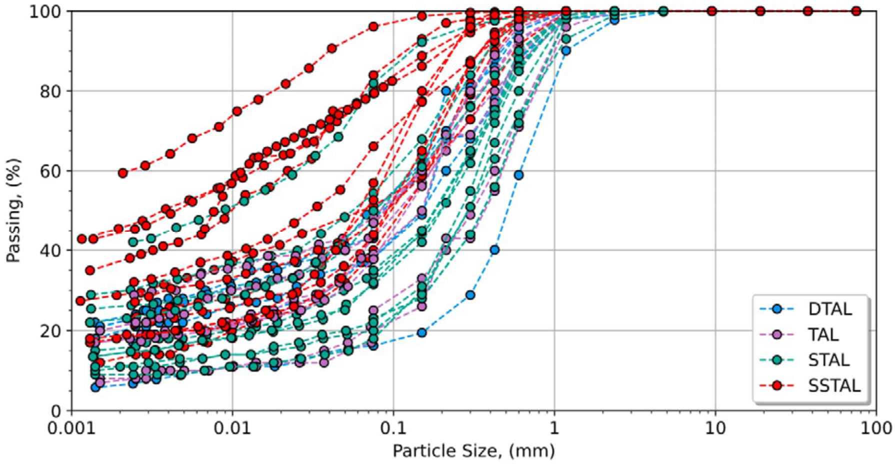

Figure 3: Particle Size Distribution (PSD) based on tailings category

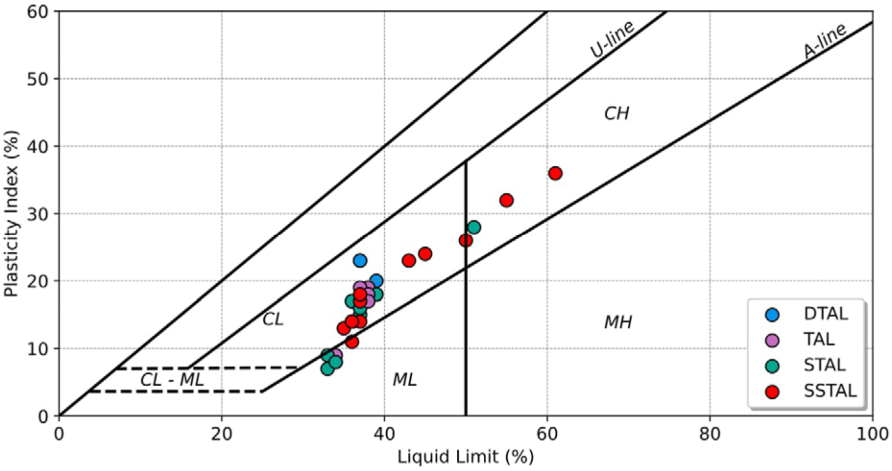

Figure 4: Atterberg Limits (AL) based on tailings category

4 RESULTS

4.1 CPTU INTERPRETATION

The tailings were initially assessed based on the framework provided by Robertson (2016) to determine the potential for contractive and dilative behaviour through the simplified CPT-based results. The results are shown in Figure 5. The darker the shaded hexagon in the figures, the more frequent that value occurs, hence the darker regions of hexagons are where the majority of values plot. The hexbin plot was chosen due to the sheer number of data, 23,376 datapoints from all 56 CPTu's. The mechanically improved tailings are primarily in the sand-like dilative zone, the sub-aerial tailings are primarily within the sand-like contractive zone with data also presenting in the sand-like dilative and transitional dilative zones. The sensitive sub-aqueous plots further within the contractive zones and lastly the sensitive sub-aqueous plots well within the clay-like contractive and sensitive clay-like contractive zones displaying the highest likelihood for contractive behaviour based on the Roberston (2016) SBTn chart.

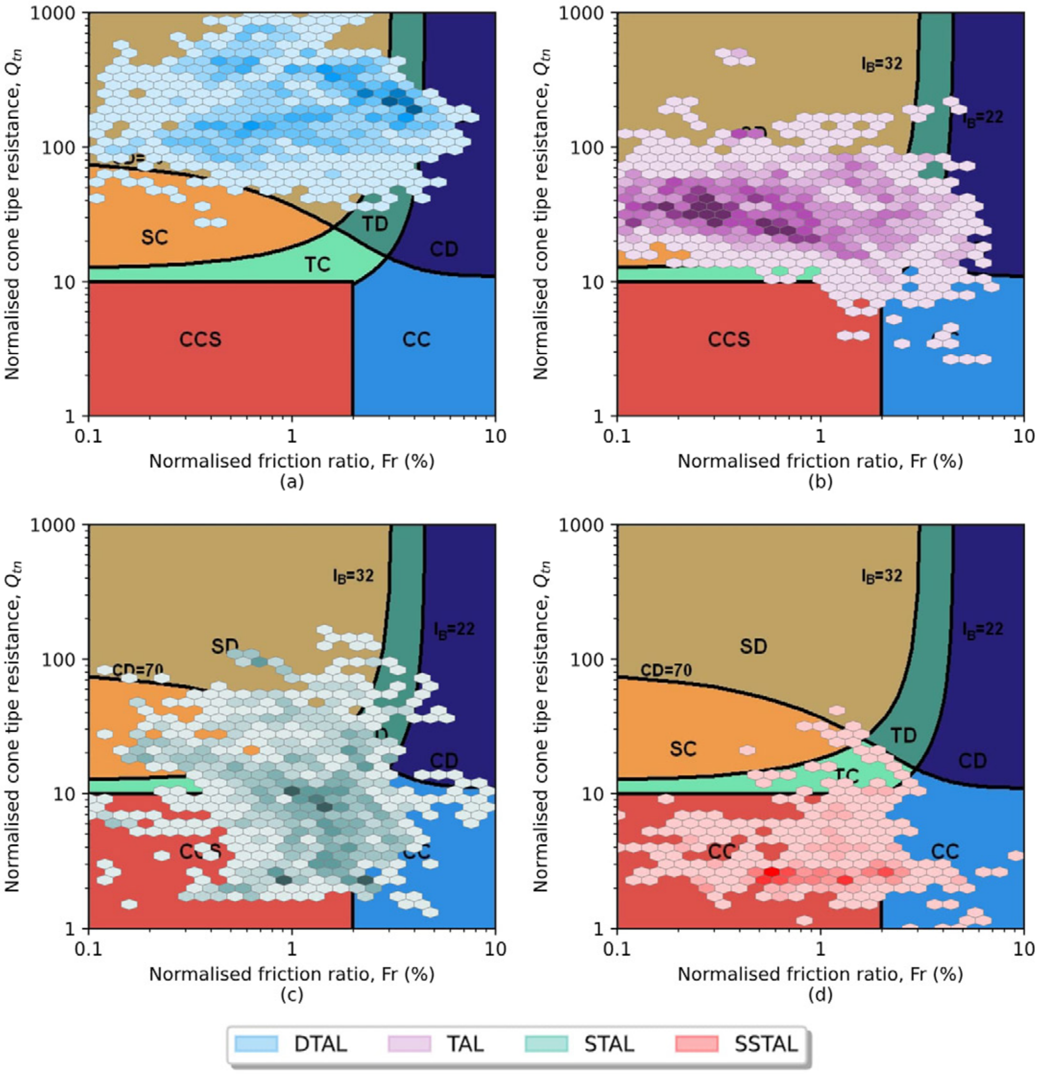

Figure 5: SBTn Chart (Robertson 2016) for various tailings material; (a) Mechanically improved (DTAL) tailings (b) Sub-aerial (TAL) tailings (c) Sub-aqueous (STAL) tailings and (d) Sensitive sub-aqueous (SSTAL) tailings

The Schneider plot (Schneider, 2008), shown Figure 6, has the added advantage of taking into consideration pore pressure. The mechanically improved (DTAL) tailings display clear dilative behaviour and as the material trends from sub-aerial (TAL) to sub-aqueous (STAL) and finally sensitive sub-aqueous (SSTAL) tailings the material becomes increasingly contractive.

The Schnieder plot can be used to assess the drainage of the CPTu during penetration (Schneider, 2008). However, caution should be applied in interpretation of these results as shear wave velocity (V_s) testing indicated the presence of microstructure, defined using a modified normalised small-strain rigidity index (K^*_G) > 330 as per Robertson (2016). Taking that into consideration, the mechanically improved (DTAL) tailings is within the drained sands region, which would be indicative of drained penetration, whereas the remaining tailings plot predominately within the transitional region. In addition to this there have been a total of 16 successful dissipation tests performed within the tailings, the t_{50} from these had a range from 90 – 1081, with a median of 439. Therefore, the dissipation tests would indicate that the penetration is essentially undrained (DeJong and Randolph, 2012).

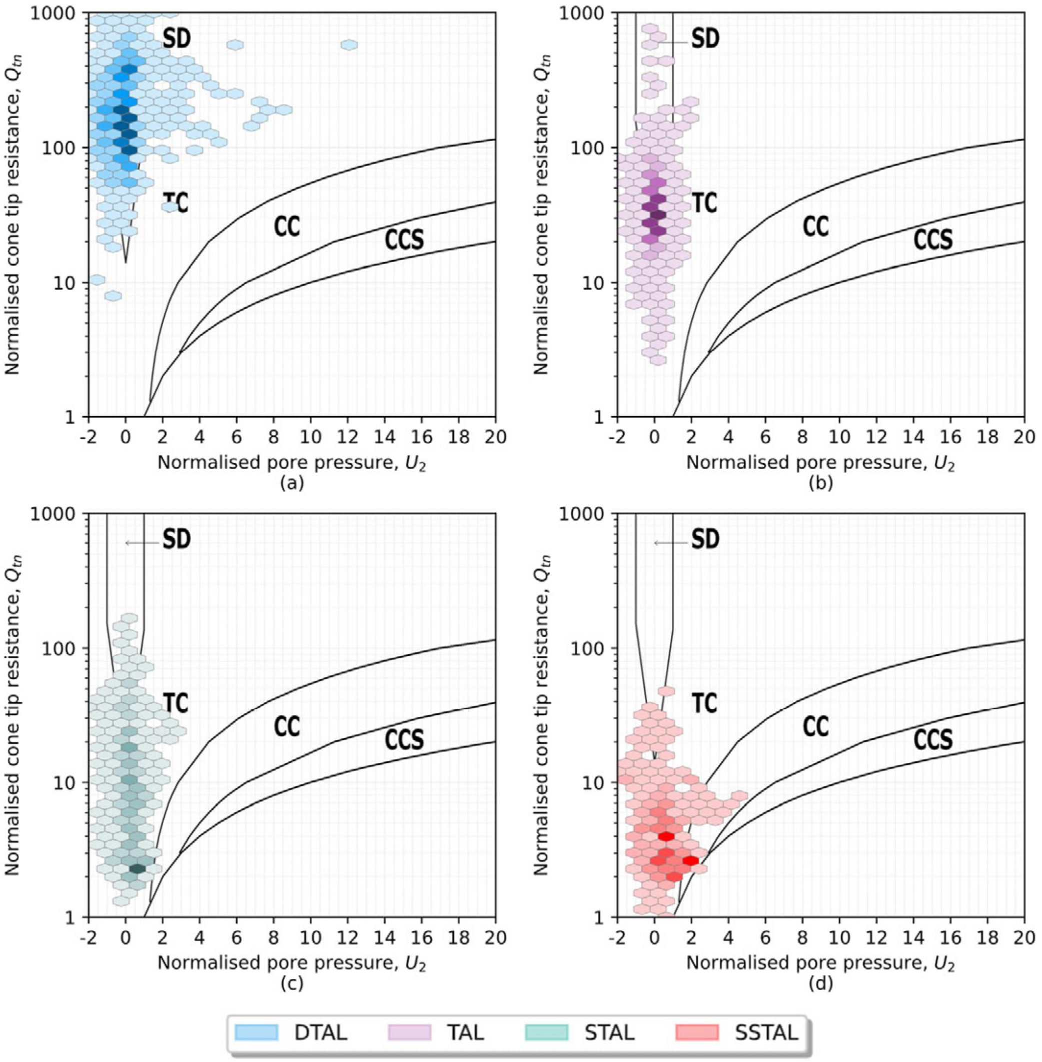

Figure 6: Schneider chart (Schneider 2008) for various tailings material; (a) Mechanically improved (DTAL) tailings (b) Sub-aerial (TAL) tailings (c) Sub-aqueous (STAL) tailings and (d) Sensitive sub-aqueous (SSTAL) tailings

4.2 CRITICAL STRESS FRICTION RATIO

Figure 7 and Figure 8 show the triaxial results displaying the deviatory stress against the mean effective stress. Figure 7 has the triaxial results categorised by tailings deposition method, while Figure 8 has the triaxial results categorised by fines content. As the CSL varies with fines content this second categorisation is useful for grouping the various CSLs derived from the triaxial results. The triaxial results also need to be considered in the context of the sample type. For the remoulded testing a more precise fines content could be targeted, whereas for the MBS the fines content has been approximated based on the PSD testing on the associated sample. However, the use of undisturbed testing does introduce some uncertainty regarding the fines content as the PSD test was conducted on a different part of the MBS as to the triaxial test. This uncertainty is considered minor in the scheme of things.

The critical state friction ratio, M, which is equal to the ratio of deviator stress to effective stress at the critical state, can be calculated from the triaxial test results. As such it is designated Mtc. Using triaxial compression as a reference case (M_{tc}) varies based depending on both deposition method and fines content. Here M_{tc} is obtained using the End of Test method commonly employed within the industry. While Bishop's Method (1971) or the Stress-Dilatancy Method is generally recommended (Ghafghazi and Shuttle, 2006) the lack of dense testing meant the End of Test method was more suitable. The trend of varying M_{tc} (and CSL) is well documented for fines content (Wood and Maeda, 2008). Interrogation of the results based on the tailings deposition method reveals that sensitive sub-aqueous and sub-aqueous tailings produces the lowest M_{tc} value ranging from 1.28 – 1.45 with the sub-aerial and mechanically improved tailings displaying a range of M_{tc} values from 1.53 – 1.64. This represents a difference of M_{tc} related to deposition method of between 7 – 12%.

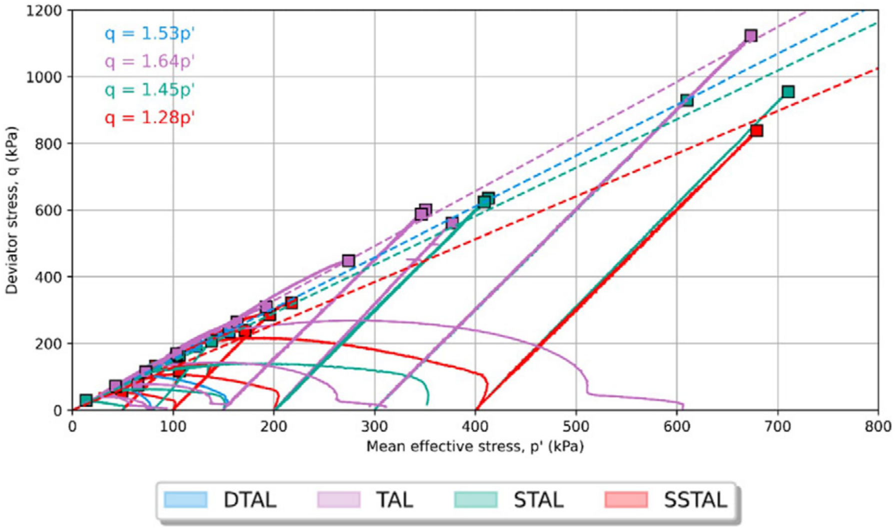

Figure 7: Triaxial test results showing deviator stress versus mean effective stress based on deposition method

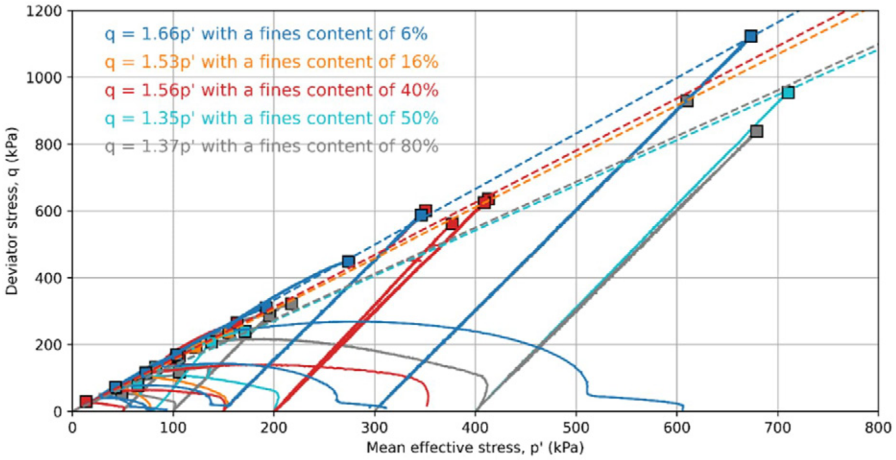

Figure 8: Triaxial test results showing deviator stress versus mean effective stress based on the fines content

Using the triaxial results categorised with fines content a correlation can be developed for M_{tc} based on the fines content, this relationship for the tailings material is shown in Figure 9. A decreasing trend of M_{tc} as fines content increases is shown with the slope being -0.0038. The decreasing trend is to be expected as the larger fines content tailings material was associated with the sub-aqueous deposition (and hence lower densities).

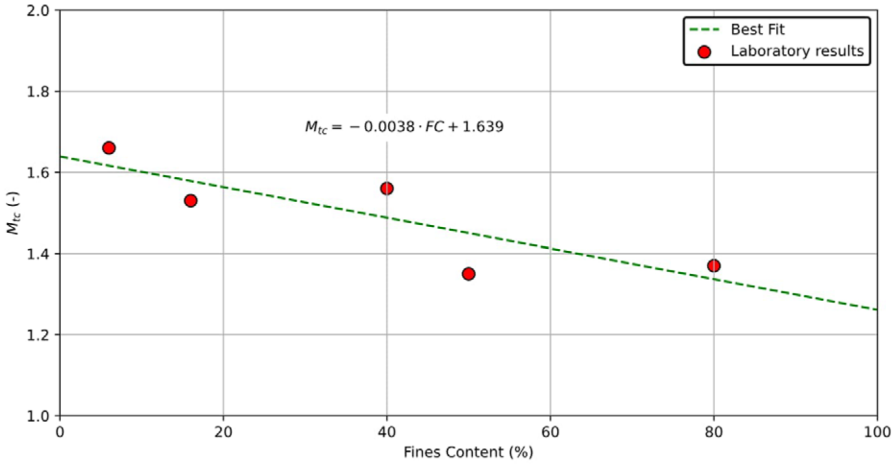

Figure 9: Critical State Friction Ratio (M_{tc}) versus Fines Content using laboratory results

4.3 CRITICAL STATE ANALYSIS

Using the triaxial test results, four CSLs in the compressibility plot were derived based on varying fines content (Figure 10). Several of the triaxial tests did not have end of test freezing implemented, these tests were not used to determine the CSLs as recommended by Reid et al. (2021). The CSLs encompass the tailings material with a fines content ranging from 6 – 80%. Using the four CSLs a region can be defined (Figure 11) where the CSL for an associated fines content between 6 – 80% can be anticipated to fall within this region. For a low fines content, the y-intercept (Γ, gamma) is 1.276 for 6% fines content. As the fines content increases Γ begins to decrease. At 40% fines content Γ is 1.007. With further increases in fines content Γ begins to increase rising to 1.058 for 50% fines content and reaching 1.195 at 80% fines content. Examining the four CSLs it can clearly be seen that the tailings material with the largest Γ has the largest slope (λ, lambda) and the tailings material with the smallest Γ has the smallest λ. This relationship suggests that the CSLs will converge at higher stress levels, which has previously been called the omega (Ω) point (Wood and Maeda, 2008) and hypothesized that it may occur with related soils. Computing the Ω-point for the CSLs produces a point at approximately *p'* = 8103 kPa and e = 0.38 for fines content 6%, 40% and 80%. The CSL for 50% does not fit neatly into this Ω-point location. However, obtaining a triaxial test to confirm the Ω-point would require an apparatus that goes up to 8MPa and be purely theoretical since the tailings will never experience loads near that value. Thus, this paragraph merely serves as an entertaining digression.

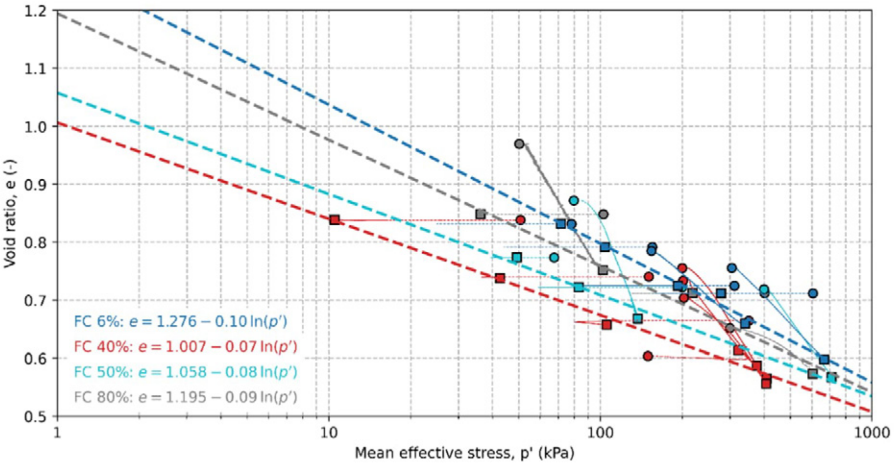

Figure 10: Critical state lines derived from the triaxial test results categorised by fines content

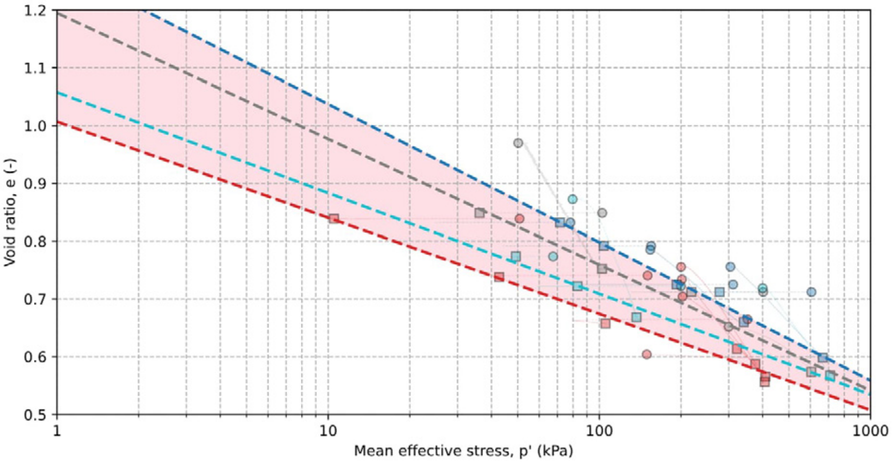

Figure 11: Critical state region defined between 6% fines content (Γ = 1.28) and 40% fines content (Γ = 1.01)

4.4 RELATING IN-SITU RESULTS TO THE CRITICAL STATE REGION

To relate the CPTu data to the CSL region, a site-specific calibration can be produced using the Soil Behaviour Type (Ic) determined from a CPTu and the laboratory PSD results from samples taken in proximity to that CPTu. The results for this form a site-specific calibration and are shown in Figure 12. Two other commonly adopted methods are shown as well, Boulanger and Idriss (2014) and Agaiby and Mayne (2020). The site-specific equation is shown in Equation (1).

$$FC = 13.83 \cdot \left(I_c^{\,1.47}\right) \tag{1}$$

The site-specific correlation is flatter than the more commonly used correlations, which indicates a wider range of potential behaviour resulting from a change in fines content than those soils that were used to develop these correlations. The advantage of a site-specific correlation as opposed to the more general correlation is that it will consider local characteristics such as grain properties, mineralogy and stress history, which all play a role in the potential behaviour of a soil. Agaiby and Mayne (2020) explored 53 well-documented geotechnical sites which would be anticipated to capture a wide range of behaviour types and that correlation more closely aligns with the site-specific correlation developed.

A limitation of creating a CSL region based on four CSLs is that there are only four discrete lines that are than extrapolated to cover an infinite number of potential CSLs. While multiple CSLs is an excellent step in the right direction, a material specific correlation can be developed relating fines content to both Γ and λ, shown in Figure 13 and Figure 14 respectively. For both functions a parabolic fit is utilised, reaching a coefficient of determination (R^2) value of 0.97 for Γ and 0.89 for λ, indicating that the data is an excellent fit for the function. This enables a more complete CSL region to be determined that can theoretically cover the entire range of fines content, shown in Figure 15. The model CSL region aligns well with the denser (dilative) side of the CSL region (lower CSL), however, the looser (contractive) side of the CSL region is considerably larger than the laboratory results indicate. There are potentially several reasons for this, such as the limitation of having a CSL at 80% fines content instead of 100% and the fact that there are limitations in preparing a loose sample in the laboratory for such high fines content.

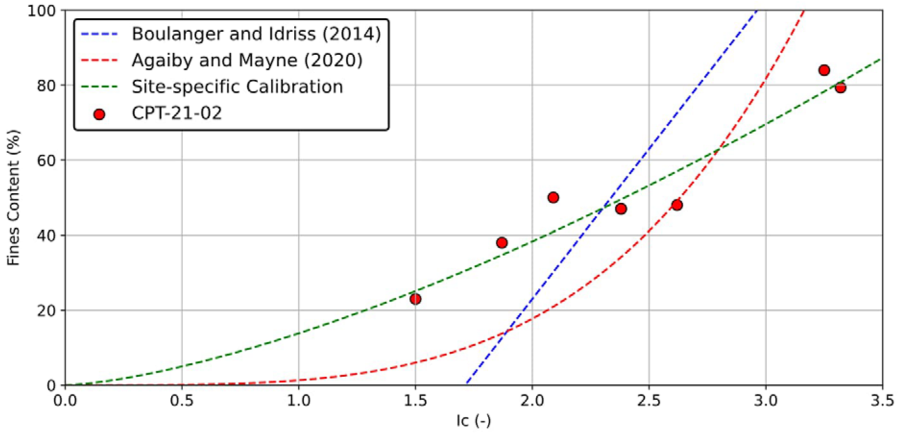

Figure 12: Site-specific fines content calibration

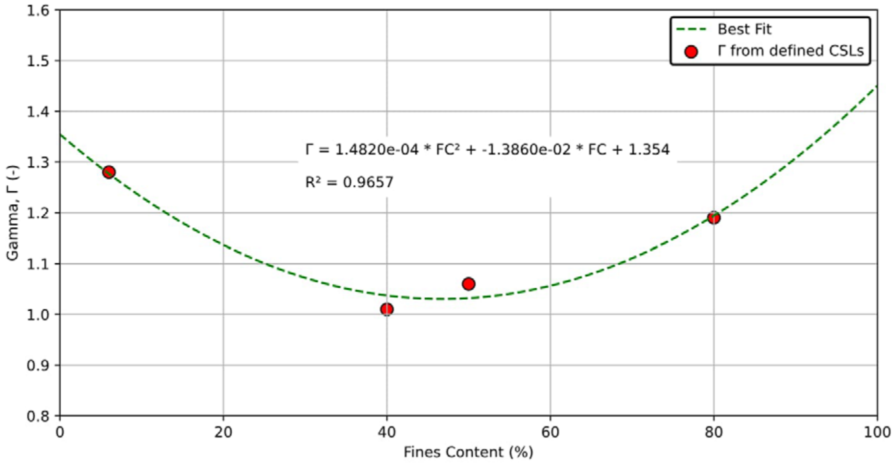

Figure 13: Gamma correlation based on the calculated result from the defined CSL

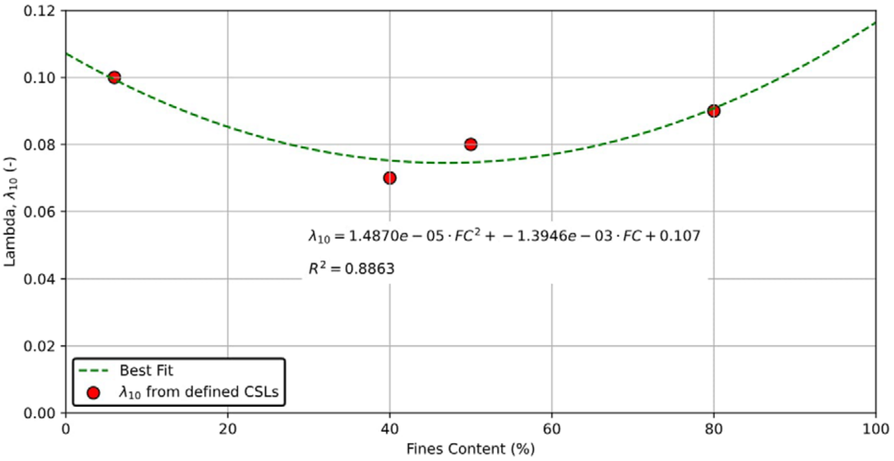

Figure 14: Lambda correlation based on the calculated result from the defined CSL

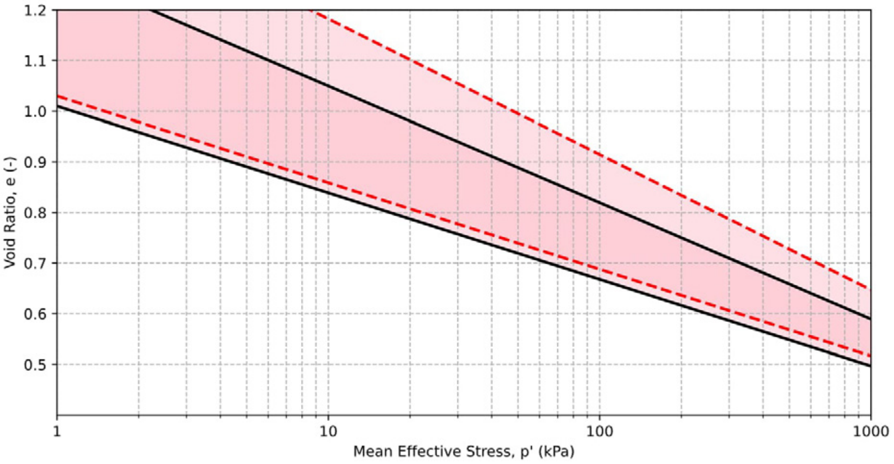

Figure 15: Laboratory region encompassed (black) CSLs function region based on four CSLs and generated (red) CSLs

With the CSL region defined and site-specific fines correlation for fines content developed, the CPTu data can now be plotted against the CSL region with each CPTu data point compared against the resultant CSL line within the CSL region. The comparison plot required the following assumptions: i) a K0 assumption of 0.6 to estimate the mean effective stress of each CPTu data point, and ii) A state parameter estimation using Jefferies and Been (2015) to determine the approximate void ratio for each CPTu datapoint. An example, the mechanically improved (DTAL) tailings is shown in Figure 16, the void ratio is approximately 0.52 when the mean effective stress is 15 kPa. For this data point the resultant CSL line points very near the lower bound of the CSL region. Data for sub-aerial (TAL) tailings is plotted in Figure 17, the mean effective stress is now approximately 38 kPa and the void ratio 0.64, the resultant CSL line has shifted upwards but is still nearer to the upper bound of the CSL region. The mean effective stress results from the CPTu's for the sub-aqueous (STAL) and sensitive sub-aqueous (SSTAL) tailings are shown in Figure 18 and Figure 19 respectively. Both STAL and SSTAL plot above the corresponding CSL, given how contractive this material has been shown, this is not surprising.

Figure 20 displays all the tailings data from the CPTu's with the CSL region shown. It is evident that a majority of the DTAL and TAL tailings can be expected to behave dilatively, with the STAL tailings moving closer to the CSL region, and the SSTAL tailings being majority within the CSL region, expected to be contractive.

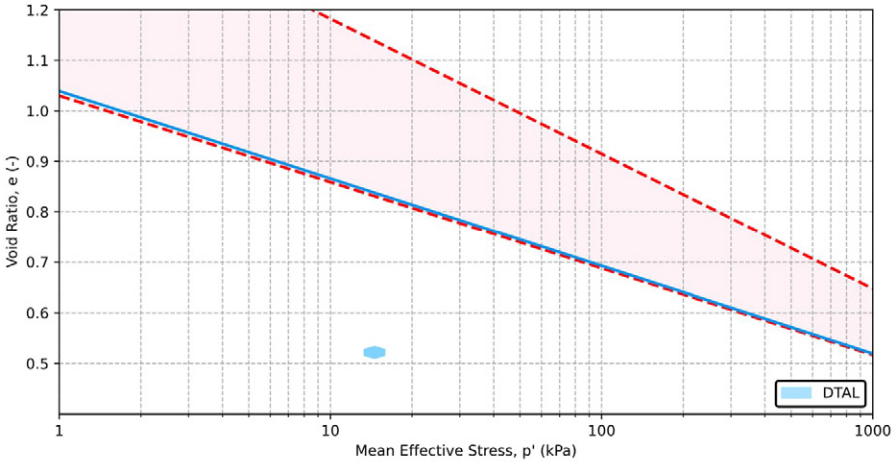

Figure 16: Modelled CSL region with example DTAL data point and corresponding CSL

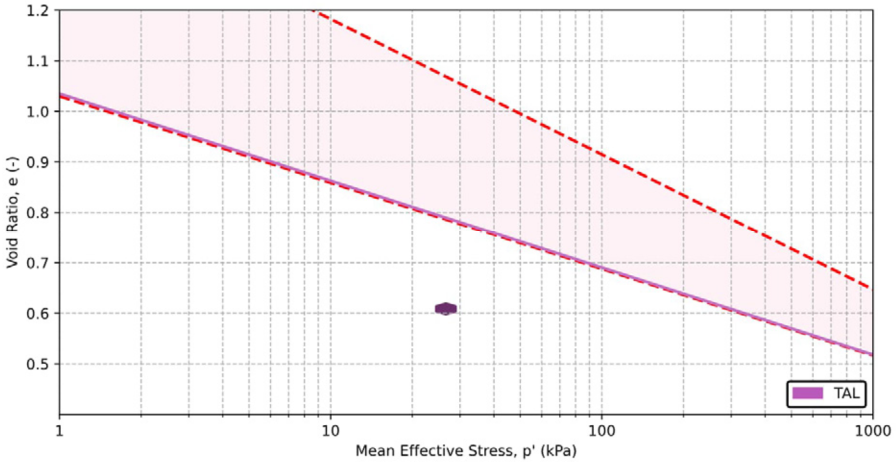

Figure 17: Modelled CSL region with example TAL data point and corresponding CSL

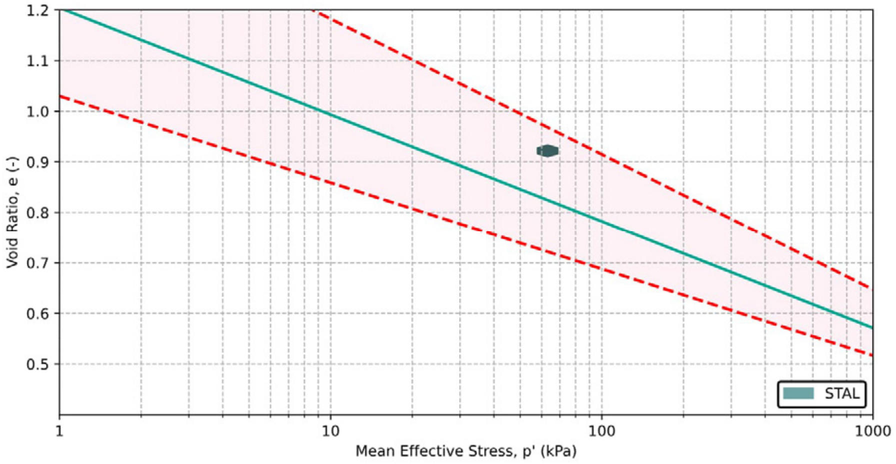

Figure 18: Modelled CSL region with example STAL data point and corresponding CSL

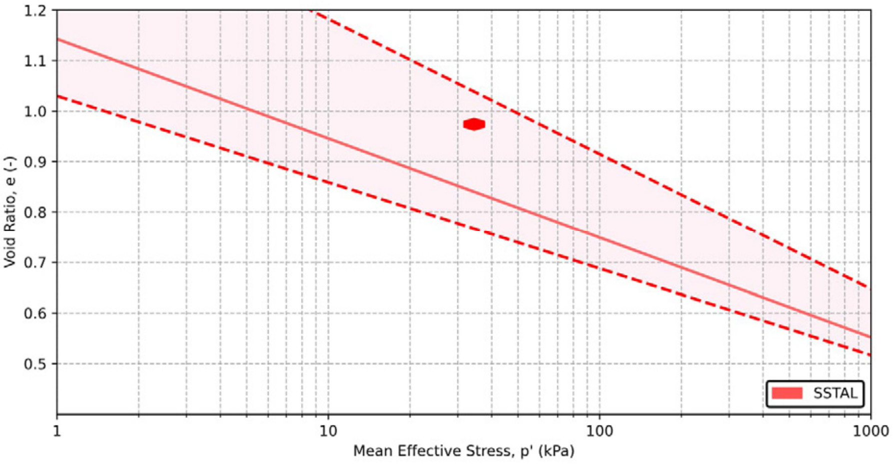

Figure 19: Modelled CSL region with example SSTAL data point and corresponding CSL

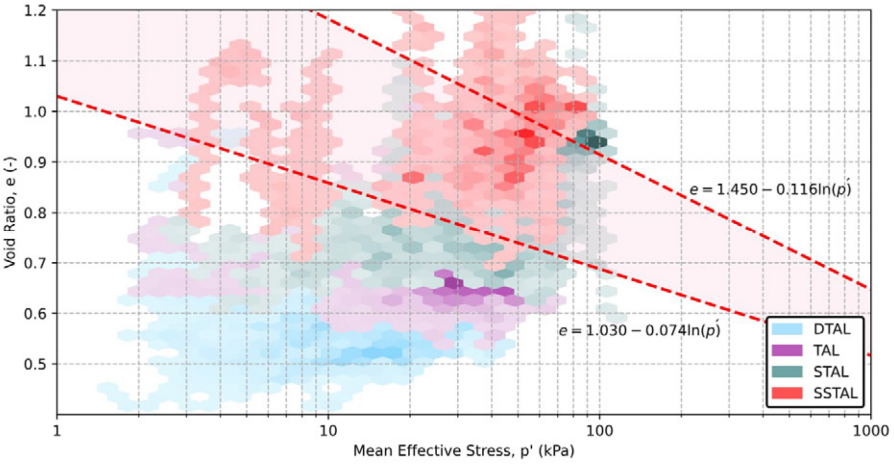

Figure 20: All CPTu results plotted over the modelled CSL region

5 DISCUSSION

The project from which these measurements were made is an upstream raised facility. As mentioned in Section 3, the TSF is a relatively young facility. This explains the low mean effective stresses of less than around 100 kPa derived from the CPTu's. The facility design philosophy considered using mechanical improvement techniques to build a structural zone, which would add resilience to the upstream raised facility. As the upstream raises continue to develop, it is expected that the mean effective stress will increase significantly causing a decrease in the void ratio. During site investigations for this TSF, MBS were retrieved, this sampling technique was utilised to minimise sample disturbance. A detailed explanation of the technique is beyond the scope of this paper but can be found in Lines et al. (2023). A total of 11 oedometer tests were performed on high quality MBSs, of which the apparent overconsolidation ratio (OCR) was calculated using the Casagrande methodology. The results indicated an apparent OCR range of 1.5 – 7.1 with a median of 2.4, indicating moderately overconsolidated tailings, most likely relating to the desiccation and microstructure present. The microstructure might be related to potential cementation well known in lateritic soils. The results suggests that some of the cementation/microstructure is regained after the tailings are deposited within the TSF and water contents are reduced via the mechanical improvement and/or crusting process. Therefore, the void ratios of the DTAL and TAL tailings are expected to follow an almost flat trend in the compressibility plot as they will follow the slope of the apparent overconsolidation line (i.e. recompression line, swelling or unloading index) on a void ratio-effective stress plot. Figure 20 is a representation of the effective stresses and void ratios estimated at the time when the CPTu surveys were conducted. With subsequent raises, the DTAL and TAL hexagon points will progressively migrate from the dilative region toward the right side of the figure and thus towards the contractive zone. An illustration of a CPTu data point of TAL and the direction and required mean effective stress increase to shift it to the CSL region is shown in Figure 21. For that specific CPTu data point an increase of approximately 120 kPa is required to relocate it from its current in situ state (dilative at the time of CPTu testing) to reach the CSL defined by its fines content. The distance between the CPTu data (each hexagon) and its corresponding CSL can be used to understand when a specific region of tailings is transitioning from a predominately dilative state to a predominately contractive state. The classification of contractive versus dilative states is useful because it helps define the type of strength parameters required for design e.g. drained strength versus undrained strength. Figure 22 displays a histogram of all the tailings material Ψ results with the dilative/contractive boundary (Ψ = -0.05) highlighted with a dashed black vertical (CDF) line. This boundary line has historically been used by practitioners to determine what type of strength parameters are more appropriate for design. Figure 22(c) shows that approximately 80% of STAL tailings data points are contractive (seen by the crossover of the CDF line and the dilative/contractive boundary). Figure 22(d) show that approximately 95% of SSTAL tailings are contractive. Using undrained shear strength to represent the strength of STAL and SSTAL is warranted based on these results. Figure 22(a) show that approximately 99% of DTAL tailings are dilative, which indicates that effective stress parameters are adequate for this unit, this might change in the future as subsequent raises increase the mean effective stress, a combination of Figure 20 and Figure 21 could be used to predict the amount of overburden required to reach this transition phase. This information is useful for designing the slope of subsequent upstream raise batters to limit the column of tailings deposited above the structural zone and providing knowledge as to when the tailings that are currently dilative may becoming contractive in the future. Figure 22(b) shows that around 80% of the TAL material is dilative and 20% is contractive. This result means that the parameter selection of TAL is not as straightforward and should be carefully considered.

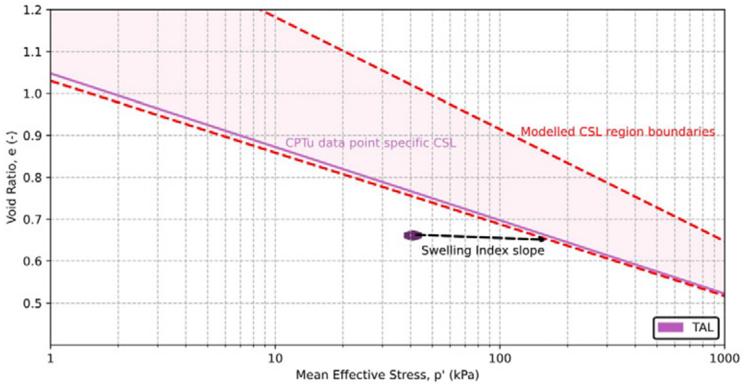

Figure 21: Illustration of TAL moving towards CSL region with increasing mean effective stress

The statistical descriptors of the state parameter estimated for each unit are summarised in Table 1. The coefficient of variation (CoV) provides insight into the relative variability of the Ψ across the different material types. A higher CoV suggests greater dispersion in the data, while a lower CoV indicates more uniformity. STAL tailings have the highest CoV (294%), meaning its Ψ values are highly variable, this CoV is larger than anticipated. In contrast, DTAL tailings have the lowest CoV (37%), suggesting that its Ψ values are relatively consistent, possibly due to the mechanical dewatering inducing a more uniform fabric. TAL and SSTAL exhibit intermediate CoV values (62% and 63%, respectively), indicating moderate variability in their state parameters. The dilative or contractive tendencies of each material can be examined using the mean ψ values, though this is a subjective threshold as a percentile may be more appropriate (i.e., a 20th percentile). However, using the mean values, DTAL (Ψ = −0.30) and TAL (Ψ = −0.10) exhibit values below the dilative/contractive threshold of ψ = -0.05, indicating dilative behaviour under shearing, with DTAL being the most dilative. STAL (Ψ = 0.03) and SSTAL (Ψ = 0.10) have mean values above the dilative/contractive threshold, meaning they are more contractive. The range of Ψ values across all the tailings types underscores their inherent variability, dependent on the deposition method, which must be carefully considered when assigning material parameters.

Table 1: Statistical summary of Ψ estimated for each tailings unit

	DTAL	TAL	STAL	SSTAL
Number of data points(n)	7,120	8,882	5,024	2,350
Minimum	-0.65	-0.40	-0.35	-0.16
Maximum	0.28	0.11	0.18	0.22
Mean	-0.30	-0.10	0.03	0.10
Std.	0.11	0.06	0.09	0.06
CoV (%)	37	62	294	63

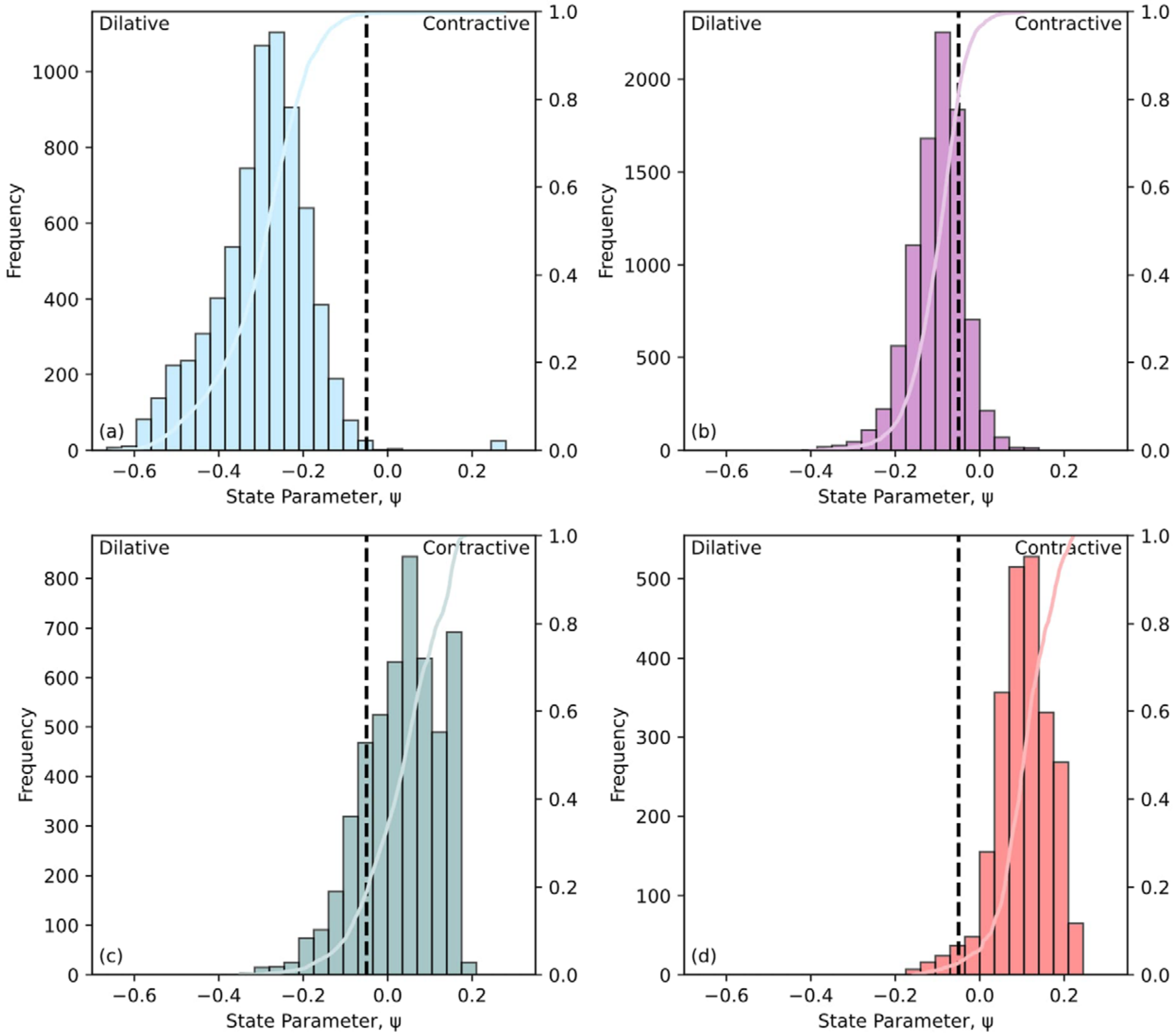

Figure 22: Histogram and CDF displaying distribution of State Parameter for each tailings category (a) DTAL (b) TAL (c) STAL and (d) SSTAL

6 SUMMARY AND CONCLUSIONS

A CPTu and laboratory investigation of tailings was undertaken on a relatively young TSF upon which mechanical improvement had recently commenced. Based upon the CPTu results and deposition methodology the tailings material was split into four groups. This included mechanically improved tailings, sub-aerially deposited tailings and two types of sub-aqueous deposited tailings. Following the site investigation a laboratory campaign was conducted with a focus on strength testing using compression triaxial. Four CSLs were developed based on fines content (5%, 40%, 50% and 80%). The CSLs displayed different slopes and intercepts, with the slopes trending towards an omega point and the intercepts varying with a decrease from 6% to 40% and then increase towards 50% and 80%. Material specific correlations for the critical state parameters M_{tc}, Ic, gamma and lambda were developed. Using the material specific correlations a CSL region generated. Using the fines correlation, the CPTu data was compared with the generated CSL region and the State Parameter estimated using Jefferies and Been (2015). On this basis the mechanically improved (DTAL) tailings were found to be 99% dilative and the sub-aerial (TAL) tailings approximately 80% dilative. Both sub-aqueously (STAL and SSTAL) tailings were found to be highly contractive, at approximately 80% for STAL and 95% for SSTAL. The variability of state parameters across tailings units shows that the deposition method and any subsequent de-watering effort such as mechanical improved has a significant impact on the potential behaviour of the tailings and whether it is dilative or contractive. Mechanical improvement of the tailings was also seen to reduce material variability which is desired from a reliability stand point. These results show the clear advantage mechanically improving can give regarding the increased strength and management of liquefactive potential. However, where mechanical improvement is not possible, sub-aerial deposition with appropriate drying times can offer a significant advantage over sub-aqueous deposition. These observations are anecdotally known by experienced tailings engineers.

The methods used in this paper provide a robust rational framework to demonstrate the effect of various tailings management practices on design outcomes. Proper deposition and pond management during operations are essential as they translate directly into strength and potential liquefaction behaviour. The plots and methods proposed here are expected to help designers use similar management strategies to plan the batters of subsequent raises based on the performance of the state parameters. For example, using the recompression index such as in Figure 21, engineers can forecast when units currently behaving as dilative can transition to contractive due to subsequent loading or upstream raises. This information is key to designing the slope of subsequent upstream batters and plan for long-term mechanical behaviour.

CRediT authorship contribution statement

Scott Lines: Writing - original draft. **Marcelo Llano-Serna**: Writing - Review and editing.

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