Influence of Fines Content on Interpretation of the CPT Tip Resistance for Liquefaction Assessment in Mine Tailings

Sartaj Gill, Edouardine-Pascale Ingabire, Vipulanantham Manmatharajan,
Morris Siu, Karl Peterson
Department of Civil and Mineral Engineering, University of Toronto, Toronto, Ontario, Canada
Keith Viles, Lawrence Clelland & Alex Sy
Klohn Crippen Berger, Vancouver, British-Columbia, Canada
Mason Ghafghazi
Department of Civil and Mineral Engineering, University of Toronto, Toronto, Ontario, Canada

ABSTRACT
Liquefaction assessment of mine tailings is currently done using empirical correlations that were developed with data mostly collected in natural soils; their applicability to tailings is yet to be proven. In-situ density represented by the state parameter is the key link between liquefaction susceptibility and the Cone Penetration Test (CPT) measurements that are commonly used to characterize tailings. Quantifying the interdependence of gradation, in-situ state parameter, and CPT measurements is a first step in developing tailings-specific liquefaction assessment methods.

In the current study, a tailings deposit comprised of silt and fine to medium sand was separated into its two enveloping particle size gradations. The gradations were then systematically mixed to identify the influence of particle size distribution on their properties. A series of triaxial compression tests were performed to determine how the friction angle, critical state line, and compressibility vary for each gradation. The results provide insights on the applicability of the fines content correction proposed in empirical CPT-based liquefaction correlations to silty mine tailings.

RÉSUMÉ
Actuellement, les analyses de potentiel de liquéfaction sont complétées en utilisant des relations empiriques développées à partir de données recueillies sur des sols naturels. Il n'a pas été prouvé que ces relations empiriques sont applicables pour les résidus miniers. La densité d'un sol peut être caractérisé à l'aide du *state parameter*. Le *state parameter* peut être évalué à partir des données mesurées lors d'un essai au piézocône, couramment utilisé pour caractériser les dépôts de résidus. Évaluer l'interdépendance entre la granulométrie, le *state parameter* et les données de piézocône constitue la première étape pour développer des méthodes d'analyse de liquéfaction qui soient spécifiques aux résidus miniers.

Dans la présente étude, plusieurs granulométries d'un dépôt de résidus miniers constitué de sable fin à moyen et de silt ont été créées. Des essais triaxiaux en compression ont été complétés pour déterminer de quelle manière la granulométrie influence l'angle de friction, la ligne d'état critique et la compressibilité. Les résultats sont utilisés pour discuter de l'applicabilité de la correction pour le pourcentage de particules fines proposée dans les méthodes empiriques pour l'évaluation du potentiel de liquéfaction.

1 INTRODUCTION

Tailings are by-products of the ore extraction process when mined rock is crushed into soil. Tailings are commonly composed of silty sand to silt and are discharged as slurry in tailings storage facilities (TSFs) contained by peripheral earth dams. TSFs are among the largest manmade features on earth that occupy vast swaths of land, reaching tens and sometimes hundreds of meters in height.

Liquefaction is the most common mechanism causing tailings dam failures. Catastrophes such as the one that occurred recently at Fundão tailings dam, Brazil (Morgenstern et al., 2016) are proof that improved methods are required to ensure stability of TSFs, and safety of the communities living near mine sites.

The current state of practice for liquefaction assessment requires penetration tests to estimate in-situ density of a deposit. The Cone Penetration Test (CPT) has become the predominant tool for site characterization in tailings, offering continuous data measurement, and excellent repeatability and accuracy. The difficulty, however, is that in-situ density is not directly measured, rather it must be interpreted from CPT tip resistance. Existing correlations are predominantly empirical and based on studies on natural clean to silty sands. The behaviour of silty soils is captured by a fines content correction (e.g. Boulanger and Idriss, 2014).

The applicability of the empirical liquefaction correlations to mine tailings lacks validation. Penetration resistance in mine tailings cannot be explained solely by the fines content correction. Mineralogy, particle shape, and plasticity are fundamental properties that influence tailings behaviour (Wijewickreme et al., 2005; Seidalinova, 2014). Furthermore, engineering properties, such as friction angle, and compressibility, that affect mechanical response of soil are often ignored in these empirical correlations.

The critical state approach, which uses a theoretically sound mechanistic framework, can be applied for liquefaction assessment of unconventional soils, such as mine tailings.

In this study, mine tailings were rigorously characterized in the laboratory. A series of tests were performed as part of a research project that aims at developing a tailings-specific framework for assessing liquefaction potential. The first step of this framework is to quantify the interdependence of gradation, in-situ state parameter, and CPT measurements. The methodology and the results of this first step are presented herein.

Mine tailings were separated into their two enveloping particle size distributions. Mineralogy and particle shape were characterized for these clean sand and pure silt gradations to identify any difference in their intrinsic properties. The gradations were then systematically mixed into five different tailings particle size distributions with fines contents of 0% 10%, 30%, 60%, and 100%. A series of drained triaxial compression tests were performed to determine how the CSL, compressibility, and friction angle vary with fines content. The results provide insights on the applicability of empirical CPT-based liquefaction correlations to silty mine tailings.

2 THE CRITICAL STATE APPROACH

The behaviour of cohesionless soils strongly depends on their density. While relative density (D_r) is a widely used density index, it is easy to show that it can be misleading (Tavenas, 1973). The state parameter (ψ) is an alternative to D_r, which captures the effects of both void ratio and confining pressure.

The state parameter is defined as the difference between the current void ratio (e) and the void ratio at critical state (e_{cs}), at the same mean effective stress (p') (Been and Jefferies, 1985). The critical state is the final state of a soil element sheared to very large strains, at which point it will continue to deform at constant void ratio, e_{cs}, constant mean effective stress, p'_{cs}, and constant deviator stress, q_{cs}. These e_{cs} and p'_{cs} values form a locus known as the Critical State Line (CSL) as illustrated in Figure 1. A semi-logarithmic linear representation is often used over p' ranges of 50 kPa to 1000 kPa, typical of most engineering problems.

The parameters that define the CSL in the $e - \log p'$ space are its intercept at p'_{cs}=1 kPa (Γ) and slope (λ_{10}). λ_{10} is associated with soil compressibility. The subscript 10 specifies that it is evaluated on a base 10.

$$e_{cs} = \Gamma - \lambda_{10}\log(p'_{cs}) \quad [1]$$

M_{tc} is the critical shear stress ratio, with the subscript 'tc' denoting the triaxial compression condition and is analogous to the critical state friction angle (φ_{cs}). M_{tc} also describes the CSL in $q - p'$ space:

$$M_{tc} = \frac{q_{cs}}{p'_{cs}} \quad [2]$$

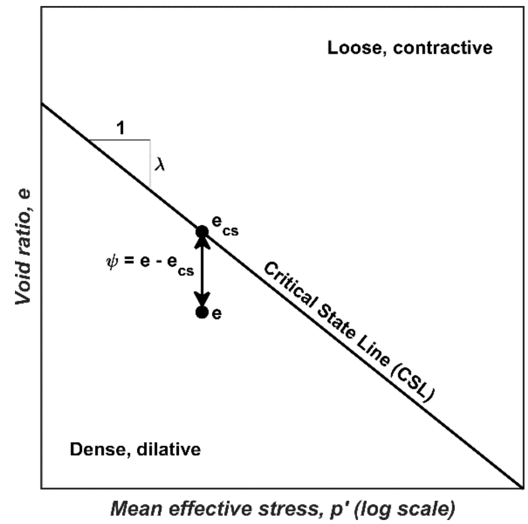

Figure 1. Definition of the critical state line and state parameter.

The value of ψ controls soil behaviour. Dense dilative soils have a negative ψ, while loose contractive soils have a positive ψ. Resistance of a given soil to static and cyclic liquefaction is uniquely related to the state parameter (Jefferies and Been, 2015).

3 EXPERIMENTAL PROGRAM

3.1 Material Tested

Mine tailings from a deposit in Sudbury, Ontario referred to as Base Metal Tailings were tested. Upon receiving bulk samples, the tailings were dried and sieved. The material is comprised of silt and medium to fine sand.

The fines were characterized as non-plastic through attempts at determining the Atterberg limits, following ASTM D4318. The specific gravity (G_s) was determined to be equal to 2.93 for both sand and silt gradations, following ASTM D854.

Five gradations of the Base Metal Tailings were created, with fines content (FC) of 0%, 10%, 30%, 60% and 100%. The sand-silt mixtures were created to ensure the materials are not gap-graded, better representing the field deposits. The grain size distributions of the five gradations are shown in Figure 2.

Maximum and minimum void ratios (e_{max} and e_{min}) were measured for each gradation following ASTM D4253 and ASTM D4254, with the exception of applicability to fines contents greater than 15%. The measured e_{max} and e_{min} values are illustrated in Figure 3. The initial decrease and then increase in void ratio as the fines content increases from 0% to 100% reflect the soil structure changing from a sand-dominated mixture to a silt-dominated mixture. Similar trends have been found by other researchers (e.g. Papadopoulou and Tika, 2008).

3.2 Particle Shape and Mineralogy

Mineralogy and particle shape were characterized for the clean sand and pure silt gradations.

Particle shape was determined by photographing particles under a petrographic microscope. Soil particles were placed on a microscope slide and immersed in a few drops of mineral oil. A cover slip was placed on top and images of the grains were captured. Petrographic microscope images of particles are shown in Figure 4. Both sand and silt-sized particles are sub-angular to angular.

Mineralogy was determined by preparing thin-sections of each gradation and observing them under a scanning electron microscope. The results of the scanning electron microscope analysis indicate that the main mineralogical components of the Base Metal Tailings are quartz, feldspar, pyrite, and ilmenite with no noticeable difference between coarse and fine fractions.

3.3 Triaxial Testing

The critical state parameters were determined for the five particle size gradations through 29 drained triaxial compression tests. For each gradation, three to five loose tests were conducted to determine their CSL. In addition, up to three dense tests were conducted to determine M_{tc}. The testing program is summarized in Table 1.

3.3.1 Specimen preparation

Specimens were reconstituted by moist tamping to achieve a wide range of initial void ratios. The diameter and height of the specimens were 50 mm and 105 mm, respectively.

Specimens were prepared in six layers using the under-compaction technique (Ladd, 1978) to minimize non-uniformity. Each layer was prepared to 5% water content for gradations with fines between 0% and 30%, and 10% water content for gradations with higher fines content. Each layer was deposited using a funnel and gently tamped to the desired void ratio. The top of each layer was scarified prior to placement layers. Frictionless end platens were used at the top and bottom of the specimens. CO_2 was flushed through the specimen at a low rate during specimen preparation to minimize the amount of air in the specimen.

3.3.2 Testing Procedures

After specimen preparation, a 20 kPa confining pressure was applied and more CO_2 was flushed through the specimen for an hour. Approximately 20 litres of de-aired water was then flushed through the specimen. Specimens were back pressurized to ensure B-values greater than 0.96 were obtained. They were then isotropically consolidated to confining pressures between 50 kPa and 400 kPa, and sheared using displacement-controlled loading at a rate of 5% axial strain per hour. Volume change, pore pressure, load, and displacement were measured during shearing.

After each test was completed, the back pressure and pore pressure valves were closed to ensure no loss of water. The cell pressure was slowly decreased to 0 kPa and the specimen was unloaded. To accurately measure the void ratio at the end of the test, the specimen and cell base were placed in a freezer for three hours. The specimen was removed from the membrane and weighed. It was then placed into an oven overnight. The dry weight of the specimen was measured, and the void ratio was calculated.

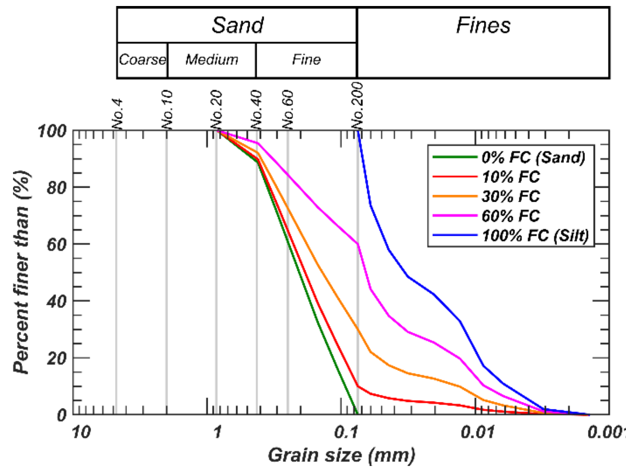

Figure 2. Grain size distribution of Base Metal Tailings.

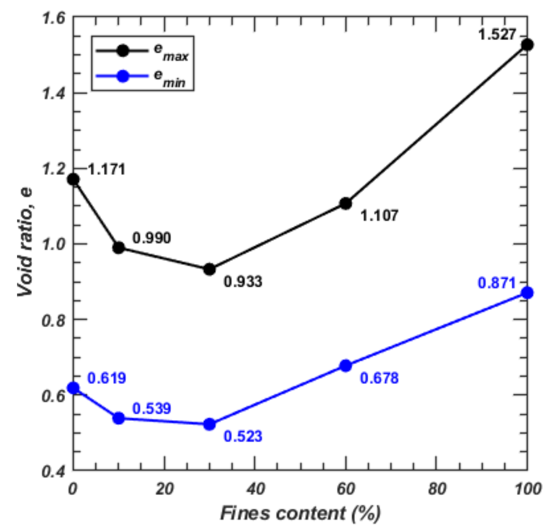

Figure 3. Maximum and minimum void ratio, e_{max} and e_{min}, of the five Base Metal Tailings gradations

Table 1. Testing program for drained triaxial compression tests for Base Mine Tailings.

Fines content (%)	No. of tests	Range of initial void ratio, e	Range of mean effective stress, p'(kPa)
0 (Sand)	7	0.84 – 1.07	50 – 350
10	6	0.75 – 1.02	50 – 400
30	7	0.69 – 0.89	75 – 400
60	3	0.85 – 0.99	50 – 250
100 (Silt)	6	0.92 – 1.20	50 – 250

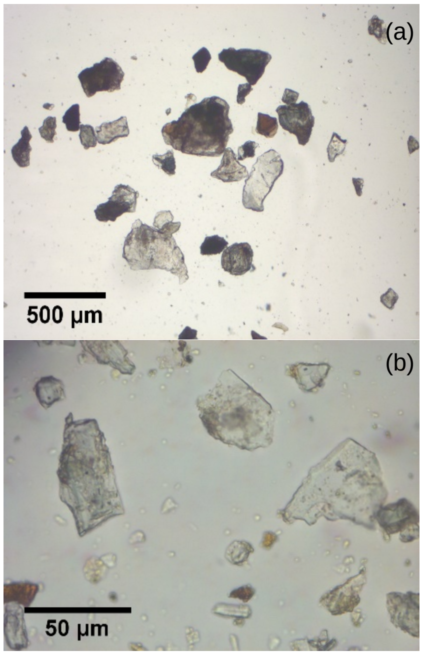

Figure 4. Images of Base Metal Tailings taken under a petrographic microscope (a) clean sand (b) silt.

4 EVALUATION OF CRITICAL STATE PARAMETERS

Figure 5 presents the results of drained triaxial compression tests for the Base Metal Tailings gradation with 0% fines content (clean sand). Figure 5a and 5c show the volumetric strain (ε_v) and the stress ratio (η) versus axial strain (ε_a), respectively. The stress ratio is defined as

$$\eta = \frac{q}{p'} \qquad [3]$$

In Figures 5a and 5c , a specimen is at critical state if the values of η and ε_v have reached a constant value. Figures 5b and 5d illustrate the CSL in $e - \log(p')$ and $q - p'$ space. The values of λ_{10} and Γ are directly interpreted from Figure 5b.

M_{tc} is evaluated by analyzing the stress dilatancy behaviour, as suggested by Bishop (1966). Dilatancy (D) is calculated as

$$D = -\frac{\dot{\varepsilon_v}}{\dot{\varepsilon_q}} \qquad [4]$$

where $\dot{\varepsilon_v}$ and $\dot{\varepsilon_q}$ are increments of volumetric and deviator strain, respectively.

In Figure 6, D is plotted against η for Test #20 to determine the maximum stress ratio (η_{max}) and peak measured dilatancy (D_{min}); the subscript 'min' being an artifact of the compression positive sign convention. Test #20 was conducted on a dense specimen of 0% FC Base Metal Tailings, as shown in Figure 5. Note that η_{max} and D_{min} occur at the same point during the test, represented with a green marker in Figure 6. In Figure 7, the values of η_{max} and D_{min} are plotted for each triaxial compression test conducted on 0% FC Base Metal Tailings. A line is fitted through the data. M_{tc} is the intercept of the fitted line at D_{min}= 0, which corresponds to the critical state.

Following the process described above, the critical state parameters (Γ, λ_{10}, and M_{tc}) were determined for all five gradations. The parameters are presented in Table 2. The critical state friction angle (φ_{cs}) was calculated using equation [6] is also presented in Table 2.

$$\sin\varphi_{cs} = \frac{3M_{tc}}{6+M_{tc}} \qquad [6]$$

The CSLs for all five gradations are illustrated in Figure 8. The CSL for the silt tailings (FC = 100%) is significantly steeper than the CSL of the sand tailings (FC = 0%). The value of λ_{10} for the silt tailings is almost twice greater than that of the sand tailings. The greater value of λ_{10} is an indication that the silt tailings are more compressible than the sand tailings.

For fines content between 0% and 30%, there is a downward shift of the CSL but no significant change in the slope. Γ decreases with increasing fines content and λ_{10} is practically constant. At FC = 60%, the CSL becomes parallel to the CSL of the silt tailings. For these two gradations, Γ increases with increasing fines content and λ_{10} remains constant.

M_{tc} is largely unaffected by particle size distribution. For both clean sand and pure silt tailings M_{tc} = 1.46. M_{tc} for the intermediate gradations is slightly higher (1.49 to 1.52). The differences are within the accuracy ranges identified by Ghafghazi and Shuttle (2009).

The effect of gradation on the CSLs can be explained by understanding how an external load applied to a soil is transferred within individual particles. In a sand-silt mixture, at lower fines content, coarser particles will carry the load and finer particles merely fill the voids. As the fines content increases, the voids are filled, and fines become part of the load-carrying soil matrix by separating the coarser particles and occupying the space among them. Earlier research shows that this transition happens when fines content exceeds 25% to 45% of the total mass, with the exact threshold being material specific (e.g. Polito and Martin, 2001). The results presented in Figure 8 are in agreement with this mechanism. The Base Metal Tailings transition from sand-like to silt-like behaviour somewhere between

Table 2. Critical state parameters for Base Metal Tailings.

Fines content (%)	Γ	λ_{10}	M_{tc}.	φ_{cs}(°)
0	1.28	0.160	1.46	36.0
10	1.24	0.160	1.49	36.6
30	1.10	0.145	1.52	37.3
60	1.41	0.270	1.50	36.9
100	1.70	0.300	1.46	36.0

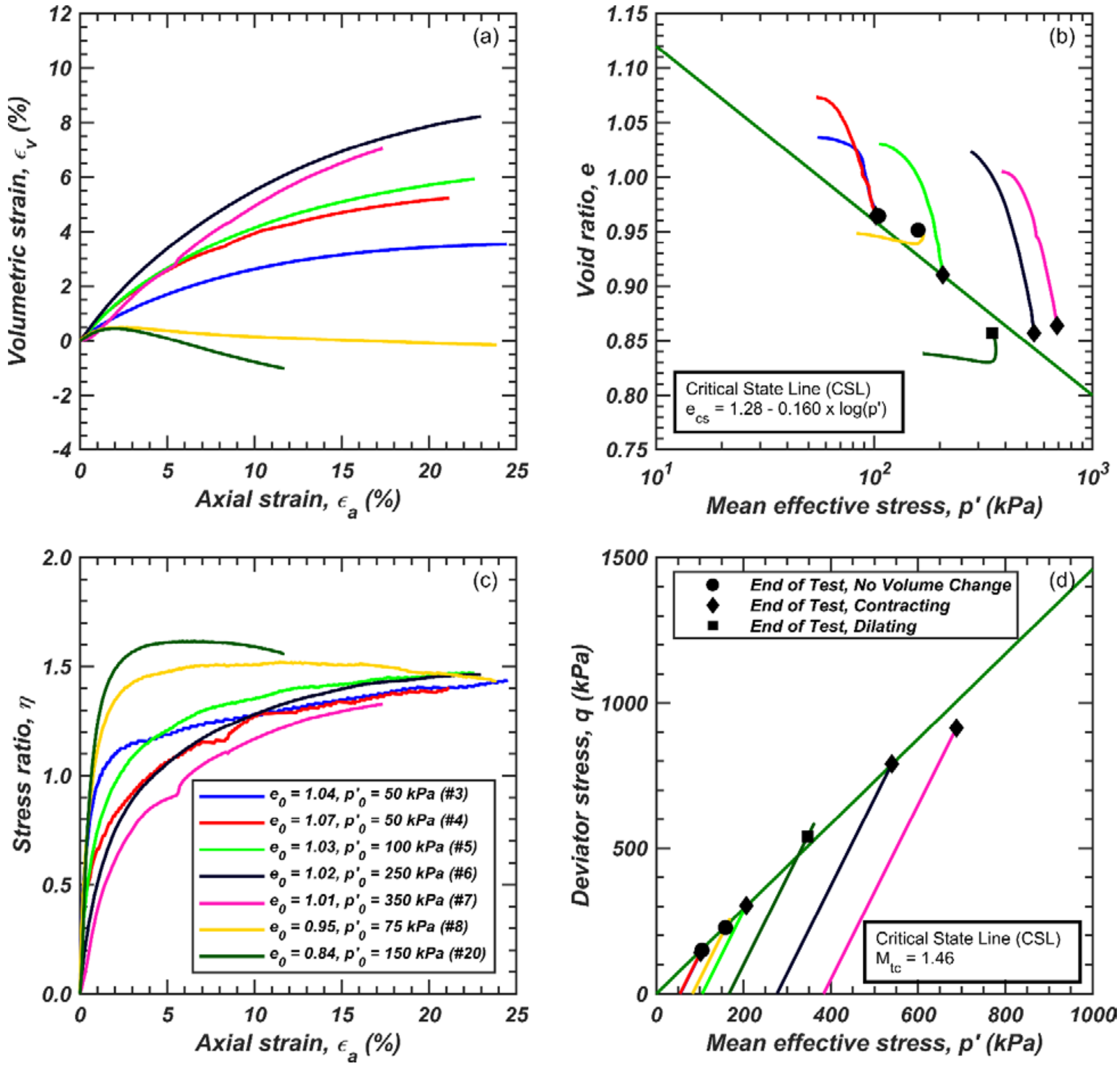

Figure 5. Results of drained triaxial compression tests conducted on Base Metal Tailings with 0% fines content (a) volumetric strain, ε_v, vs axial strain, ε_a, (b) void ratio, e, vs mean effective stress, p', (c) stress ratio, η, vs axial strain, ε_a, (d) deviator stress, q, vs mean effective stress, p'.

30% FC and 60% FC. The transition is gradual for the Base Metal Tailings, given the fact that the tailings tested are not gap-graded.

Olson and Stark (2003) noted a similar increase in the value of λ_{10} as fine particles are added to a sand. However, the study suggested that the effect of grain angularity is as important as the fines content. In the current study, for the Base Metal Tailings, particle shape is similar for all the gradations tested, so the change in λ_{10} is caused solely by the increase in fines content.

Carrera et al. (2011) studied the effect of particle size distribution on four gradations of tailings with fines content between 0% and 100%. Their data also show that M_{tc} remains relatively unchanged for materials with a similar mineralogy and particle shape, regardless of the fines content. For the Base Metal Tailings, there is no influence of fines content on M_{tc}, thus confirming this observation.

5 BACKGROUND ON CONE PENETERATION

The cone penetration test with pore water pressure measurements (CPTu) provides three measurements: tip resistance (q_t), sleeve friction (f_s), and pore pressure (u_2).

Initial work performed to determine ψ from CPT data included calibration chamber testing on sands for which CSL parameters were known. Chamber test data were processed to develop dimensionless relations of the form:

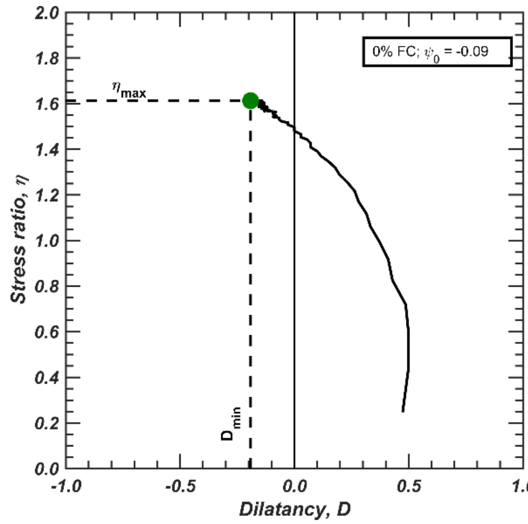

Figure 6. Stress ratio, η, versus dilatancy, D, for a drained triaxial compression test on a dense specimen of Base Metal Tailings with 0% fines content (Test #20).

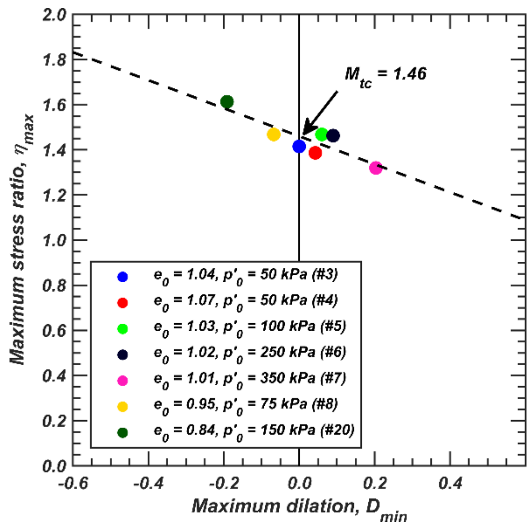

Figure 7. Maximum stress ratio, η_{max}, versus maximum dilatancy, D_{min}, for triaxial compression tests conducted on Base Metal Tailings with 0% fines content.

$$Q_p(1 - B_q) + 1 = \bar{k}\exp(-\bar{m}\psi) \quad [7]$$

where Q_p is the tip resistance normalized by the mean effective stress and B_q is the normalized pore water pressure (Been et al., 1988). B_q provides an index for the drainage conditions during cone penetration by comparing the measured pore pressure (u_2) to the hydrostatic pressure (u_0).

$$Q_p = \frac{q_t - p}{p'} \quad [8]$$

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \quad [9]$$

The two coefficients $\bar{k}$ and $\bar{m}$ in equation [7] depend on λ_{10} and M_{tc}, making the relation between Q_p and ψ soil-specific (Jefferies and Been, 2016).

$$\frac{\bar{k}}{M_{tc}} = 3 + \frac{0.85}{\lambda_{10}} \quad [10]$$

$$\bar{m} = 11.9 - 13.3\lambda_{10} \quad [11]$$

6 INFLUENCE OF FINES CONTENT ON CPT TIP RESISTANCE

The differences in soil behaviour observed by interpretation of the laboratory results are attributed to the variation in the particle size distribution of each Base Metal Tailings gradation. As such, a transition from sand-like to silt-like behaviour was identified for a fines content between 30% and 60%. The sandy tailings (FC < 30%) exhibited a similar behaviour, captured by a similar value in λ_{10}. The silty tailings (FC > 60%) have a greater compressibility, expressed by a significant increase in λ_{10}.

This transition in soil behaviour results in a decrease of the tip resistance for silty tailings, as illustrated in Figure 9. This figure illustrates the relation between the normalized tip resistance (q_{t1N}) and ψ for a drained cone penetration (B_q = 0). The subscript '1N' indicates that q_t is corrected to an equivalent value measured at σ'_v = 100 kPa, and further normalized by the atmospheric pressure.

q_{t1N} is obtained by converting Q_p to Q, which is the tip resistance normalized by the vertical effective stress. Q_p and Q are related through the coefficient of lateral earth pressure at rest (K_0).

$$q_{t1N} = \frac{C_N q_t}{P_a} = \frac{q_t}{P_a}\left(\frac{P_a}{\sigma'_{vc}}\right)^m \quad [12]$$

$$Q = \frac{Q_p\,(1+2K_0)}{3} \quad [13]$$

$$Q = \frac{q_t - \sigma_v}{\sigma'_v} \approx \frac{q_t}{\sigma'_v} \quad [14]$$

K_0, was estimated using the Jacky (1944) equation ($K_0 = 1 - \sin\varphi$) and φ_{cs} values. For discussion, a stress level of σ'_v= 100 kPa is assumed, such that the value of the overburden correction factor, C_N, is 1.0. Thus, Q is equal to q_{t1N}. In Figure 9, there are two groups of curves, with q_{t1N} being reduced by half when transitioning from the sandy to the silty tailings. The liquefaction triggering curves proposed by Boulanger and Idriss (2014) indicate a

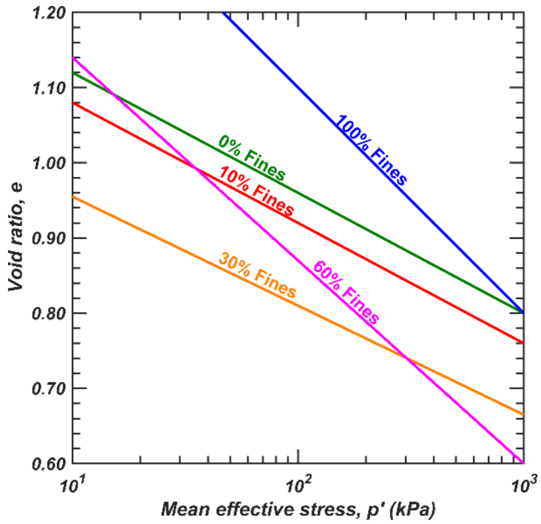

Figure 8. Critical state lines in $e - \log(p')$ space for Base Metal Tailings with varying fines content.

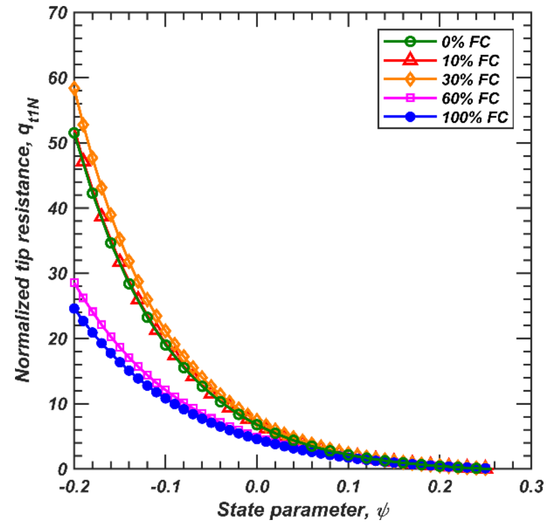

Figure 9. Influence of Fines Content on $q_{t1N} - \psi$ relation (drained penetration, σ_v'= 100 kPa).

reduction of q_{t1N} in the same order of magnitude between clean sands (FC ≤ 5%) and sandy silts (FC ≥ 70%).

The effect of drainage conditions is not captured in Figure 9, as penetration is assumed to be drained for all gradations. Partially drained and undrained conditions will typically result in a decrease in q_{t1N} (Jaeger, 2010). It can be expected, as such, that a progressive downward shift of the $q_{t1N} - \psi$ curves would be observed as the fines content increases from 0% to 100%, and drainage conditions transition from fully drained to fully undrained. Nevertheless, the jump in q_{t1N} values between the 30% FC and 60% FC gradations will likely remain.

Arguably, when evaluating q_{t1N} within the critical state framework, the overburden correction is unnecessary since its influence is captured by ψ. There is also no need for a fines content correction because any influence of the material properties is captured by parameters such as λ_{10} and M_{tc}, among others, that capture soil behaviour.

The correlations presented in equations [10] and [11] to evaluate $\bar{k}$ and $\bar{m}$ were developed as a first approximation of the dimensionless parameter group $Q_p\left(1 - B_q\right) + 1$, but it provides a good basis to quantify the interdependence of gradation, in-situ ψ, and CPT measurements. Ghafghazi and Shuttle (2008) demonstrated that $\bar{k}$ and $\bar{m}$ can be assessed through numerical modeling, resulting in a more accurate estimation of ψ.

The work performed in the current study follows the recommendations of Been (2016) for evaluating engineering properties of mine tailings. This can appear as a big investment in effort, time, and cost during the design phase, but provides the necessary parameters for sound and scientifically defensible liquefaction assessment in mine tailings and presents the potential for significant cost savings and/or increased safety in implementation.

Plewes et al. (1992) and Been and Jefferies (1992) have proposed empirical relations for a preliminary assessment of λ_{10} from CPT data. Certain case studies suggest that these correlations result in an adequate

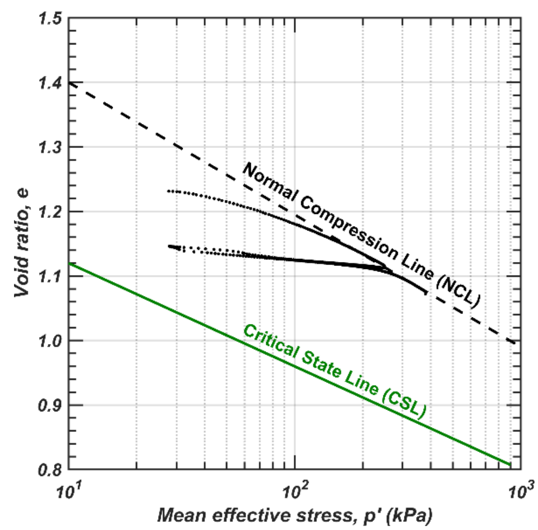

Figure 10. Comparison of CSL and NCL for 0% fines content Base Metal Tailings.

approximation of the in-situ ψ (Been et al, 2012). However, these correlations present a lot of scatter, particularly for tailings (Reid, 2014).

A simpler method of estimating λ_{10} could be by performing one-dimensional consolidation tests. K_0 consolidation tests were conducted as part of the characterization of the Base Metal Tailings and the results suggest that for all the five gradations, the slope of the normal compression line (NCL) for consolidation tests performed on loose samples is parallel to the CSL. One example is illustrated in Figure 10 for the 0% FC tailings. Similar observations were reported in literature on a variety of clean and silty sands to silts (e.g. Olson and Stark, 2003). Further research on the matter would be needed, but consolidation tests appear to be a promising inexpensive and quick means of estimating λ_{10} for CPT interpretation.

7 CONCLUSIONS

The engineering properties of a tailings deposit from Sudbury, Ontario were characterized through index tests, and drained triaxial compression tests. The differences in soil behaviour observed by interpretation of the laboratory results were attributed to the variation in the particle size distribution. Sandy tailings with fines content of 0%, 10%, and 30% exhibited similar behaviour, captured by a similar value in λ_{10} and M_{tc}. Silty tailings with fines contents of 60% and 100% have greater compressibility, expressed by a significant increase in λ_{10}. The transition from sand-like to silt-like behaviour was identified to occur between 30% and 60% fines content.

Interpretation of the laboratory results suggests a decrease in CPT tip resistance, q_{t1N}, at identical state parameters, ψ, when transitioning from sand-like to silt-like behaviour and ignoring the effects of drainage conditions. Future work will include detailed numerical modelling of the CPT penetration in tailings and incorporating the effects of drainage conditions.

8 ACKNOWLEDGEMENTS

The authors greatly appreciate the financial support of Klohn Crippen Berger, Ontario Centres of Excellence (project 27337) and NSERC (EGP 506108-2016).

9 REFERENCES

American Society for Testing and Materials, "D4253 - Maximum Index Density and Unit Weight of Soils Using a Vibratory Table".

American Society for Testing and Materials, "D4254 - Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density".

American Society for Testing and Materials, "D4318 - Liquid Limit, Plastic Limit, and Plasticity Index of Soils".

American Society for Testing Materials, "D854 - Specific Gravity of Soil Solids by Water Pycnometer".

Been, K. 2016, "Characterizing Mine Tailings for Geotechnical Design", *Australian Geomechanics*, vol. 51, no. 4, pp. 59-78.

Been, K. & Jefferies, M. 1985, "A State Parameter for Sands", *Géotechnique,* vol. 35, no. 2, pp. 99-112.

Been, K., Crooks, J.H.A. & Jefferies, M.G. 1988, "Interpretation of Material State from the CPT in Sands and Clays", Penetration Testing in the UK., Thomas Telford, London, pp.89-92

Been, K., Romero, S., Obermeyer, J. & Hebeler, G. 2012, "Determining in situ state of sand and silt tailings from the CPT", *Tailings and Mine Waste '12*, pp. 325

Been, K. & Jefferies, M. 1992, "Towards Systematic CPT Interpretation", *Predictive Soil Mechanics: Proc. Wroth Memorial Symp.*, pp. 121.

Bishop, A.W. 1966, "Sixth Rankine Lecture: Strength of soils as engineering materials", *Géotechnique,* vol. 16, no. 2, pp. 91-130.

Boulanger, R.W. & Idriss, I.M. 2014, "CPT and SPT Based Liquefaction Triggering Procedures", No. UCD/CGM-14/01, University of California, Davis, California.

Carrera, A., Coop, M. & Lancelotta, R. 2011, "Influence of Grading on the Mechanical Behaviour of Stava Tailings", *Géotechnique*, vol. 61, no. 11, pp. 935-946.

Ghafghazi, M. & Shuttle, D. 2008, "Interpretation of sand state from cone penetration resistance", *Géotechnique*, vol. 58, no. 8, pp.623-634.

Ghafghazi, M. & Shuttle, D. 2009, "Confidence and accuracy in determination of the critical state friction angle", *Soils and Foundations,* vol. 49, no. 3, pp. 391-395.

Jaeger, R.A., DeJong, J.T., Boulanger, R.W., Low, H.E. & Randolph, M.F. 2010, "Variable Penetration Rate CPT in an Intermediate Soil", *CPT '10: 2nd Int. Symp. Cone Penetration Test*, 9-11 May 2010, Huntington Beach, CA.

Jaky, J. 1944, "The Coefficient of Earth Pressure at Rest, In Hungarian "A Nyugalmi Nyomas Tenyezoje", *J. Soc. Hung. Eng. Arch*. (Magyar Mernok es Epitesz-Egylet Kzlonye), pp. 355-358.

Jefferies, M. & Been, K. 2016, *Soil Liquefaction: a Critical State Approach*, 2nd ed, CRC Press.

Ladd, R.S. 1978, "Preparing Test Specimens Using Undercompaction", *Geotech. Testing J.,* vol. 1, no. 1, pp. 16-23.

Morgenstern, N.R., Vick, S.G., Viotti C.B., Watts, B.D., 2016. Report on the Immediate Causes of the Failure on the Fundão Dam.

Olson, S.M. & Stark, T.D. 2003, "Use of Laboratory Data to Confirm Yield and Liquefied Strength Ratio Concepts", *Can. Geotech. J.,* vol. 40, pp. 1164-1184.

Papadopoulou, A. & Tika, T., 2008, "The Effect of Fines on Critical State and Liquefaction Resistance Characteristics of Non-plastic Silty Sands", *Soils and Foundations*, vol. 48, no. 5, pp. 713-725.

Plewes, H.D., Davies, M.P. & Jefferies, M. 1992, "CPT Based Screening Procedure for Evaluating Liquefaction Susceptibility", *Proc. 45th Can. Geotec. Conference*. 26-28 October 1992, Toronto, pp.41-49.

Polito, C.P. & Martin II, J.R. 2001, "Effects of Nonplastic Fines on the Liquefaction Resistance of Sands", ASCE, *J. Geotech. & Geoenv. Eng.,* vol. 127, no. 5, pp. 408-415.

Reid, D. 2014, "Estimating Slope of Critical State Line from Cone Penetration test - an Update", *Can. Geotech. J.,* vol. 52, no. 1, pp. 46-57.

Tavenas, F.A. 1973, "Difficulties in the use of relative density as a soil parameter" in *Evaluation of relative density and its role in geotechnical projects involving cohesionless soils*, E.T. Selig & R.S. Ladd, American Society for Testing and Materials, Philadelphia, pp. 478-486.

Seidalinova, A. 2014, *Monotonic and Cyclic Shear Loading Response of Fine-Grained Gold Tailings*, University of British Columbia (MASc Thesis).

Wijewickreme, D., Sanin, M.V. & Greenaway, G.R. 2005, "Cyclic Shear Response of Fine-Grained Mine Tailings", *Can. Geotech. J.*, vol. 42, no. 5, pp. 1408-1421.