

Liquefaction Susceptibility Evaluation of Mine Tailings Using CPT

Contreras Iván A., Ph.D., P.E., D.G.E., Barr Engineering Co., USA

Grosser Aaron, P.E., D.G.E., Barr Engineering Co., USA

Abstract

Saturated, fine-grained, low-plasticity materials are often characterized for liquefaction susceptibility using cone penetration tests (CPTs). Often times the CPT soundings indicate the tailings material is dilative and thus not susceptible to liquefaction. Two side-by-side CPT soundings were performed in a mine tailings deposit at a standard penetration rate (20 mm/s) and a fast penetration rate (200 mm/s). The data were used to assess liquefaction susceptibility of the deposit using commonly accepted methodologies. Therefore, a change in the penetration rate suggests that some commonly used methodologies may incorrectly indicate dilative behavior when, in fact, actual behavior is contractive. This paper presents the data, procedures to evaluate liquefaction susceptibility, and the differences encountered regarding susceptibility prediction between two penetration rates and considerations in assessing liquefaction susceptibility.

Introduction

Liquefaction is characterized by a sudden decrease of shear strength from the yield strength to the steady-state strength, which can be substantially lower under undrained conditions induced by static or dynamic loading (Poulos et al., 1985). The loss in shear strength during liquefaction is so significant that a sizeable portion of the soil mass, rather than just the soil along a sliding surface, temporarily assumes the consistency of a thick liquid. The consequences of liquefaction include flow slides of sloping ground, lateral displacement of retaining structures, tilting or sinking of foundations, ground rupture, formation of sand boils, and floating of light buried structures (Terzaghi et al., 1996). Liquefaction has been the mechanism responsible for many tailings basin failures around the world, including the recent failure of Samarco's Fundão tailings storage facility in Brazil (Morgenstern et al., 2016).

Olson and Stark (2002, 2003) suggested a detailed procedure for liquefaction analysis of earthen structures involving three basic steps: (1) liquefaction susceptibility evaluation, (2) liquefaction triggering analysis, and (3) post-triggering/flow-failure stability analysis.

- **Liquefaction Susceptibility Evaluation:** In the first step, foundation materials are evaluated to determine whether they are contractive (i.e., susceptible to strength loss due to strain-softening behavior) or dilative (i.e., strain-hardening behavior).
- **Liquefaction Triggering Analysis:** In the second step, the contractive materials are further evaluated to determine whether liquefaction will be triggered (i.e., whether the anticipated seismic or static shear stresses will exceed the yield shear strength). In the case of seismic triggering, a site-response analysis is completed. However, in the case of static triggering, the analysis is more complex due to uncertainty of the loading mechanisms.
- **Post-Triggering/Flow-Failure Stability Analysis:** In the third step, slope stability analyses are performed using the pre-failure geometry and the liquefied shear strength of the contractive materials anticipated to trigger. In this step, slope stability analyses determine whether the applied static shear forces are greater than the available shear resistance. The computed factor of safety is then used to assess the post-triggering stability and likelihood of flow liquefaction.

A detailed description of the liquefaction analysis procedure is provided by Olson and Stark (2003). A number of methods for assessing liquefaction susceptibility exist (i.e., first step above), many of which rely on in-situ testing such as CPT or standard penetration testing (SPT). The methods that utilize CPT data are based on soundings performed at a standard penetration rate of 20 mm/s. However, comparison of side-by-side CPT soundings performed by the authors at a standard penetration rate (20 mm/s) and a fast penetration rate (200 mm/s) suggest that some commonly used methodologies may incorrectly indicate dilative behavior, when, in fact, the actual behavior is contractive. This paper presents details of the evaluation and discussion of the results for one CPT probe, as well as considerations for assessing liquefaction susceptibility of mine tailings using the CPT.

Background

Soils most susceptible to liquefaction are saturated, cohesionless (or fine-grained soils of low plasticity), loose enough to be contractive, and of sufficiently low permeability to experience no significant drainage during the period of undrained shearing or ground shaking. These characteristics are determined by the method of deposition, geologic age, and stress history of the deposit (Terzaghi et al., 1996).

Mine tailings comprise the uneconomical residue left from the mineral processing of the ore body to extract the desired mineral. Mineral processing generally involves the size reduction and separation processes to achieve liberation and concentration of the desired mineral. The residue commonly known as tailings consists of middling and gangue material with particle sizes ranging from coarse (i.e., sand size) to fine (i.e., clay size). In many instances, the size reduction can result in very fine material that can be clay size, which may or may not necessarily contain clay minerals. In the case of conventional tailings, they are typically deposited hydraulically from a slurry.

Mine tailings are typically considered highly susceptible to liquefaction because they are commonly composed of non-plastic or low-plasticity solids. Furthermore, the potential for mine tailings to liquefy in response to triggering events is related to the fact that these materials are hydraulically deposited; thus, the materials come to equilibrium under very loose conditions. Additionally, tailings are recent deposits of a very young geologic age, which is typically associated with greater potential for liquefaction. Furthermore, the mine tailings do not undergo any additional loading other than the overburden stresses from continued tailings deposition and dam construction (resulting in nearly normally consolidated deposits). Thus, the saturated, very loose condition, stress history, and young geologic age of the mine tailings generally results in contractive behavior during undrained shearing and makes them highly susceptible to liquefaction.

In summary, mine tailings deposits typically display characteristics from the method of deposition, geologic age, and stress history which make them highly susceptible to liquefaction. As a result, liquefaction is a relevant mode of failure that is commonly evaluated at tailings basins. When performing the liquefaction analyses of these deposits the first step, liquefaction susceptibility assessment, is required.

Liquefaction Susceptibility Assessment in Geotechnical Practice

Multiple state-of-the-practice methodologies exist to assess liquefaction susceptibility of soils in geotechnical engineering practice. The majority of them utilize in-situ tests (i.e., SPT or CPT) to estimate the state of the deposit and assess susceptibility. Others, involving fine-grain soils, utilize index properties (Bray and Sancio, 2006). Commonly used methods that utilize CPT data include those by Olson and Stark (2003), Olson (2009), Robertson (2016), Jefferies and Been (2015), and Winckler et al. (2014). The following briefly describes each of these methods and how they are used to evaluate liquefaction susceptibility:

Olson and Stark (2003) and Olson (2009) – Tip Resistance from CPT: This methodology is based on in-situ measured CPT data tip resistance. The methodology proposed by Olson (2009), supported by previous work by Olson and Stark (2003), uses a relationship between the normalized tip resistance (q_{ti})

and vertical effective stress (σ'_{vo}) to define the boundary that separates contractive from dilative soils based on material compressibility. The boundaries between contractive and dilative materials were defined based on back-analyses of liquefaction case histories. The compressibility of the material is based on the slope of the critical state line, λ_{10} , measured in e -log σ'_{mean} space.

Winckler et al. (2014) – Dynamic Pore-Water Pressure from CPT: This methodology, proposed by Winckler et al. (2014), is based on in-situ measured dynamic pore-water pressure from CPT data. It uses the relationship between the dynamic pore-water pressure (u_2) measured by the CPT and the in-situ pore-water pressure (u_0) to determine the normalized pore-water pressure (P). Positive P values are associated with contractive soils and negative values are associated with dilative soils.

Jefferies and Been (2015) – Tip, Sleeve Resistance and Dynamic Pore-Water Pressure from CPT: This methodology is based on a dimensionless penetration $Q_t (1-B_q)+1$, which uses tip resistance and dynamic pore-water pressure (u_2) and the normalized sleeve friction ratio (F_r) plotted in a chart for several state parameter lines (ψ). It was postulated by Jefferies and Been (2015) that the soils with a state parameter (ψ) lower than -0.05 are dilative while the soils with a ψ larger than -0.05 are contractive.

Robertson (2016) – Tip and Sleeve Resistance and Dynamic Pore-Water Pressure from CPT: This methodology proposed by Robertson (2016) is also based on in-situ measured CPT data and represents a refinement (update) of prior work by Robertson (2010). It uses a relationship between the dimensionless normalized corrected tip resistance (Q_m) and normalized friction ratio (F_r) plotted with respect to soil behavior types (SBTs). This defines the boundary that separates contractive from dilative soils based on an equivalent clean sand dimensionless, normalized, corrected tip resistance (Q_m) value of 70.

The four methodologies described above were used by the authors to assess liquefaction susceptibility of two side-by-side CPT soundings performed in a mine tailings deposit at a standard penetration rate (20 mm/s) and a fast penetration rate (200 mm/s).

Further details regarding each of these methodologies, as well as the results of the assessment, are provided in the following sections with the objective of quantifying the liquefaction susceptibility of the mine tailings.

Data Used in the Susceptibility Assessment

Method of deposition, geologic age, and stress history of the deposit are typical characteristics related to the susceptibility to liquefaction. Data used in the assessment are associated with a mine tailings deposit where hydraulic deposition is used; thus, the tailings come to equilibrium under very loose conditions. Similarly, the tailings have been deposited within the last three decades, making them very young

geologically. Finally, the stress history of the data presented in this paper corresponds to a normally consolidated soil (i.e., OCR equal to unity) since none of the mechanisms leading to over-consolidation are present. Since the tailings discussed herein have been hydraulically deposited and essentially normally consolidated, they are generally in a fairly loose condition. As a result, they are expected to exhibit mostly contractive behavior under undrained conditions and thus are susceptible to liquefaction.

The tailings discussed herein correspond to silty material with 75 to 100 percent passing No. 200 US sieve and a low clay-size fraction (0 to 10 percent). Data used in the assessment were presented previously in a separate publication, and further details on the subsurface conditions and CPT equipment can be found in Contreras and Grosser (2009).

Figure 1 shows the typical results of two adjacent CPT soundings performed at the site but at different penetration rates. CPT-S represents the sounding performed at the standard rate of 20 mm/s (shown by the dashed line), whereas CPT-F represents the sounding performed at 200 mm/s (shown by the continuous line). The upper 12 m were predrilled due to the presence of a dense granular layer; this layer is not shown for clarity. In a few instances during the fast penetration, the depth measuring device slipped during cone advancement; thus, the depth in the fast sounding is slightly shifted (i.e., greater than the standard sounding) and is not precisely correct. However, no attempts were made to correct for the slippage.

Figure 1 includes the plot of the corrected tip resistance (q_t) versus depth for both soundings CPT-S and CPT-F. It can be seen from Figure 1 that, in general, the corrected tip resistance for CPT-F (i.e., fast rate 200 mm/s) is lower than the corrected tip resistance for CPT-S (i.e., standard rate 20 mm/s). This lower corrected tip resistance is attributed to the associated increase of dynamic pore-water pressure due to fast penetration rate. The couple of instances where the CPT-F tip is higher than the CPT-S are attributed to the slippage previously described. They are, however, general shape indicators in tip resistance that can be used to correlate with depths.

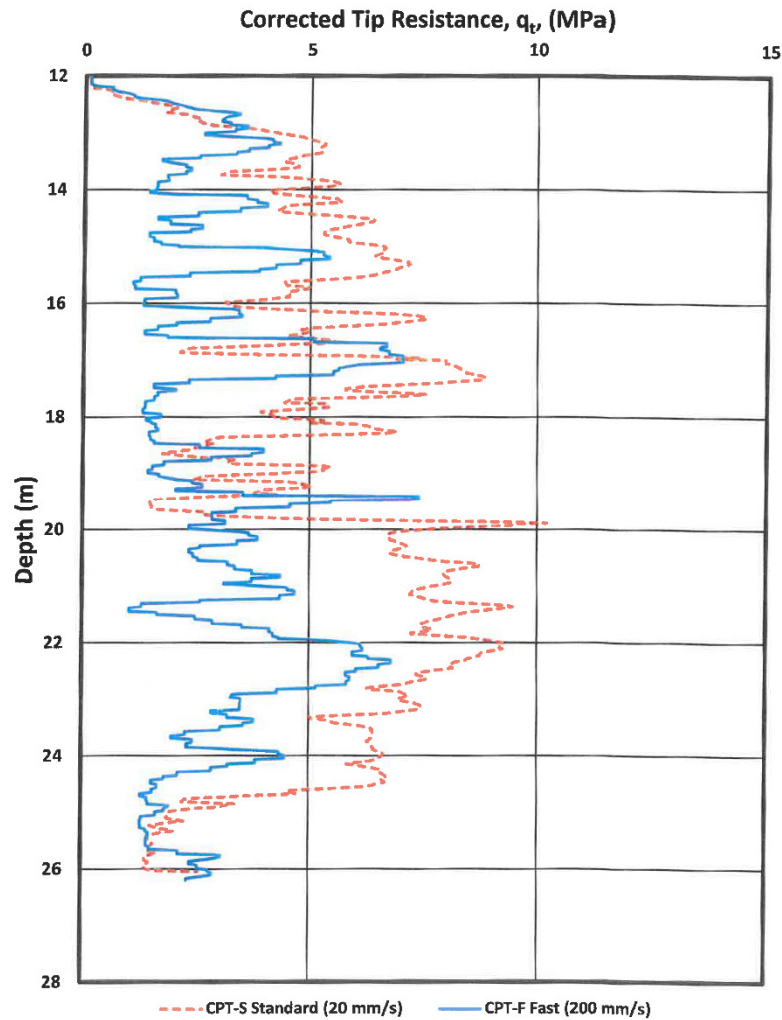


Figure 1. Corrected tip resistance versus depth for CPT-S and CPT-F

Figure 2 includes the plot of dynamic pore-water pressure (u_2) versus depth for CPT-S. The dynamic pore-water pressure for CPT-S is almost linear (except between depths of 17.8 to 19.8 m) and practically coincides with the in-situ pore-water pressure (u_0) distribution at this location (shown by the solid circles) based on the equilibrium pore-water pressures from dissipation tests. This behavior indicates that cone penetration for sounding CPT-S mostly takes place under drained conditions.

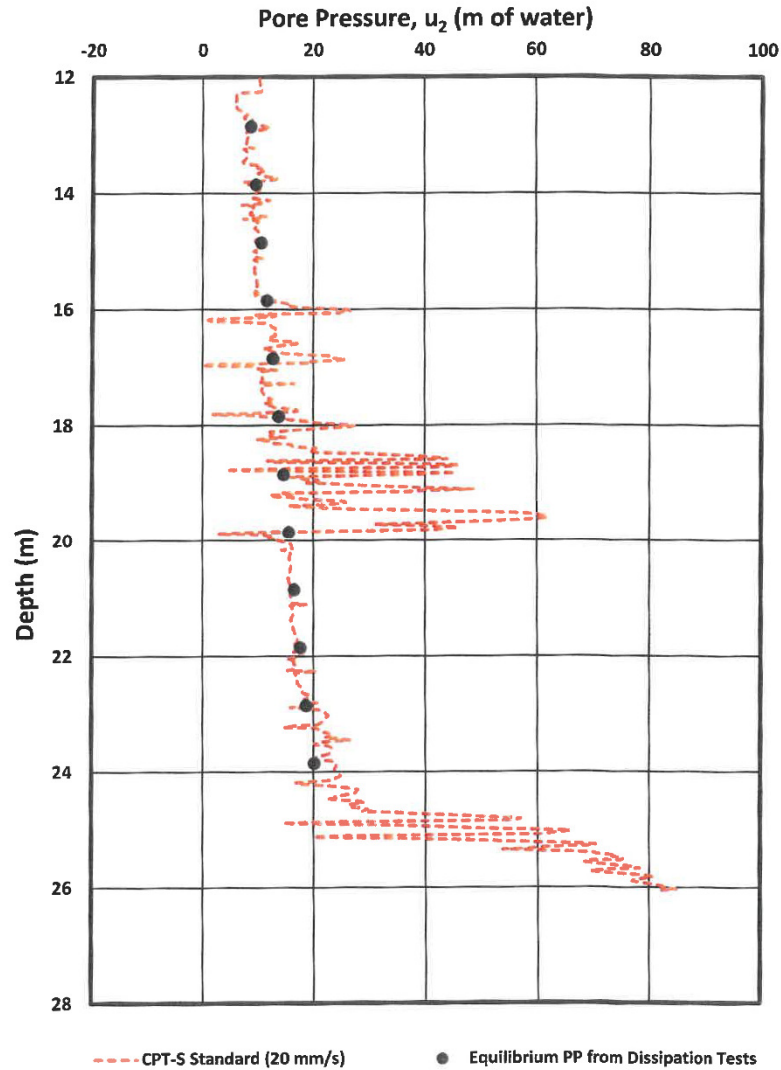


Figure 2. Dynamic and equilibrium pore-water pressure versus depth for CPT-S

Figure 3 includes the plot of dynamic pore-water pressure (u_2) versus depth for CPT-S and CPT-F. Figure 3 also includes a series of solid triangles on the ordinate axis which represent the depths where penetration stopped for CPT-F due to rod addition or other reasons. Figure 3 shows that pore-water pressures for CPT-F (fast penetration rate) increases significantly (in certain zones) from the pore-water pressures measured in sounding CPT-S (standard penetration rate). It is interesting to note that in the CPT-F sounding, the depths or zones where the pore-water pressure decreases to the in-situ pore-water pressure coincides with the depths at which cone penetration was stopped due to rod addition or other reasons, thereby dissipating pore-water pressure over a very short period of time. The process of rod changing and short stops has an effect on the overall dynamic pore-water pressure distribution.

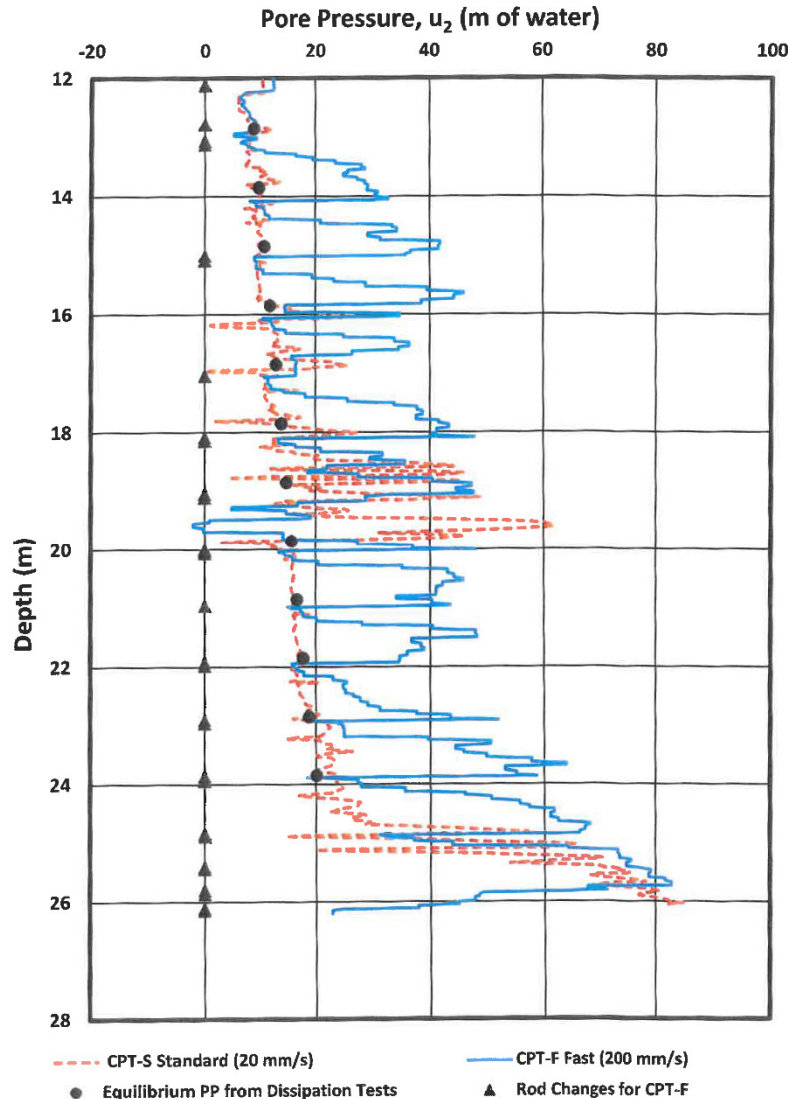


Figure 3. Dynamic pore-water pressure versus depth for CPT-S and CPT-F

In low permeability soils at the standard penetration rate, the effect of rod changing is not typically reflected in the dynamic pore-water pressure distribution results because they do not dissipate the pore-water pressure as fast as the tailings at the site. However, the tailings materials at the site have a relatively high permeability such that the pore-water pressure generated during the fast penetration dissipates fairly quickly.

The results shown in Figures 1 through 3 illustrate that the tailings at the site develop positive shear-induced pore-water pressures during fast loading and likely undrained shear. These results further support the hypothesis that the tailings at the site are likely contractive. To further assess the behavior of the tailings at the site their susceptibility to liquefaction was evaluated.

Liquefaction Susceptibility Assessment

The following four methods that utilize CPT data were used in the liquefaction susceptibility assessment: Olson (2009), Robertson (2016), Jefferies and Been (2015), and Winckler et al. (2014).

Olson and Stark (2003) and Olson (2009)

Olson (2009) proposed an updated CPT-based relationship for liquefaction susceptibility consisting of three boundaries based on material compressibility. These boundaries were to apply in the case of compressible soils, including mine tailings. The three tentative boundaries proposed by Olson (2009) include the original boundary from Olson and Stark (2003), based on Fear and Robertson (1995) for low compressible materials ($\lambda_{10} = 0.03$), a new boundary for medium compressibility materials ($\lambda_{10} = 0.06$), and a new boundary for high compressibility materials ($\lambda_{10} = 0.17$). Each of the three boundaries was based on the estimated compressibility of the material (Jefferies and Been, 2006) in terms of the slope of the critical state line (λ_{10}) associated with the liquefaction case histories contained within the database presented by Olson and Stark (2003).

Figure 4 shows the data from Figures 1 and 2 in the relationship between the normalized tip resistance (q_{t1}) and vertical effective stress (σ'_{v0}). Figure 4 includes three tentative boundary lines that separate contractive from dilative soils based on material compressibility. The material at the site is characterized with a critical state line of $\lambda_{10} \sim 0.17$ and thus classifies as high compressibility. It can be seen from Figure 4 that a large number of points associated with CPT-S fall to the right of the high compressibility boundary line indicating dilative behavior, whereas almost all the points associated with CPT-F fall to the left of the boundary line indicating contractive behavior. Therefore, based on the Olson and Stark (2003) correlation, CPT-F predicts that almost all of the tailings material in the sounding is contractive while CPT-S predicts that only a portion of it is contractive with a significant portion exhibiting dilative behavior.

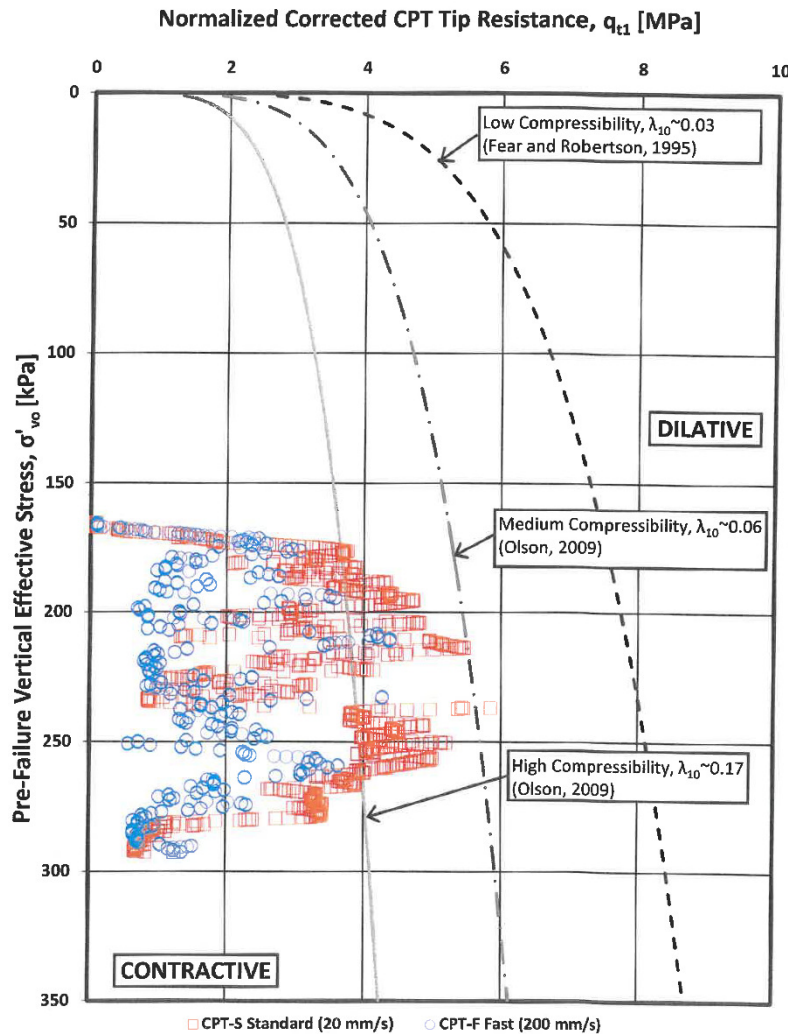


Figure 4. Liquefaction susceptibility assessment for CPT-S and CPT-F based on soil compressibility. Olson (2009)

Winckler et al. (2014)

Winckler et al. (2014) proposed this approach based on the observation that materials not susceptible to liquefaction will tend to increase in volume when sheared (i.e., dilative behavior), inducing a reduction in dynamic pore-water pressure with respect to the in-situ pore-water pressure. Conversely, materials susceptible to liquefaction will tend to decrease in volume when sheared (i.e., contractive behavior), whereby generating an increase in dynamic pore-water pressure. The contractive or dilative nature of the materials can then be characterized by CPT pore-water pressure measurements using the normalized pore-water pressure parameter (P) defined by the following equation:

$$P = \frac{u_2 - u_o}{\sigma'_{vo}} \quad (1)$$

The normalized pore-water pressure parameter (P) is the difference between dynamic pore-water pressure (u_2) measured from the CPT and the in-situ pore-water pressure (u_o) normalized by the vertical effective stress (σ'_{vo}). Positive values are associated with contractive behavior (i.e., susceptible to strength loss due to strain-softening behavior) and negative values are associated with dilative behavior (i.e., strain-hardening behavior).

Figure 5 shows the data from Figures 1 and 2 in the relationship between the normalized pore-water pressure (P) and depth. Also in Figure 5 is the boundary presented by Winckler et al. (2014), separating positive and negative values associated with contractive and dilative behavior, respectively. It can be seen in Figure 5 that the majority of the data associated with CPT-S fall to the left of the boundary line (i.e., $P < 0$), indicating dilative behavior of the tailings at the site. In fact, only a small portion of the points (i.e., at depths between 18–20 m and greater than 23 m) indicate contractive behavior (i.e., $P > 0$).

On the other hand, Figure 5 also shows that the majority of the points associated with CPT-F fall to the right of the boundary line (i.e., $P > 0$) indicating contractive behavior of the tailings at the site. In fact, only a small portion of the points, mainly near the depths where penetration stopped for CPT-F due to rod addition or other reason, indicate dilative behavior (i.e., $P < 0$).

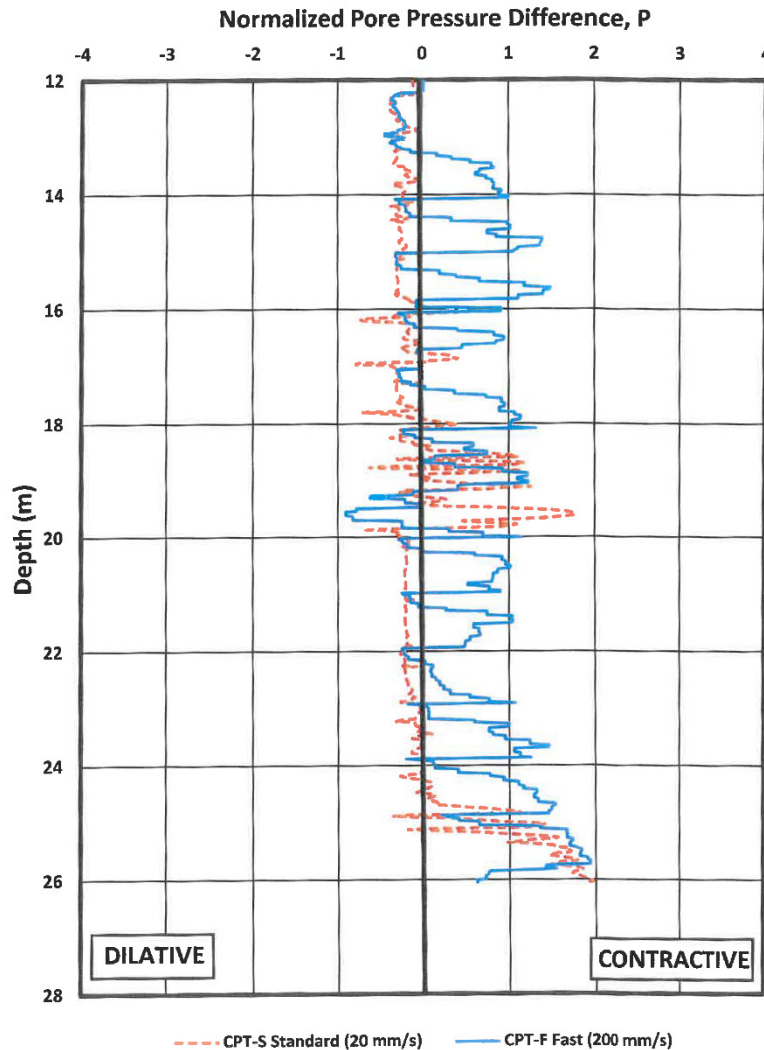


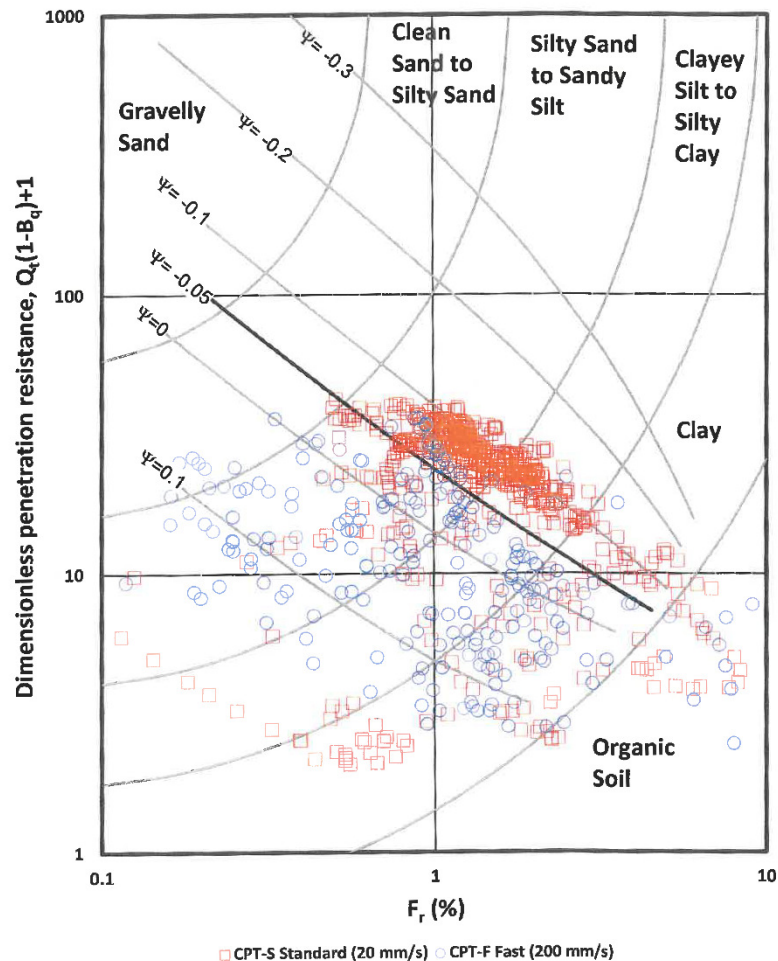
Figure 5. Liquefaction susceptibility assessment for CPT-S and CPT-F based on normalized pore-pressure parameter (P)
Winckler et al. (2014)

Jefferies and Been (2015)

Jefferies and Been (2015) proposed this methodology based on a dimensionless penetration parameter, $Q_t (1-B_q)+1$, and the normalized sleeve friction ratio (F_r) plotted in a log-log chart. Several lines representing different state parameter lines (ψ) are incorporated in the chart. It was postulated by Jefferies and Been (2015) that the soils with a state parameter (ψ) lower than -0.05 are dilative while the soils with a ψ larger than -0.05 are contractive.

Figure 6 shows the data from Figures 1 and 2 (i.e., CPT-S and CPT-F) in the proposed chart using the dimensionless parameter, $Q_t (1-B_q)+1$, and the normalized sleeve friction ratio (F_r). It can be seen in

Figure 6 that the majority of the points associated with CPT-S fall above the boundary line (i.e., $\psi < -0.05$), indicating dilative behavior of the tailings at the site. In fact, only a small portion of the points indicate contractive behavior (i.e., $\psi > -0.05$).



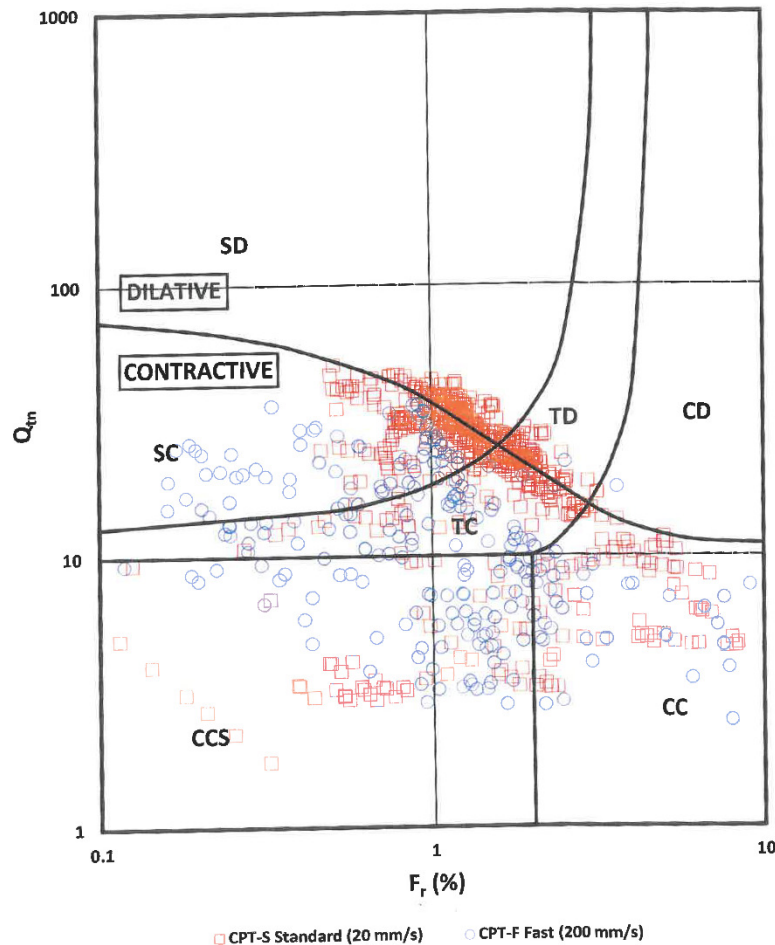
**Figure 6. Liquefaction susceptibility assessment for CPT-S and CPT-F based on penetration parameter $Q_t (1 - B_q) + 1$, normalized sleeve friction ratio (F_r), and state parameter lines (ψ)
Jefferies and Been (2015)**

On the other hand, Figure 6 also shows that the majority of the points associated with CPT-F fall below the boundary line (i.e., $\psi > -0.05$), indicating contractive behavior of the tailings at the site. In fact, only a small portion of the CPT-F points indicate dilative behavior (i.e., $\psi < -0.05$).

Robertson (2016)

Robertson (2016) proposed this methodology based on the dimensionless normalized corrected tip resistance (Q_{tn}) and normalized friction ratio (Fr) plotted with respect to SBTs. This methodology represents a refinement (update) of a prior work by Robertson (2010). Robertson (2016) postulated that the contour of the dimensionless normalized corrected tip resistance (Q_{tn}) equal to 70 separates contractive and dilative material response.

Figure 7 shows the data from Figures 1 and 2 (i.e., CPT-S and CPT-F) in the chart proposed by Robertson (2016) using the dimensionless normalized corrected tip resistance (Q_{tn}) and normalized friction ratio (Fr) plotted with respect to SBTs. It can be seen from Figure 7 that practically all data associated with CPT-F plots below the Q_{tn} line equal to 70, indicating contractive material behavior. On the other hand, the data associated with CPT-S has a significant number of data points plotting above the Q_{tn} line equal to 70, indicating dilative material behavior. Therefore, based on the Robertson (2016) chart, CPT-F predicts that almost all of the tailings material in the sounding is contractive, while CPT-S predicts that only a portion of it is contractive with part of it exhibiting dilative behavior.



**Figure 7. Liquefaction susceptibility assessment for CPT-S and CPT-F based on penetration parameter Q_{tn} and normalized sleeve friction ratio (F_r)
Robertson (2016)**

Conclusions

The first step in the procedure for liquefaction analysis of earthen structures involves the performance of a liquefaction susceptibility assessment. In this step, typically in-situ test data such as CPT are used to assess the state of the material. The most common methods for evaluation of liquefaction susceptibility that utilize CPT data include Olson and Stark (2003), Olson (2009), Robertson (2016), Jefferies and Been (2015), and Winckler et al. (2014). These methods are based on soundings performed at a standard penetration rate of 20 mm/s.

The authors collected data on CPT soundings performed at the standard rate (20 mm/s) and a fast penetration rate (200 mm/s). This comparison of side-by-side CPT soundings is presented and discussed in

Figures 1 through 3. The data from the side-by-side CPT soundings were used to assess liquefaction susceptibility using the methods previously mentioned. It should be noted that this approach has not been used for assessment of strength parameters.

The following provides conclusions of the comparison of the side-by-side CPT soundings performed at standard (CPT-S) and fast rates (CPT-F) as well as the subsequent liquefaction susceptibility assessment of the tailings.

- CPT-S mostly takes place under drained conditions (i.e., little or no pore-pressure generation).
- CPT-F yields lower tip resistance attributed to the generation of excess pore-water pressure during cone penetration. These results indicate contractive behavior of the tailings.
- Tailings at the site were hydraulically deposited and essentially normally consolidated and thus generally encountered in a fairly loose condition. Therefore, they are expected to exhibit mostly contractive behavior under undrained conditions.
- When using Olson (2009) and Robertson (2016) methodologies for liquefaction susceptibility, CPT-F predicts that almost all of the tailings material in the sounding is contractive while CPT-S predicts that only a portion is contractive—with a significant portion exhibiting dilative behavior.
- When using Jefferies and Been (2015) and Winckler et al. (2014) methodologies for liquefaction susceptibility, CPT-F predicts that almost all of the tailings material in the sounding is contractive while CPT-S predicts that only a very small portion of it is contractive—with the majority portion exhibiting dilative behavior.
- The results of the susceptibility assessment presented herein suggest that some commonly used methodologies may incorrectly indicate dilative behavior when, in fact, actual behavior is contractive. Therefore, in some of these methodologies the boundary between dilative and contractive may be susceptible to adjustments.
- Mine tailings that have been hydraulically deposited, essentially normally consolidated, and encountered in the field in a fairly loose condition are expected to exhibit mostly contractive behavior. Therefore, it is prudent to assume that mine tailings with such characteristics are contractive.

CPT is probably the best tool to assess liquefaction susceptibility of soils. The current methodologies can be improved and adjusted based on the results presented herein.

Acknowledgements

The help of Mr. Matt Walker in preparation of the figures for this paper is really appreciated. Review and

comments provided by Dr. Gonzalo Castro during the preparation of this manuscript are greatly appreciated.

References

- Bray, J.D., and Sancio, R.B. 2006. "Assessment of the Liquefaction Susceptibility of Fine-Grained Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 132(9): 1165-1177.
- Contreras, I.A., and Grosser, A.T. 2009. *Evaluation of CPT response under fast penetration rate in silty soils*. Proceedings of the *University of Minnesota 57th Annual Geotechnical Engineering Conference*, Minnesota Geotechnical Society, Minneapolis, MN.
- Fear, C.E., and Robertson, P.K. 1995. "Estimating the Undrained Strength of Sand: A Theoretical Framework." *Canadian Geotechnical Journal*, 32(4), 859-870.
- Jefferies, M., and Been, K. 2006. *Soil Liquefaction: A Critical State Approach*. CRC Press, Taylor & Francis Group, New York, NY, 512 pp.
- Jefferies, M., and Been, K. 2015. *Soil Liquefaction: A Critical State Approach*. Second Edition. CRC Press, Taylor & Francis Group, New York, NY, 690 pp.
- Morgenstern, N.R., Vick, S.G., Viotti, C.B., and Watts, B.D. 2016. *Fundão Tailings Dam Review Panel, report on the Immediate Causes of the Failure of the Fundão Dam*. August 25, 2016.
- Olson, S.M. 2009. "Strength Ratio Approach for Liquefaction Analysis of Tailings Dams." In Proceedings of *University of Minnesota 57th Annual Geotechnical Engineering Conference*, Minnesota Geotechnical Society, Minneapolis, MN.
- Olson, S.M., and Stark, T.D. 2002. "Liquefied Strength Ratio from Liquefaction Flow Failure Case Histories." *Canadian Geotechnical Journal*, 39(3): 629-647.
- Olson, S.M., and Stark, T.D. 2003. "Yield Strength Ratio and Liquefaction Analysis of Slopes and Embankments." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 129(8): 727-737.
- Poulos, S. J., Robinsky, E. I., and Keller, T. O. 1985. Liquefaction resistance of thickened tailings. *Journal of Geotechnical Engineering*, 111(12), 1380-94.
- Robertson, P.K. 2010. "Evaluation of Flow Liquefaction and Liquefied Strength Using the Cone Penetration Test." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 136(6): 842-853.
- Robertson, P.K. 2016. "Cone penetration test (CPT)-based soil behaviour type (SBT) classification system — an update." *Canadian Geotechnical Journal*. 53(12): 1910-1927
- Terzaghi, K., Peck, R.B., and Mesri, G. 1996. *Soil Mechanics in Engineering Practice, Third Edition*. John Wiley & Sons, Inc., New York, NY, 549 pp.
- Winckler, C., Davidson, R., Yenne, L., and Pilz, J. 2014. "CPTu-Based State Characterization of Tailings Liquefaction Susceptibility." In Proceedings of *Dams and Extreme Events, 34th Annual USSD Conference*, San Francisco, CA.