# Screening for flow liquefaction for tailings and natural soils by CPTU

Détection de liquéfaction par écoulement pour les résidus et les sols naturels par CPTU

**Paul Mayne**
*Emeritus Professor, Geosystems Engineering Group, Georgia Tech, Atlanta, GA USA, paul.mayne@ce.gatech.edu*

James Sharp
*President, ConeTec Group, Burnaby, BC Canada*

ABSTRACT: As an alternative to current available methods for evaluating flow liquefaction potential of mine tailings and natural soils (e.g. Robertson 2010; Jefferies & Been 2015), the evaluation of yield stress ratio (YSR) by CPTU offers a simple means of identifying contractive versus dilative soil behavior. The CPTU method for YSR is based on a nexus between a theoretical cavity expansion-critical state formulation for clays involving 206 natural deposits (n = 1254) and a statistical analyses of CPT chamber tests on 26 sands (n = 706). Intermediate soils are linked via the CPT material index, $I_c$. The methodology is applied to several case studies (e.g., Cadia tailings, Australia; Fundão tailings dam failure, Brazil) in direct comparison to the $Q_{tn-cs} < 70$ and state parameter $\Psi > -0.05$ approaches that show similar results are obtained for all 3 methods. An advantage of the YSR approach is that it easily lends itself to estimating a future soil/ tailings state with additional surcharge..

RÉSUMÉ : Une alternative aux méthodes actuellement disponibles pour évaluer le potentiel de liquéfaction par écoulement des résidus miniers et des sols naturels (par exemple Robertson 2010; Jefferies & Been 2016), l'évaluation du rapport de limite d'élasticité (YSR) par le CPTU offre un moyen simple d'identifier les sols à comportement contractants par rapport à ceux au comportement dilatants. La méthode CPTU pour YSR est basée sur un lien entre une formulation théorique de l'état critique d'expansion de la cavité pour les argiles impliquant 206 dépôts naturels (n = 1254) et une analyse statistique des tests en chambre CPT sur 26 sables (n = 706). Les sols intermédiaires sont liés via l'indice des matériaux CPT, $I_c$. La méthodologie est appliquée à plusieurs études de cas (par exemple, résidus de Cadia, Australie; rupture du barrage de résidus de Fundao, Brésil) en comparaison directe avec les approches $Q_{tn-cs}$ <70 et l'angle de dilatance $\Psi > -0.05$ qui montrent des résultats similaires sont obtenus pour les 3 méthodes. Un avantage de l'approche YSR est qu'elle se prête facilement à l'estimation d'un état futur du sol / des résidus avec une surcharge additionnelle.

KEYWORDS: cone penetration, critical state, liquefaction, mine tailings, yield stress

## 1 INTRODUCTION

Flow liquefaction manifests as a rapid and brittle undrained loss of soil strength that occurs in mine tailings dams, hydraulic fills, and natural sandy to silty soil deposits. Static or flow liquefaction most often occurs in saturated contractive soils on sloping ground, and may be triggered under static conditions such as a rise in the phreatic surface or water infiltration following a heavy rainfall. Flow liquefaction may also be triggered by transient earthquake loading.

Soils prone to flow liquefaction are characterized by their "contractive" soil behavior, whereby volumetric strains decrease during shear, in contrast to "dilative" soil response, whereby volumetric strains increase. Moreover, these soils tend to be brittle and exhibit a rapid loss of strength at low strain levels, resulting in rapid and progressive flow failures.

The identification of soil conditions susceptible to flow liquefaction can be made on the basis of conventional rotary drilling, high quality sampling, and careful laboratory testing, combined with in-situ testing and geophysical measurements; however, at great cost in terms of time and money (Robertson et al., 2000). This is especially true for sands, silty sands, and silts because undisturbed sampling methods (e.g., freezing, gel sampling) are quite difficult and expensive. As an alternative, the use of in-situ tests offer the expedient and economic assessment of flow liquefaction potential, particularly in mine tailings where screening is often used during all stages of dam construction.

Of practical use, the cone penetration test (CPT), especially piezocone testing (CPTU), offers three continuous recordings of soil response with depth: cone tip resistance ($q_t$), sleeve friction ($f_s$), and dynamic porewater pressure ($u_2$), thus well suited for the identification and screening of flow liquefaction problems. Additional data, including shear and compression wave velocities, can be obtained during seismic cone tests (SCPTu).

### 1.1 *State parameter*

Current methods for the screening and evaluation of flow liquefaction potential of tailings, hydraulic fills, and natural loose soil deposits rely on an evaluation of the state parameter ($\Psi$) defined as (Been & Jefferies 1985):

$$\Psi = e_0 - e_{cs} \quad (1)$$

where $e_0$ = initial void ratio and $e_{cs}$ = void ratio at critical state for a constant mean effective stress p' within the context of critical-state soil mechanics (CSSM), as presented in Figure 1.

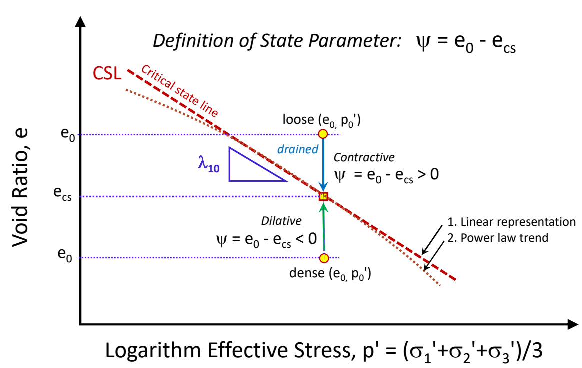


Figure 1. Representation of critical state parameter Ψ in graph of void ratio versus logarithm of mean effective stress

The critical state line (CSL) is conventionally represented as a straight line in e-ln(p') plot by slope $\lambda$, or alternatively in a plot of void ratio (e) versus log(p') plot by slope $\lambda_{10}$, but also as a curved relationship in a power law format, as detailed by Reid et al (2020).

When the soil behavior shows a decrease in volume, such as loose sands and silts, the contractive response is indicative of possible instability and collapse, thus prone to flow liquefaction. In contrast, dense soils exhibit an increase in volume termed dilatant or dilative response and considered not susceptible to flow liquefaction. As such, a value of $\Psi = 0$ signifies the CSSM threshold for the contractive-dilatant boundary.

### 1.2 *Cone penetration technology*

The three readings ($q_t$, $f_s$, $u_2$) obtained by CPTU are utilized to evaluate soil stratigraphy, soil behavioral types, and a suite of geoparameters that are needed in engineering analyses and design. The measurements are often post-processed into net readings, such as net cone resistance ($q_{net} = q_t - \sigma_{vo}$), excess porewater pressure ($\Delta u = u_2 - u_0$), and effective cone resistance ($q_E = q_t - u_2$), or in terms of normalized and dimensionless parameters, including: $Q = q_{net}/\sigma_{vo}'$, $U = \Delta u/\sigma_{vo}'$, $B_q = \Delta u/q_{net}$, and $F = 100 \cdot f_s/q_{net}$ (%), where $\sigma_{vo}$ = total overburden stress, $u_0$ = hydrostatic porewater pressure, and $\sigma_{vo}'$ = effective vertical stress. Additional details can be found in Lunne, Robertson, & Powell (1997).

## 2 CPT SCREENING METHODS

Herein, three methods for the screening of flow liquefaction potential by CPT are considered: (1) $\Psi = -0.05$ criterion (Jefferies & Been 2015); (2) $Q_{tn,cs} = 70$ threshold, as described later in Section 2.2 (Robertson 2010a); and (3) yield stress ratio at critical-state, or YSR ≈ 2.8 (Mayne & Sharp 2019).

Additional post processing of CPT for flow liquefaction concerns are discussed by Olson & Stark (2002, 2003), and Monfared & Sadrekarimi (2013) but not covered here.

### 2.1 *State parameter approach*

Been et al. (1986; 1987) established a framework for assessing $\Psi$ in sands that describes initial state, soil behavior, strength, and compressibility using laboratory testing and a number of intermediate geoparameters which were correlated to normalized CPT parameters (Q, $B_q$, F) from large scale chamber tests and laboratory triaxial results on reconstituted soil samples. Extensions to the method for silts and clays are described by Been et al. (2012), Been (2016), and Jefferies & Been (2015).

In the stand-alone CPT approach, the slope of the CSL is found either from normalized sleeve friction (Plewes et al. 1992):

$$\lambda_{10} \approx 0.1 \cdot F(\%) \tag{2}$$

or alternatively using their definition of CPT material index:

$$I_c{}^* = \sqrt{\{3 - \log[Q \cdot (1 - B_q) + 1]\}^2 + \{1.5 + 1.3\log(F)\}^2} \tag{3}$$

which is related to slope of the CSL by the expression:

$$\lambda_{10} \approx 1/(34 - 10 \cdot I_c{}^*) \tag{4}$$

The state parameter $\Psi$ is found from:

$$\Psi = -\frac{1}{m'} \cdot \ln\left[\frac{Q_p(1 - B_q) + 1}{k'}\right] \tag{5}$$

where $Q_p = (q_t - p_0)/p_0'$ = normalized cone resistance in terms of mean stress, $p_0' = ⅓\sigma_{vo}'(1 + 2 \cdot K_0)$, with $K_0$ = lateral stress coefficient. The terms k' and m' are empirical fitting parameters found through the following trends:

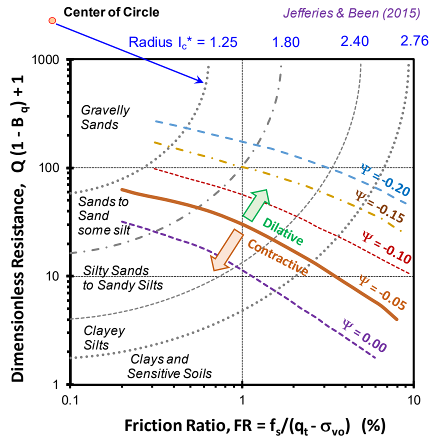


Figure 2. Screening for contractive-dilative soils using state parameter $\Psi$ approach by Jefferies & Been (2015).

$$m' = 11.9 - 13.3 \cdot \lambda_{10} \tag{6}$$

$$k' = M_c \cdot (3 + 0.85/\lambda_{10}) \tag{7}$$

where the friction parameter $M_c = 6 \cdot \sin\phi'/(3 - \sin\phi')$ is found within the context of CSSM.

In lieu of the theoretical critical state threshold $\Psi = 0$, a practical value $\Psi = -0.05$ was adopted, thus contractive soils prone to flow liquefaction are identified when $\Psi > -0.05$. The general concept of the state parameter approach is shown in Figure 2.

### 2.2 *Normalized cone resistance approach*

An update to the soil behavioral type (SBT) charts uses a modified cone tip resistance: $Q_{tn} = (q_{net}/\sigma_{atm})/(\sigma_{vo}'/\sigma_{atm})^n$ where $\sigma_{atm}$ = reference stress equal to atmospheric pressure, and n = exponent that varies from 0.5 for clean sands, 0.75 in silts, to 1.0 for intact clays. Specifically, the exponent n is found by iteration:

$$n = 0.381 \cdot I_c + 0.05 \cdot \sigma_{vo}'/\sigma_{atm} - 0.15 \leq 1.0 \tag{8}$$

where a simplified CPT material index ($I_{cRW}$) is given by:

$$I_{cRW} = \sqrt{(3.47 - \log Q_{tn})^2 + (1.22 + \log F)^2} \tag{9}$$

In another approach, Robertson (2010) defined regions within CPT soil behavior type charts to identify potential soil layers that may be susceptible to flow liquefaction and cyclic liquefaction, as well as define undrained versus drained response and contractive versus dilative behavior. Robertson (2010) found that normalized cone resistance adjusted for fines content, designated ($Q_{tn,cs}$), trended over a range of state parameter from $0.0 < \Psi < -0.20$, such that:

$$\Psi = 0.56 - 0.33 \cdot \log(Q_{tn,cs}) \tag{10}$$

where $Q_{tn,cs} = K_c \cdot Q_{tn}$ is the normalized equivalent cone resistance for clean sands. The adjustment factor is found from:

$$\text{For } I_c \leq 1.64: \quad K_c = 1 \tag{11}$$

For $I_c > 1.64$: $K_c = 5.581 \cdot I_c^3 - 0.403 \cdot I_c^4 - 21.63 \cdot I_c^2 + 33.75 \cdot I_c - 17.88$

For the case $\Psi = -0.05$ at the contractive-dilative boundary, the associated value of $Q_{tn,cs} = 70$ (Robertson 2009), as shown in Figure 3.

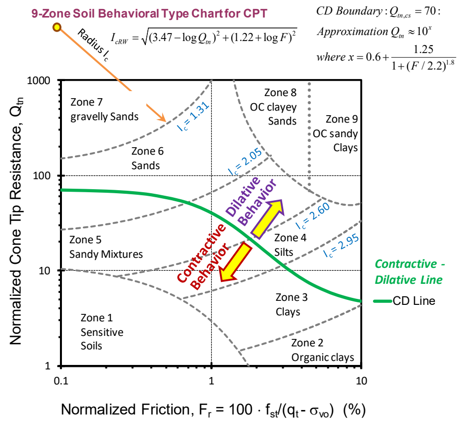


Figure 3. Screening for contractive-dilative soils using normalized cone resistance equivalence for clean sands by Robertson (2010).

## 2.3 *Yield stress from CPT*

The yield stress, $\sigma_p'$ (or preconsolidation) of soils can be evaluated from CPT net resistance and material index, $I_c$ (Mayne 2017; Agaiby & Mayne 2019):

$$\sigma_p' = 0.33(q_{net})^{m_p'} \tag{3}$$

where $m_p'$ is an exponent that depends upon soil type (Mayne et al. 2009): $m_p'$ = 1.0 (intact inorganic clays), 0.9 (organic clays), 0.85 silts, 0.80 (silty sands to sandy silts), 0.72 (clean uncemented quartz-silica sands). The exponent has been related to the CPT material index, $I_{cRW}$, as shown in Figure 4.

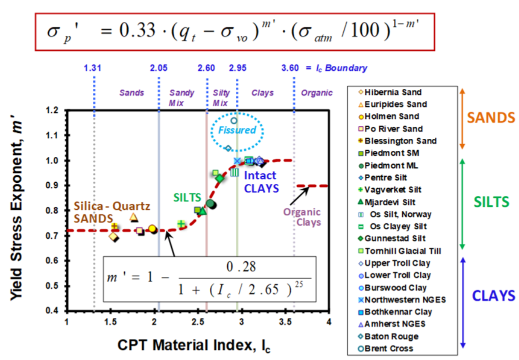


Figure 4. Exponent for evaluating yield stress in soils from CPT material index (after Mayne, Coop, Springman, Huang, & Zornberg 2009)

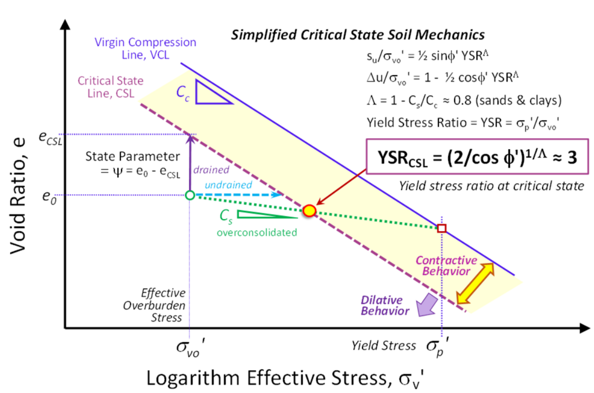


Figure 5. Screening for contractive-dilative threshold from YSR method using simplified critical state soil mechanics (after Mayne & Sharp 2019)

The normalized form is the yield stress ratio (YSR), or apparent overconsolidation ratio (AOCR):

$$YSR = \sigma_p'/\sigma_{vo}' \tag{4}$$

For simple shear, Figure 5 shows that the value of YSR at the critical state line can be found from (Mayne & Sharp 2019):

$$YSR_{csl} = (2/\cos\phi')^{1/\Lambda} \tag{5}$$

where $\Lambda$ = 0.8 is a CSSM parameter related to the compression and swelling lines. For friction angles between 20° ≤ $\phi'$ ≤ 40°, the range gives: $2.6 < YSR_{CSL} < 3.3$.

Interestingly, Jefferies & Been (2006) discuss the value of OCR at critical state for triaxial compression mode, however their overconsolidation ratio is expressed in terms of mean effective stress, designated $R_p$. Specifically, $R_p$ at the CSL has a value of 2 for Modified Cam Clay and 2.7 for the original Cam Clay constitutive soil model.

The evaluation of $\phi'$ for equation (5) is obtained from CPT by sorting drained behavior ($I_c \le 2.6$) typically associated with sands, from undrained response ($I_c > 2.6$) that is characteristic of clayey soils. Thus, for the case of drained CPT response at a standard rate of push of 20 mm/s, the value $I_c \le 2.6$:

$$\phi' = 17.6° + 11.0° \cdot \log(Q_{tn}) \tag{6}$$

Undrained penetration occurs when $I_c > 2.6$, therefore:

$$B_q > 0.05: \quad \phi' \approx 29.5° B_q^{0.121} \cdot [0.256 + 0.336 \cdot B_q + \log(Q)] \tag{7}$$

$$B_q \le 0.05: \quad \phi' \approx 8.18° \cdot \ln(2.13 \cdot Q) \tag{8}$$

For overconsolidated soils, the Q is replaced with $Q' = Q/YSR^{\Lambda}$ (Ouyang & Mayne 2019).

# 3 CASE HISTORIES

The three CPT screening methods for flow liquefaction are applied to four case studies involving a natural loose sandy deposit and three tailings dam deposits. Two of the tailings were very loose and resulted in failures, while the third tailings consisted of dense compacted soils.

## 3.1 *Jamuna Bridge, Bangladesh*

The western slopes of the Jamuna Bridge site experienced over 30 submarine flow slides in very young natural sandy sediments. Details are provided by Yoshimini et al. (1999) who discuss the normally consolidated fine-medium sands which contained 15 to 30% mica content. Mean grain size ($D_{50}$) ranged from 0.1 to 0.2 mm and percent fines (PF) varied from 2 to 10%. Figure 6 shows the mean profiles of $q_t$ and $f_s$ from 22 CPTs at the site with the corresponding material index ($I_c$) with depth.

Application of the aforementioned CPT screening procedures are presented in Figure 7. The state parameter approach of J&B hovers around the threshold value $\Psi \approx -0.05$, thus indicating marginal flow liquefaction potential while the R'10 method determines a rather consistent $Q_{tn\text{-}cs} \approx 50$ which is well below the threshold of 70 and therefore strongly contractive and prone to flow liquefaction. The YSR method indicates contractive soils below 3 m, in fact, the soils may have been forced to YSR < 1 indicating underconsolidation at depths greater than 16 m, therefore unstable and very susceptible to flow liquefaction.

## 3.2 *Compacted Tailings, Western Canada*

A compacted tailings facility in western Canada is used as an example for the quantification of primarily dilative soils (Mayne

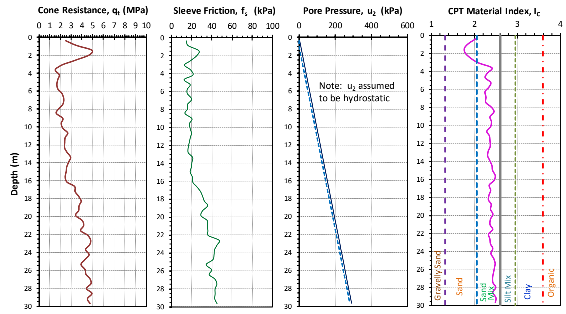


Figure 6. Mean CPT profiles for natural sands at Jamuna Bridge that experience flow liquefaction (data from Yoshimini et al. (1999)

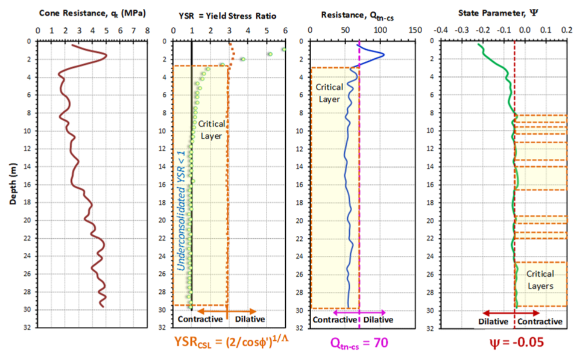


Figure 7. Application of three screening methods for flow liquefaction in natural loose sands at Jamuna Bridge, Bangladesh

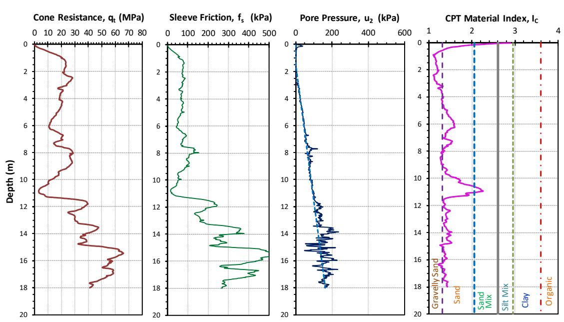


Figure 8. Representative CPT profile for compacted tailings sands in Western Canada (data from Mayne & Sharp 2019)

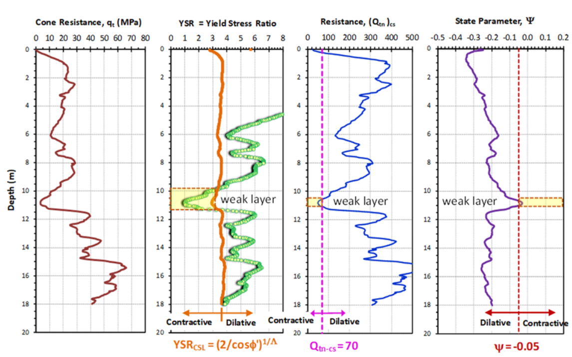


Figure 9. Application of three screening methods for contractive-dilative soil behavior in compacted sand tailings in Western Canada

& Sharp 2019). Results from representative piezocone testing are shown in Figure 8 with the profiles of $q_t$, $f_s$, $u_2$, and $I_c$ with depth. In terms of the SBTn system, the index $I_c$ indicates mainly the presence of sands (zone 6) and gravelly sands (zone 7), except for a limited zone of a sandy mixture (zone 5) at depths of between 10 to 11 m.

Post-processing the CPT data is shown for the Western Canada tailings site are shown in Figure 9. All three methods clearly categorize that the majority of the soil profile consists of dilative geomaterials, excepting the thin loose layer encountered at depths of 10 to 11 m which is clearly identified as contractive. This special case study shows the consistency of all three approaches in assessing contractive and dilative soil behavior.

### 3.3 *Cadia Tailings Failure, Australia*

A gold tailings facility in the New South Wales area of Australia failed on 09 March 2018 with the release of slurry. Luckily no fatalities or pollution occurred, however, the reconstruction efforts were projected to take approximately 2 years for the restoration of the impoundment facilities. Details concerning the mine operations, geotechnical data, analyses, and causes of the embankment failure are given by Jefferies et al. (2019).

Figure 10 shows a representative CPTU in the area of failure, with corresponding profiles of $q_t$, $f_s$, $u_2$, and $I_c$ with depth. The results indicate the presence of very silty to clayey soil types within the upper 58 m of the sounding. Many sandy lenses or stringers are notable throughout most of the profile.

Application of all 3 post-processing approaches for Cadia are presented in Figure 11. The J&B approach shows a consistently highly contractive soil profile with Ψ≈ +0.10 and the Robertson (2010) method a rather constant profile $Q_{tn-cs}$ ≈20 with depth. Moreover, the CPT-evaluated YSR ≈ 1 throughout the depths also indicates the presence of highly contractive soils.

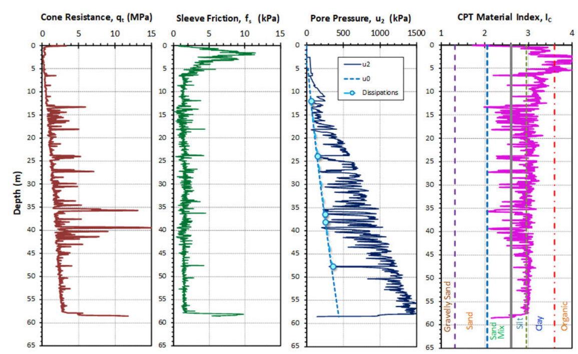


Figure 10. Representative CPT profile in gold tailings that experienced flow liquefaction at Cadia Valley, Australia

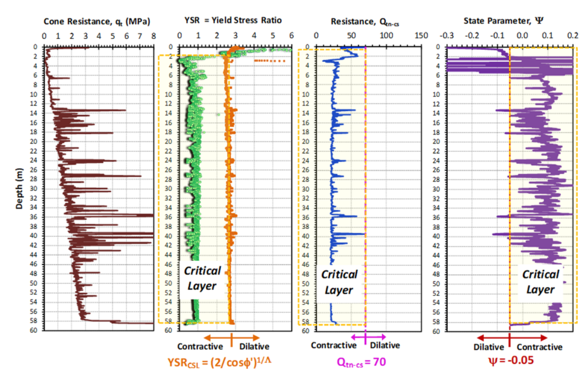


Figure 11. Application of three screening methods for flow liquefaction to tailings embankment failure at Cadia Valley, Australia

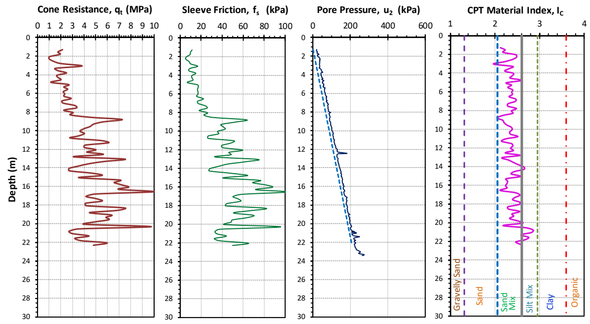


Figure 12. Representative CPT profile F02 in iron ore tailings that experienced catastrophic flow liquefaction failure at Fundão, Brazil

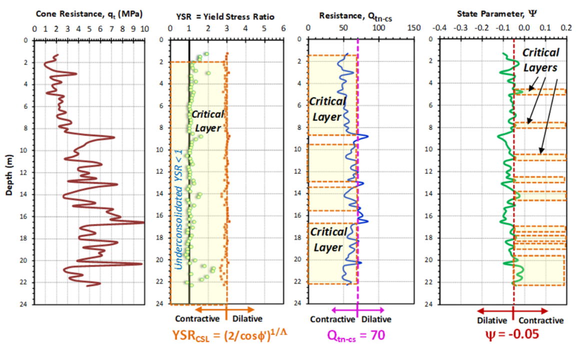


Figure 13. Application of three flow liquefaction screening methods at Fundão tailings dam, Brazil

### 3.4 *Fundão Tailings Failure, Brazil*

On 05 November 2015, the spectacular failure of an iron ore tailings dam just southeast of Belo Horizonte, Brazil resulted in 19 deaths, extensive environmental damage, and widespread contamination (Reid 2019). The dam failure released 44 million $m^3$ of toxic mine tailings into the Doce River. Full details on the geotechnical aspects of the construction history of the tailings, CPT results, laboratory testing, stability analyses, and forensic studies are reported by Morgenstern et al. (2016).

Profiles of $q_t$, $f_s$, $u_2$, and $I_{cRW}$ from CPTU sounding F02 are presented in Figure 12. The 3 screening approaches for flow liquefaction are shown in Figure 13 where the YSR and $Q_{tn,cs}$ methods clearly show the fragile condition of the tailings, yet the Ψ approach barely indicates instability and likely collapse, mostly localized zones of contractive soils in the upper 16 m.

A rather similar conclusion was reached by Schafer et al. (2019) in their comparison of CPTU screening methods for flow liquefaction susceptibility at Fundão.

## 4 ADDITION OF NEW SURCHARGES

The YSR method easily allows the asssessment of future conditions and the contractive-dilative state of the tailings deposit due to the placement of new surcharge and fill. With the Ψ approach and $Q_{tn-cs}$ method, this is not so straightforward.

The conceptual evaluation of an existing soil fill or tailings embankment is depicted in Figure 14 showing the profile of yield stress and current effective overburden stress. As new fill or surcharge is added, the corresponding increase in $\sigma_{vo}'$ results in a reduction in the YSR profile. For the case shown, the fill is initially dilative throughout the entire thickness of 30 m. However, as additional surcharge is added, the profile becomes contractive in the lower portions.

Additional discussion on this issue is given by Mayne & Styler. Moreover, Styler et al. (2018) provide several actual case studies involving sand fill at various times after surcharge placement and the associated CPT results at these various stages of loading.

## 5 DISCUSSION

The yield stress ratio approach is based on a simple nexus that links an analytical solution for clays based on spherical-cavity expansion theory and critical-state soil mechanics (SCE-CSSM) and statistical results originally obtained from CPT chamber tests on sands (Mayne 2017). Initial calibration of the SCE-CSSM solution for YSR was made for 206 natural clays that had been subjected to laboratory consolidation testing of undisturbed samples and field piezocone tests with data taken at corresponding elevations (Chen & Mayne 1996). Chamber tests from 26 different sands provided over 600+ CPT data points for statistical analyses (Mayne 2001). Together these were incorporated to identify a common link in the interpretation to allow a simplified approach that relates yield stress to net cone resistance and soil type (Mayne, Coop, Springman, Huang, & Zornberg 2009). A final step provided a direct relationship between the soil behavior type to the CPT material index ($I_c$) that was calibrated using a variety of sands, silts, clays, and mixed soil types from 93 natural soil deposits (Agaiby & Mayne 2019).

Thus, the basis of the YSR approach is quite different from the Ψ method of J&B'15 which was formulated from testing of reconstituted sands and tailings. The calibrated findings of the YSR approach are primarily obtained from natural soil deposits tested by in-situ CPT soundings to depths of 30 or 40 m.

Some additional limitations to the YSR approach can be stated. As the initial formulation of the YSR approach focused on clays, the critical state adopted the simple linear e-log($\sigma_v'$) form that is commonly associated with consolidation results. The extension of this assumption to sands and silty sands may in fact have limited application over certain stress ranges. Much discussion has arisen in the geotechnical literature over the utilization of a more complex and curved critical state line for coarse-grained soils, as suggested by Figure 1. For instance, the reader is directed to the works of Pestana & Whittle (1995), Li & Wang (1998), and Reid et al. (2020) for additional debate and details on this issue.

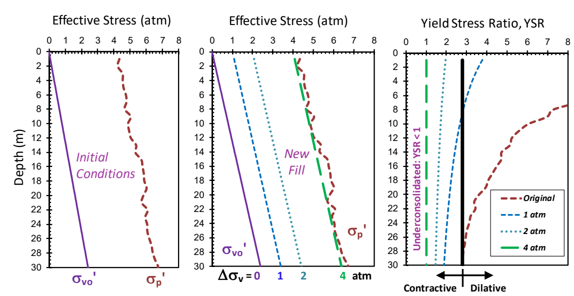


Figure 14. Conceptual changes in YSR due to new surcharge placement on existing tailings dam

## 6 CONCLUSIONS

A CPT method for evaluating profiles of yield stress ($\sigma_p'$) and yield stress ratio (YSR = $\sigma_p'/\sigma_{vo}'$) in soils finds use in screening flow liquefaction and the demarcation of contractive versus dilatant soils, especially important in mine tailing deposits. The YSR method is based on CPT data obtained from over 93 natural clays, silts, sands, and mixed soil types.

Within the context of critical-state soil mechanics, contractive soil response can be identified when YSR < $(2/\cos\phi')^{1/\Lambda}$ (≈ 2.8). As supported by results from a number of case studies, the YSR approach is compatible with existing criteria expressed in terms of state parameter where $\Psi > -0.05$ and normalized cone resistance adjusted for fines content, or $Q_{tn,cs} < 70$, are used to identify contractive soils. An advantage of the YSR approach is the ease in projecting the future state conditions (contractive or dilative) behavior due to placement of new fill.

Of final note, the use of multiple methods for screening flow liquefaction in mine tailings is warranted due to uncertainties in the approaches, as concluded by Schafer et al. (2019).

## 7 ACKNOWLEDGMENTS

The authors thank Professor David Reid from UWA for supplying the digital CPT data at Cadia Valley.

## 8 REFERENCES

Agaiby, S.S. and Mayne, P.W. 2019. CPT evaluation of yield stress in soils. *Journal of Geotechnical & Geoenvironmental Engineering* 145(12): doi.org/10.1061/(ASCE)GT.1943-5606.0002164.

Been, K. and Jefferies, M.G. 1985. A state parameter for sands. *Geotechnique* 35(2): 99-112.

Been, K., J.H.A. Crooks, D.E. Becker and M.G. Jefferies. 1986. The cone penetration test in sands: Part I: State parameter interpretation. *Geotechnique* 36(2): 239–249.

Been, K., M.G. Jefferies, J.H.A. Crooks and L. Rothenburg. 1987. The cone penetration test in sands: Part II, general inference of state. *Geotechnique* 37(3): 285–299.

Been, K.; Romero, S.; Obermeyer, J. & Hebeler, G. 2012. Determining in-situ state of sand and silt tailings from the CPT. *Proc. 12th Tailings and Mine Wastes Conference*, Keystone, Colorado State University.

Been, K. 2016. Characterizing mine tailings for geotechnical design. *Geotechnical and Geophysical Site Characterization 5*, Vol. 1 (Proc. ISC-5, Gold Coast), Australian Geomechanics Society: 41–55.

Chen, B.S.Y. and Mayne, P.W. 1996. Statistical relationships between piezocone measurements and stress history of clays. *Canadian Geotechnical Journal* 33 (3), pp. 488-498.

Jefferies, M., Morgenstern, N.R., Van Zyl, D., and Wates, J. 2019. *Report on NTSF Embankment Failure, Cadia Valley Operations for Ashurst*, Australia, Document Number H356804-00000-22A-230-0001: 119 pages. https://www.newcrest.com/

Li, X. S. and Wang, Y. 1998. Linear representation of steady-state line for sand. *J. Geotech. Geoenviron. Engng* 124 (12): 1215–1217.

Lunne, T., Robertson, P.K. and Powell, J.J.M. 1997. *Cone Penetration Testing in Geotechnical Practice*, CRC Press, Blackie Academic & Professional, London: 418 p.

Mayne, P.W. 2001. Stress-strain-strength-flow parameters from enhanced in-situ tests. *Proceedings, International Conference on In-Situ Measurement of Soil Properties & Case Histories* (In-Situ 2001), Bali, Indonesia, 27-47. Download: www.usucger.org

Mayne, P.W., Coop, M.R., Springman, S., Huang, A-B., and Zornberg, J. 2009. State-of-the-Art Paper (SOA-1): Geomaterial Behavior and Testing. *Proc. 17th Intl. Conf. Soil Mechanics & Geotechnical Engineering*, Vol. 4 (ICSMGE, Alexandria, Egypt), Millpress/IOS Press Rotterdam: 2777-2872. Download: www.issmge.org

Mayne, P.W. 2017. Stress history of soils from cone penetration tests. 34th Manual Rocha Lecture, *Soils & Rocks*, Vol. 40 (3), Sept-Dec., Brazilian Society for Soil Mechanics, Saö Paulo: 203-218. http://www.soilsandrocks.com.br/

Mayne, P.W., Styler, M., Woeller, D.J. and Sharp, J. 2017. Identifying contractive soils by CPT material index for flow liquefaction concerns. Paper ID 827, *Proceedings GeoOttawa 2017: 70 Years of Canadian Geotechnics and Geoscience*, Canadian Geotechnical Society, Ottawa ON: www.cgs.ca

Mayne, P.W. and Styler, M. 2018. Soil Liquefaction Screening Using CPT Yield Stress Profiles. *Geotechnical Earthquake Engineering and Soil Dynamics V: Liquefaction Triggering, Consequences, and Mitigation* (GSP 290, Proc. GEESD-V, Austin), ASCE, Reston, VA: 605-616.

Mayne, P.W. and Sharp, J. 2019. CPT approach to evaluating flow liquefaction using yield stress ratio. *Proceedings of Tailings and Mine Waste 2019*, Vancouver, Published by the Institute of Mining Engineering, University of British Columbia: 655-670. tailingsandminewaste.com

Monfared, S.D. and Sadrekarimi, A. 2013. An overview of existing methods for estimating state parameter from cone penetration test results. *Proceedings GeoMontreal*, 66th Canadian Geot. Conf., Canadian Geotechnical Society, Ottawa: 7 pages.

Morgenstern, N.R., Vick, S.G., Viotti, C.B. and Watts, B.D. 2016. *Fundão tailings dam review panel: Report in the immediate causes of the failure of the Fundão Dam*. Cleary Gottlieb Steen & Hamilton LLP, New York. http://fundaoinvestigation.com/

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 & Geoenvironmental Engineering*: 129(8): 727–737.

Ouyang, Z. and Mayne, P.W. 2019. Modified NTH method for assessing effective friction angle of normally consolidated and overconsolidated clays from piezocone tests. *Journal of Geotechnical & Geoenvironmental Engineering* 145(10), ASCE doi.org/10.1061/(ASCE)GT.1943-5606.0002112

Pestana, J.M. and Whittle, A.J. 1995. Compression model for cohesionless soils. *Geotechnique* 45 (4): 611-631.

Plewes, H. D., Davies, M. P., and Jefferies, M. G. 1992. CPT based screening procedure for evaluating liquefaction susceptibility. *Proc. 45th Canadian Geotechnical Conference*, Vol. 4, BiTech Publishers, Vancouver, BC, Canada, 1–9.

Reid, D. 2019. Additional analyses of the Fundão Tailings storage facility: In-situ state and triggering conditions. *Journal of Geotechnical & Geoenvironmental Engineering* 145(11): 04019088

Reid, D., Fourie, A., Ayala, J.L, et al. 2020. Results of a critical state line testing round robin programme. *Geotechnique* (14 Dec 2020): https://doi.org/10.1680/jgeot.19.P.373

Robertson, P. K. 2009. Interpretation of cone penetration tests - A unified approach. *Canadian Geotechnical J.* 46(11): 1337–1355.

Robertson, P.K. 2010. Evaluation of flow liquefaction and liquefied strength using the cone penetration test. *Journal of Geotechnical and Geoenvironmental Engineering* 136 (6): 842–853.

Robertson, P.K., C.E. Wride, B.R. List, U. Atukorala, K.W. Biggar, P.M. Byrne et al. 2000. The CANLEX project: Summary and conclusions. *Canadian Geotechnical Journal* 37(3): 563–591.

Schafer, M., Dugie, M., Roda, A. and Wightman, A. 2019. State parameter estimation by CPTU interpretation for liquefaction susceptibility: a comparison of methods. *Proc. Geo St. John's*, NL (72nd Canadian Geotechnical Conference), Paper No. 552.

Styler, M.A., Mayne, P.W., McGowan, D. and Sharp, J.T. 2018. Predicting changes in static liquefaction susceptibility using cone penetration tests. *Proceedings, The Mine Waste and Tailings Conference*, Session 10, Paper 41, Brisbane: tailings.ausimm.com

Uzielli, M. and Mayne, P.W. 2019. Probabilistic assignment of effective friction angle of sands and silty sands from CPT using quantile regression. *Georisk: Assessment & Management of Risk for Engineered Systems and Geohazards* 13(4): 272-275. DOI: 10.1080/17499518.2019.1663388