

Trends for the Monotonic Response of Mine Tailings Under Critical State Soil Mechanics

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ABSTRACT

Static liquefaction has been associated with several failures of tailings storage facilities (TSFs) around the world. The failures result in devastating consequences for the environment and for civil infrastructure, as well as losses of human life. In this study, we present trends for the response of mine tailings to monotonic loading considering a) triaxial tests, b) bender element tests, and c) consolidation tests performed on mine tailings. These materials have a broad range of states, particle size distributions, and compressibility. The trends are evaluated in the context of static liquefaction using critical state soil mechanics framework. In particular, we present trends for shear strength (residual and peak), state and brittleness soil indexes, instability stress ratios, and dilatancy. Besides, we highlight that mine tailings mechanical properties reflect both the properties of the particles themselves and the relative proportions of different particle sizes. For instance, the observed trends suggest that particle gradation influences the small strain stiffness, and dilatancy; the proportion of voids to the size of fine particles influence strength, and particle shape affects dilatancy. Finally, static liquefaction screening indexes are proposed based on the observed trends.

INTRODUCTION

The static liquefaction of mine tailings has caused numerous recent failures, e.g., the 2015 Fundao failure in Brazil (Morgenstern et al., 2016), the 2018 Cadia failure in Australia (Morgenstern et al., 2019), and the 2019 Brumadinho failure in Brazil (Robertson et al., 2019). These failures have triggered international debates regarding the safety of TSF systems. In particular, the conditions that result in static liquefaction of mine tailings remain a considerable concern affecting the financial viability of mines and the willingness of governments to allow mining. From a technical standpoint, it is worth highlighting that static liquefaction is just another facet of soil behavior under loading, and hence it should be explained under a mechanistic framework. Arguably, CSSM is now the preeminent methodology for understanding static liquefaction, having been used in the mining industry by the expert panels retained to investigate recent TSF failures.

In terms of mine tailings, the experimental studies that have evaluated their mechanical response and the associated mechanical parameters are somewhat limited compared to sand materials. In a broader perspective, the mechanical properties in particulate materials (including mine tailings) reflect both the properties of the particles themselves and the relative proportions of the different particle sizes, which affect how easily particle movements create new contacts and the available space of particles to move into. In this study, we present trends for mechanical-based parameters that control the response of mine tailings, in the context of static liquefaction. Another aspect that we highlight is the influence of the relative proportions of particle sizes on the macro mechanical response of mine tailings. The trends are presented using results from 53 mine tailings materials (including available data from the recent failures previously discussed), which have been processed in a uniform manner. Finally, we provide screening indexes for the assessment of static liquefaction in mine tailings using insights from the observed trends.

MATERIAL DATABASE

The whole database consists has 53 different mine tailings material, 7 of them were generated as part of this study and the rest were compiled from Shuttle and Cuning (2007), Anderson and Eldridge (2011), Bedin et al. (2012), Schnaid et al. (2013), Been (2016), Li and Coop (2018), Li and Coop (2019), Raposo (2016), Torres (2016), Morgenstern et al. (2016), Riemer et al. (2017), Li (2017), Robertson et al. (2019), Macedo and Petalas (2019), Gill (2019), Reid and Fanni (2020), Reid et al. (2018), Reid et al. (2020), Fourie and Papageorgiou(2001), and Carrera (2011). The mine tailings database corresponds to different ores (i.e., gold, iron, silver, copper, zinc, platinum) covering a broad range of fine contents ($FC = 0 - 100 \%$), initial confining stress ($20 - 6000 \text{ kPa}$), specific gravity ($G_s = 2.63 - 4.89$), and states (i.e., very loose to dense). The following properties were evaluated for each material: the critical state line (CSL), the stress ratio at critical state (M_{tc}), the state-dilatancy parameter (χ), the stiffness-confinement dependence parameters (A, B) according to $G = A \cdot F(e) \cdot (p/p_a)^B$, where $F(e)$ represent the functional form proposed by Hardin and Richart (1963) and Pestana and Whittle (1995).

TRENDS IN THE MECHANICAL RESPONSE OF MINE TAILINGS

Critical state parameters and stiffness

Figure 1a shows a histogram of M_{tc} values for tailings in our database and sand materials obtained from Jefferies and Been (2016). It can be observed that M_{tc} values for mine tailings are generally larger compared to sands, which has also been observed in previous studies (e.g., Reid, 2015). This is due to the angularity associated with mine tailings as a product of the mineral processing. Figure 1b, shows the variation of the A coefficient with the initial state parameter, suggesting a good correlation. Hence, larger A values are generally associated with dense materials and lower A values are generally associated with loose materials. Furthermore, parameters A and B have shown to be dependent on particle shape and grain size distribution in sands (Cho et al., 2006; Payan et al., 2015). A, specifically, represents a volumetric-blended measure of soil particle stiffness. We explored the stiffness dependence on the particle size distribution of mine tailings using the α and β parameters ($V_s = \alpha \left(\frac{p}{1kPa}\right)^\beta$, where V_s is the shear wave velocity from bender tests). α and β are shear wave velocity counterparts of A and B and are used to integrate the sand data from Cho et al. (2006) in Fig. 1c and 1b. The trends indicate that as C_u increases α decreases and β increases. This is consistent with Payan et al. (2015) and suggest that the overall effect of the irregularities introduced by different particle sizes is to hinder particle mobility and their ability to attain dense packing configurations leading to lower V_s (lower α) that are more susceptible to changes in stresses (higher β).

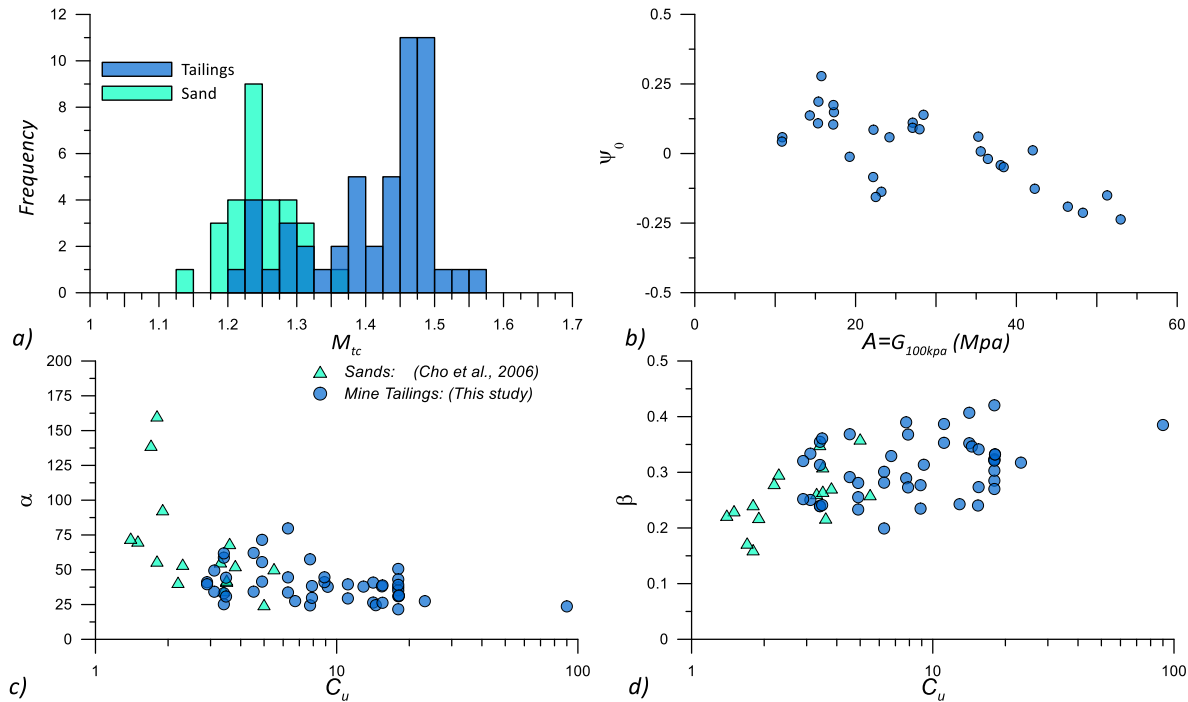


Figure 1. a) Distribution of M_{tc} values for tailing and sands, b) A versus ψ_0 , c) Variation of α and C_u and d) Variation of β and C_u .

Residual and peak strength

In Figure 2 we discuss trends in terms of peak and residual shear strengths. Fig. 2a and 2b shows the variation of Su_r/σ'_0 and Su_y/σ'_0 in terms of ψ_0 along with similar trends for sands with different compressibility extracted from Sadrekarimi (2013) and Jefferies and Been (2016). By examining Fig. 2a, the effect of compressibility is clearly observed, i.e., Su_r/σ'_0 in the case of sand materials increases with the increase of compressibility. In particular, the trends extracted for the Lagunillas sandy silt are more consistent with the overall variation of strength for mine tailings. The variation of Su_y/σ'_0 in Fig. 2b suggests that Su_y/σ'_0 tends to be larger in mine tailings compare to the sands in Jefferies and Been (2016) when ψ is lower than 0.1. To bring the effects of compressibility, we normalized the state parameter by λ_e . This normalization may also cancel out some fabric-related effects as compressibility is expected to be influenced by fabric.

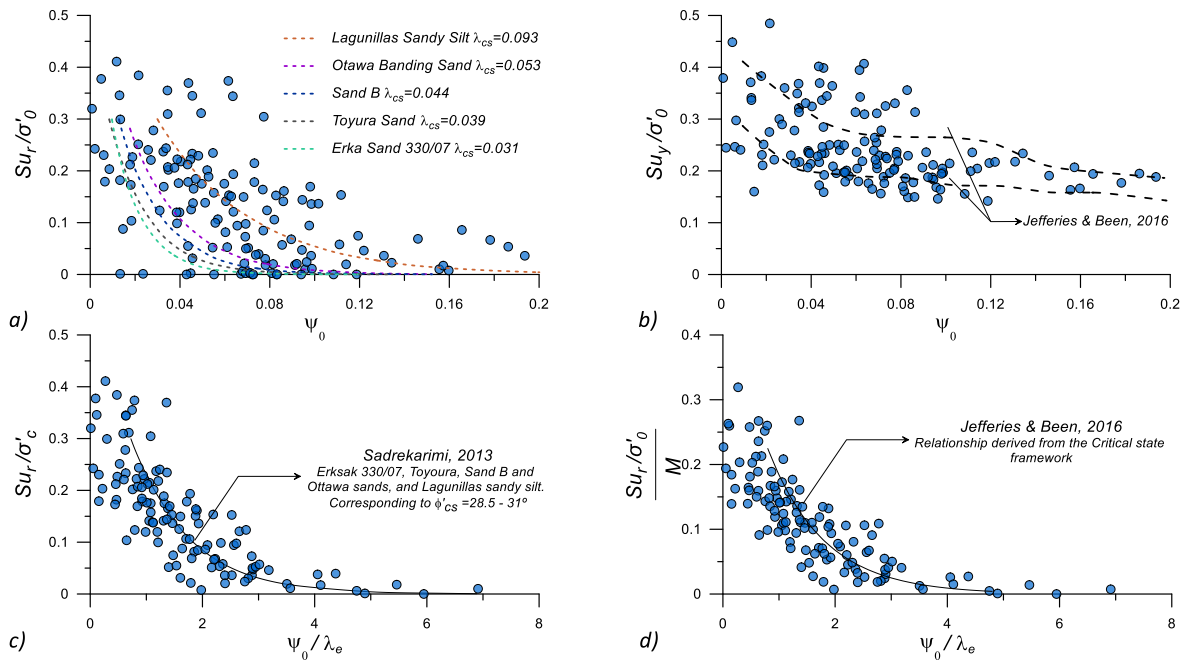


Figure 2. Su_r/σ'_0 and Su_y/σ'_0 vs the initial state parameter (ψ_0) ((a) and (b), respectively); c) Su_y/σ'_0 versus ψ_0/λ_e and (d) $Su_y/(M\sigma'_0)$ versus ψ_0/λ_e .

Fig. 2c shows the variation of Su_r/σ'_0 versus ψ/λ_e , now it can be observed that bringing λ_e decreases the variability in the trends, and the normalized trends for mine tailings are now more consistent with those for sand materials reported by Sadrekarimi (2013). Besides, in Figure 2d to account for the effects of angularity in strength, we further normalized the Su_r/σ'_0 by M_{tc} , and plotted the results in terms of ψ/λ_e . Recall that from CSSM concepts (e.g., Jefferies and Been, 2016) $Su_r/(M\sigma'_0) = 0.5\exp(-\psi/\lambda_e)$, which is also plotted in Figure 2d.

State and brittleness and instability stress ratio

In Figure 3, the flow liquefaction cases that correspond to full softening and partial softening, consistent with Soares and Viana da Fonseca (2016), are presented in red and yellow colors, respectively. Figure 3a and 3b shows the relationship between parameters to represent the state and brittleness of a soil material. Fig. 3a shows the relationship between I_b and ψ/λ_e , along with the data from Smith et al. (2019), and the upper and lower bounds they proposed. It can be observed that our data is consistent with these upper and lower bounds. Of note, the trends suggest that flow liquefaction cases with partial softening may have in general a I_b larger than 0.25 and a ψ/λ_e larger than 0.75, whereas the flow liquefaction cases with full softening may be associated with I_b values higher than 0.6 and ψ/λ_e values larger than 1.5. Fig. 3b shows the relationship between I_b and I_p . As expected I_p increases with the increase of I_b , and I_p values higher than 2.5 seem to be indicative of flow liquefaction with partial softening, whereas values larger than 10 may be indicative of potential flow liquefaction with full softening.

Figure 3c shows the variation of the normalized instability stress ratio η_{IL}/M_{tc} and the normalized state parameter (ψ_0/λ_e), for the cases where partial or full softening (i.e., flow liquefaction) was observed in undrained triaxial tests. As expected, η_{IL}/M_{tc} tends to decrease with the increase of ψ_0/λ_e . In addition, we observe η_{IL}/M_{tc} values that are generally in the range of 0.6 to 1 for flow liquefaction cases with partial softening, and values lower than 0.6 for flow liquefaction cases with full softening.

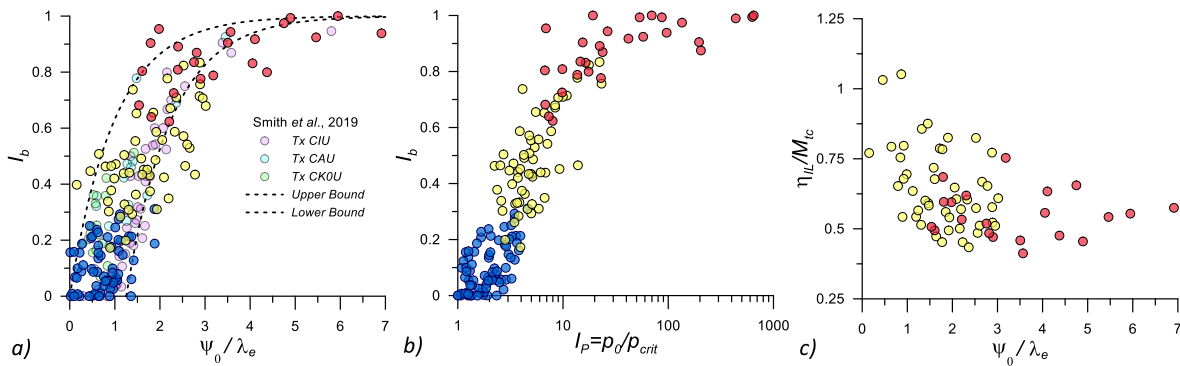


Figure 3. a) Relationship between I_b and ψ/λ_e , b) I_b versus I_p and c) Variation of the normalized instability stress ratio (η_{IL}/M_{tc}) versus ψ/λ_e .

Dilatancy

Figure 4a shows the variation of the maximum dilatancy in triaxial CD tests versus ψ_0 , considering the mine tailings from this study and data available in Jefferies and Been (2016) for sand materials. If we fit the data to the relationship suggested by Been and Jefferies (1985), given by $D_{min} = \chi\psi$ we obtain representative χ values of 3.0 for sands, and 4.0 for tailings. This suggests that mine tailings have an average stronger scaling of dilatancy compared with sands, given a similar state parameter. This can be explained considering that χ can be thought as a kinematic parameter related to the

potential of particulate materials to re-accommodate particles. Given the more angularity of mine tailings compared to sands, mine tailings seem to have, on average, a higher potential on re-accommodating particles. Figure 4b shows the variation of χ and C_u/D_{50} for mine tailings and some well-known sand materials (i.e., Erksak, Braster, Changi, Fraser, Nerlek, and Ticino sands). The data for sands was obtained from Jefferies and Been (2016). It can be observed that the χ values in sands vary in a narrow range between 3.5 and 5.0, which correspond to C_u and C_u/D_{50} values that are also in a narrow range (1 to 3, and 3 to 10, respectively). In the case of mine tailings, we observe that χ tends to decrease with the increase of C_u/D_{50} , which is consistent with observations from DEM simulations (Yan and Dong, 2011). We also noticed that the lowest χ values (lower than 1.4) correspond to materials with large FC (larger than 85%) and important clay size fractions. This observation is consistent with the findings from (Cola and Simonini, 2002). The materials 26 and 31 (which correspond to the Cadia and Brumadinho failures previously discussed) showed large χ values (5.8 and 7.2, respectively). These large values may be associated with the large angularity on these materials, and bonding effects, as suggested by Robertson et al. (2019) based on inspections of scanning electron microscope (SEM) images from the Brumadinho tailings.

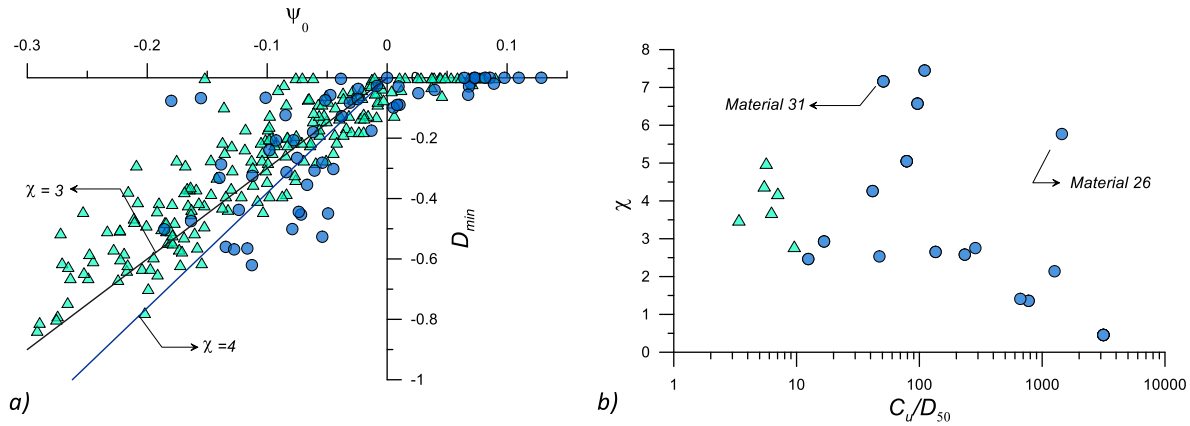


Figure 4. a) Variation of ψ and D_{min} for sands and mine tailings. b) Variation of χ and C_u/D_{50}

CONCLUSION

In this study, we have used critical state soil mechanics (CSSM) concepts to examined salient trends on the mechanical response of mine tailings, highlighting the role the relative proportions of different particles sizes, and particle properties. Our results suggest that mine tailings fit the same framework as natural sands, with the key difference of showing a much larger M_{tc} and somewhat larger χ , both attributed to underlying particle shape, which then affects standard correlations. Thus, the mechanical response of mine tailings can be reasonably well explained once CSSM-based parameters such as Γ , λ_e , ψ , M_{tc} , χ , N , and G are incorporated. We have observed that particle gradation influences the small strain shear stiffness and dilatancy, which is consistent with previous

observations on sands. An increase in C_u typically reflects on a decrease in α and χ , and an increase in β . Additional salient conclusions from this study include: 1) The M_{tc} values in mine tailings (in the order of 1.4) are larger, on average, compared to M_{tc} values on natural sands (in the order of 1.2). This is associated to the particle shape of mine tailings, which tend to have more angular particles compared to the subrounded grains found in natural soils. 2) Parameter A that controls the magnitude of G correlates well with ψ_0 . 3) Compressibility can have an important effect on Su_r/σ'_0 , and controls Su_y/σ'_0 . Hence, it should be carefully considered in evaluating appropriate Su_r/σ'_0 and Su_y/σ'_0 design values. 4) The trends suggest that flow liquefaction cases with partial softening may have in general I_b , ψ/λ , and I_p values larger than 0.25, 0.75, and 2.5, respectively. Whereas flow liquefaction with full softening is associated with I_b , ψ/λ , and I_p values higher than 0.6, 1.5, and 10, respectively. The normalized instability stress ratio (η_{IL}/M_{tc}) for flow liquefaction cases with full softening was, in general, lower than 0.6. We recommend using these values as part of screening procedures in engineering practice.

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