Variation of steady state parameters within an iron ore tailings storage facility

Variation des paramètres d'état critique dans une installation de stockage de résidus de minerai de fer

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ABSTRACT: The projection of the steady state line (SSL) in void ratio (e) versus mean effective stress (p') space is affected by the intrinsic properties of a soil: particle size distribution, particle shape and mineralogy. Accordingly, the SSL characterisation of a soil deposit can be an onerous task because a series of triaxial tests is required to obtain the SSL of several combinations of intrinsic properties present in the deposit. This has led to the research of correlations between the SSL and easily measured index properties. Recent research suggests that the e – p' projection of the SSL of soils with low plasticity index (PI) is correlated to the minimum void ratio (e_{min}). The current work explored this approach in the determination of the SSL of two types of iron ore tailings extracted from the same deposit. One tailings type had a low PI (0 - 7%), whereas the other tailings type had an intermediate PI (4 - 18%). The results confirmed the variability of SSL parameters expected in tailings deposits. Furthermore, the correlation between e_{min} and the vertical position of the SSL in e-log(p') space of the low plasticity tailings were in good agreement with a previous correlation reported in the literature. Such agreement was not observed for the tailings of intermediate PI. This result highlights the advantages and limitations of correlating e_{min} to the SSL of tailings.

RÉSUMÉ : La projection de la ligne à l'état stable « steady state line » (SSL) dans le rapport de vide (e) par rapport à l'espace moyen de contrainte effective (p ') est affectée par les propriétés intrinsèques d'un sol: distribution granulométrique, forme de particule et minéralogie. En conséquence, la caractérisation SSL d'un dépôt de sol peut être une tâche onéreuse car une série de tests triaxiaux est nécessaire pour obtenir le SSL de plusieurs combinaisons de propriétés intrinsèques présentes dans le dépôt. Cela a conduit à la recherche de corrélations entre le SSL et des propriétés d'index facilement mesurées. Des recherches récentes suggèrent que la projection e-p de SSL des sols à faible indice de plasticité (PI) est corrélée au taux de vide minimum (emin). Le travail actuel a exploré cette approche dans la détermination du SSL de deux types de résidus de minerai de fer extraits du même dépôt. Un type de résidus avait un PI faible (0 à 7%), tandis que l'autre type de résidus avait un PI intermédiaire (4 à 18%). Les résultats ont confirmé la variabilité des paramètres SSL attendus dans les dépôts de résidus. En outre, la corrélation entre emin et la position verticale du SSL dans l'espace e-log (p ') des résidus à faible plasticité était en bon accord avec une corrélation précédente rapportée dans la littérature. Un tel accord n'a pas été observé pour les résidus de PI intermédiaire. Ce résultat souligne les avantages et les limites de la corrélation entre emin et le SSL des résidus.

KEYWORDS: steady state parameters, iron ore tailings, minimum void ratio, plastic fines

1 INTRODUCTION

The steady state line (SSL) reflects the combined effect of the various intrinsic properties of a soil: particle size distribution (PSD), particle shape and mineralogy. An understanding of the steady state parameters enables an understanding of the mechanical behaviour of a soil. Within the mining industry, this enhanced and vigilant understanding of a soil, or more particularly, tailings material, has become increasingly necessary. The importance of this understanding is illustrated by the recent catastrophic failures of Mount Polley and Fundão Tailings Storage Facilities (TSFs). Both of these failures resulted in financial, social and material losses (Morgenstern et al. 2016 and Morgenstern et al. 2015).

The outer walls of TSFs are generally built of the same tailings material that is impounded in the facility. Accordingly, it is imperative that the mechanical behaviour of the tailings is understood and can be predicted. This can be achieved, in part, by having an understanding of the SSL parameters (Jefferies and Been 2006).

The SSL parameters Γ, λ and M are often used for engineering purposes. Γ and λ describe the SSL in e – log (p') space (Eq. 1), whereas M describes the SSL in q – p' space (Eq. 2).

$$e_c = \Gamma - \lambda \log_{10} p' \tag{1}$$

$$q = M.p' \tag{2}$$

The experimental determination of a SSL requires a suite of triaxial tests. Given the dependence of the SSL on intrinsic soil properties, the SSL within a single TSF varies due to the variability of tailings properties. Accordingly, the characterisation of a TSF from a SSL standpoint may require the testing of several types of tailings to gain an understanding of SSL variability within the TSF (Jefferies and Been 2006). Recent research results suggest that for low plasticity soils the e – log (p') projection of the SSL, and particularly Γ, can be correlated to the minimum void ratio (e_{min}) (Torres-Cruz 2016). Such correlation is useful in selecting the types of tailings whose SSLs can be experimentally determined in order to best understand the variability of SSLs within a TSF.

The purpose of the current paper is to explore the applicability of the Γ-e_{min} correlation presented by Torres-Cruz (2016) to two iron ore tailings types with low and intermediate PI. The results highlight the advantages and limitations of correlating e_{min} to the SSL of tailings.

2 DESCRIPTION OF TAILINGS MATERIAL

The two tailings types considered are processed by two plants that mill different grades of iron ore found in the banded iron formation (BIF) and the Kuruman formation and whose predominant mineralogies are magnetite and haematite, respectively. The high grade ore from the BIF is processed using dense media separation (cycloning and drumming). The resulting tailings exhibit low plasticity and are dark grey in colour with a shiny lustre. The lower grade ore from the Kuruman formation is processed in a plant that uses a jigging or gravity separation methodology. The resulting tailings exhibit intermediate plasticity and are bright red in colour. Each tailings stream is deposited in separate compartments of the same TSF. Samples of each tailings material type were collected at various locations along the beaches of deposits and will be called H- (high grade) and L- (low grade) type tailings.

The PSDs corresponding to sixteen L tailings and seven H tailings are shown in Figure 1. The PSDs were determined by TMH 1 Methods A1(a), A5 and A6. Overall, the L tailings show little variation in PSD shape with the exception of three outliers. It is noted, however, that the sizes of 30 – 40 % of the material tested has not been characterised due to the particles being smaller than 0.002 mm which corresponds to the lower bound of applicability of the hydrometer analysis. Conversely, the H tailings show a larger variability in PSD and have a more limited percentage of particles smaller than 0.002 mm.

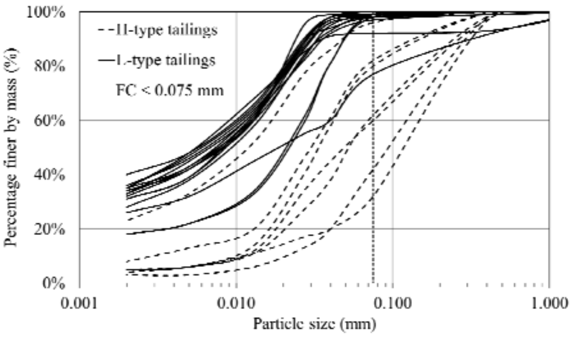

Figure 1. Particle size distribution curves for H and L tailings

Five samples of H tailings and five of L tailings were selected for further testing based on variability in fines content (FC) and shape of the PSD. Of the selected H tailings samples, the FC range was 62 – 85 %, PI range was non-plastic to 7 %, liquid limit (LL) was 0 – 16 %, the Activity (PI / % < 2μm) range was 0 – 1.4 and the ρ_s range was 3.78 – 4.44 g/cm^3. Of the selected L tailings samples, the FC range was 77 – 99 %, PI range was 4 – 18 %, LL was 14 – 29 %, the Activity range was 0.2 – 0.5 and the ρ_s range was 3.72 – 4.06 g/cm^3. The PI and LL values were obtained following the Casagrande cup and thread rolling methods.

Samples H1 of H tailings, and L1 of L tailings were chosen to have their plasticity further investigated with the falling cone method as per BS 1377 Part 2: 1990. When the plasticity of these samples had been initially investigated with the Casagrande cup and thread rolling, sample H1 was found to be non-plastic and sample L1 exhibited PI = 11. Using the results of the fall cone test, the flow curves of both samples was defined with nine points (Figure 2). These well-defined flow curves allowed for an alternative estimation of PI using the approach suggested by Feng (2001). In this approach, the flow curve is modelled as a straight line in a doubly logarithmic space. The LL is then taken as the water content at d = 20 mm, and the plastic limit (PL) is taken as the water content at d = 2 mm. Following Feng's approach, the PI of both samples increased, with H1 yielding PI = 7, and L1 yielding PI = 18.

The fact that the flow curve H1 could be defined at lower water contents than for L1 is also an indicator of the different nature of these two materials. That is, in the low plasticity H tailings the water content was more easily distributed uniformly than in the higher plasticity L tailings. Thus, when attempts were made to prepare specimens of L1 at water contents smaller than about 20%, the specimen would exhibit lumps which rendered it inadequate for fall cone testing. Conversely, even at small water contents, the moisture could be more easily distributed in the specimens of H1 tailings, hence enabling fall cone testing on drier specimens.

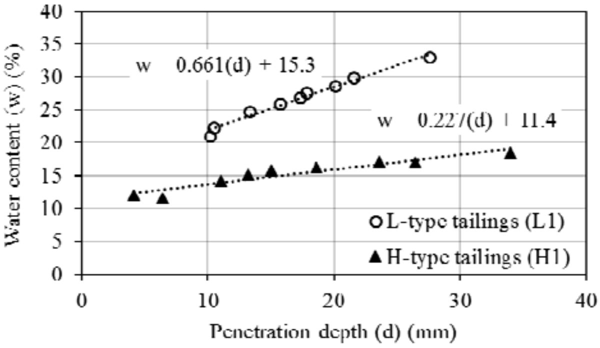

Figure 2. Flow curves for L and H tailings using the falling cone method

The maximum void ratio (e_{max}) was determined using the ASTM D4254 funnel deposition method. The mould that was used was not as large as the standard mould, however the dimensional guidelines for fabricating a special mould were adhered to. The mould dimensions are 79.7 mm in diameter, 103.4 mm in height and a volume of 519 mL (measured by the water filling method). It is noted that the ASTM D4254 method is only applicable to soils with less than 15 % by mass passing the 0.075 mm sieve. Regardless, the method was adopted herein out of a desire to adopt a standardised procedure.

The same mould used for e_{max} was used for the e_{min} determinations. The first method that the authors tried to use to determine e_{min} was the vibratory table method described by ASTM D4253. Similar to the case with e_{max}, this standard is only applicable to soils with less than 15 % by mass passing the 0.075 mm sieve. However, the authors tried to use it due to the lack of an alternative standard for fine-grained soils. After conducting a few vibratory table tests on the H and L tailings it became clear as to why the method is only be applicable to coarser soils. This is because the surcharge weight becomes jammed in the mould due to the fine material that gets lodged between the surcharge weight and the sides of the extension collar. Removal of the surcharge weight at the end of each test hence resulted in disturbance of the test specimen which led to poor repeatability of results. For instance, two L tailings specimens were tested eight and ten times respectively. The range of e_{min} values was 0.97 - 1.06 (standard deviation = 0.03) and 0.97 - 1.09 (standard deviation = 0.04). These wide void ratio ranges implied a failure to comply with ASTM D4253 which requires that the tests be continued until consistent density or unit weight values within ± 2 % are obtained. Consequently, this testing methodology was discontinued and a non-standard method was employed.

The non-standard e_{min} method entails filling the mould and extension collar in forty layers of equal mass such that material of approximately 10 – 20 mm in height extends past the top of the mould and into the extension collar. After pouring each layer into the mould, it is struck with a rubber mallet eight times (twice on each orthogonal side). Once all forty layers have been poured into the mould and compacted, a standard surcharge weight in accordance with ASTM D4253 (13.8 kPa) is placed into the collar and the mould is struck another eight times. Thereafter, the surcharge weight and extension collar are removed and the mass and void ratio are determined. The e_{min} values determined by the non-standard method were all within 0.01 of each other and therefore this method was deemed more reliable due to good repeatability. This non-standard method is described in greater detail in Torres-Cruz (2016), who also presents evidence that the method produces results that are consistent with the e_{min} values as calculated from modified Proctor compaction tests.

A trend of direct linear correlation was observed between e_{max} and e_{min} (Figure 3) as expected from Cubrinovski and Ishihara (2002). Due to the relatively similar shape of PSDs of the L tailings, more similar index void ratios were anticipated, however the values of e_{max} cover a range of almost 0.4, and the e_{min} values a range of just over 0.2. This variation of e_{max} and e_{min} values is probably a result of difference in PSD for particles smaller than 0.002 mm. As noted above such particles make up 40% of the L tailings and their PSD is not reflected in Figure 1.

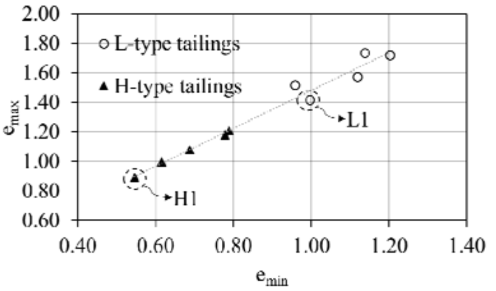

Figure 3. e_{min} (non-standard procedure) versus e_{max} (ASTM D4254)

3 SSL EXPERIMENTAL PROGRAMME

Samples H1 (FC = 62 %) and L1 (FC = 98%) were selected for SSL testing due them being representative of the different compartments of the TSF.

In order to develop SSLs the current work adopted the methodology suggested by Jefferies and Been (2006) which uses both Consolidated Undrained (CU) and Consolidated Drained (CD) triaxial tests with specimens prepared to low relative densities that result in contractive behaviour. The size of the specimens was 50 mm in diameter by 100 mm in height.

The specimens of H1 were prepared by moist tamping in 5 layers of equal mass and height in order to achieve a target and uniform void ratio. Each layer was premixed with distilled water at about 5% moisture content. The layers were allowed to cure for at least two hours. In this procedure, the initial moisture of the layers allows the development of suction such that the specimen remains stable without any kind of external support when the split mould is removed.

Preparation of specimens of sample L1 by the moist tamping method proved impossible because the specimens fell apart when the split mould was removed. This is believed to be due to difficulties in mixing the moisture uniformly in the specimen. In order to prepare specimens that were both contractive and uniform, the specimens of L1 were thus formed following the procedure that is generally used for coarse grained soils. This method entails preparing the specimen on the triaxial base pedestal with the rubber membrane, porous stone and filter paper already in place on the pedestal. A split former mould is placed around the membrane. The specimens were prepared by dry tamping 5 layers of equal mass and height taking care not to tear the membrane. Once the specimen is formed a small vacuum is applied through the top cap before removing the mould.

Post shear void ratios were measured using the method proposed by Verdugo and Ishihara (1996) but using the minor modifications described by Hemer et al. (2016).

4 RESULTS AND CORRELATIONS

The p' – ε_a plots (Figure 4) as well as the pwp – ε_a (CU tests) and e – ε_a (CD tests) plots (Figure 5) for the H1 and L1 tailings suggest that most specimens reached steady state. However, when this was not the case the extrapolation proposed by Carrera et al. (2011) was applied. Similarly, this extrapolation was also used when there were abrupt changes in the readings potentially due to the formation of failure planes. Selected test results are also shown in Table 1.

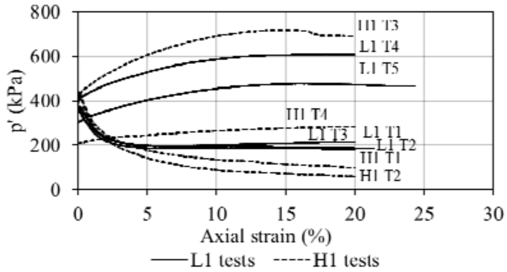

Figure 4. Plots of p'– ε_a for each H and L tailings triaxial test

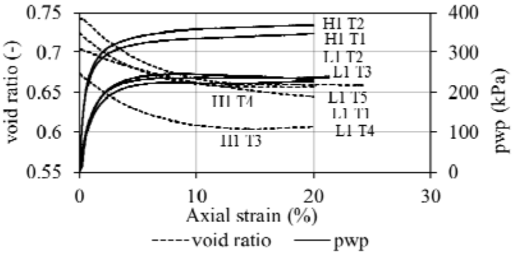

Figure 5. Plots of e – ε_a and pwp – ε_a for each H and L tailings triaxial test

The SSLs in e – log (p') and q – p' space are presented in Figures 6-8 and the SSL parameters are summarised in Table 1. It is noted that the determined M values are close to 1 which is significantly lower than the values reported for other tailings materials which tend to be closer to 1.3 (e.g. Jefferies and Been 2006). It is hypothesized that the low M values might be due to the fact that both materials exhibit at least some plasticity thus leading the tailings to develop M values that are generally characteristic of clayey materials. For instance, Schofield and Wroth (1968) published values of M for various clays of 0.888 – 1.020. According to Yu (1998), M values for clays are normally between 0.8 and 1.0.

The results were compared to the correlation between e_{min} and Γ_{50} presented by Torres-Cruz (2016) as shown in Figure 9. The data upon which the Torres-Cruz (2016) correlation was made is of soils with PI ≤ 12. The H1 tailings are in agreement with the correlation. The L1 tailings however do not fit into the correlation at all. A possible reason for this is that for the L1 tailings PI was measured to be 11 or 18, depending on the method, whereas for H1 PI was 0 or 7. The higher PI of L1 with respect to H1, probably explains why L1 does not fit the correlation, whereas H1 does. It is interesting though, that if only the Casagrande cup and the thread rolling methods had been used to measure PI = 11 in sample L1, it would not be clear why this soil does not fit a correlation that was developed for soils with PI ≤ 12. The potentially higher plasticity of sample L1 only became evident when measuring PI = 18 using the Feng (2001) approach which relies on fall cone testing. This latter approach is deemed preferable by the authors owing to the greater repeatability of the fall cone test. Further testing is still underway to more confidently define the SSLs of H1 and L1 tailings, and better understand the differences in their behaviour.

Table 1. Results of SSL testing programme

Test no.	*Test type*	*e_s**	*p'_s** (kPa)*	*Γ_{50}****	*M*
H1 T1	CU	0.700	62	0.71	1.00
H1 T2	CU	0.711	37	-	-
H1 T3	CD	0.627	606	-	-
H1 T4	CD	0.659	307	-	-
L1 T1	CU	0.685	196	0.73	1.04
L1 T2	CU	0.703	187	-	-
L1 T3	CU	0.675	227	-	-
L1 T4	CD	0.657	600	-	-
L1 T5	CD	0.666	458	-	-

*e_s: void ratio at steady state **p'_s: mean effective stress at steady state ***Γ_{50}: Void ratio value of SSL with mean effective stress of 50 kPa.

5 CONCLUSIONS

The results of an SSL testing programme on two different iron ore tailings have been presented. The SSL parameters were presented and notably, the M values for both materials were unusually low when compared to previously reported tailings. A possible reason for this is that the tailings tested herein exhibited some plasticity and a lower M value is a characteristic of plastic soils. The results were compared to a recent correlation between e_{min} and Γ_{50} and it was found that the material with a smaller PI correlated well with the data. Conversely, the material with higher PI did not fit the correlation.

Although additional testing is still underway, the preliminary results herein suggest that: 1) Discrepancies between the different methods of measuring PI can lead to important misinterpretations of soil behaviour, 2) the M value of tailings with even limited plasticity can be significantly lower than the value of non-plastic tailings, and 3) the Γ_{50}-e_{min} correlation proposed by Torres-Cruz (2016) should be used exclusively with low plasticity soils (PI ≤ 12).

6 ACKNOWLEDGEMENTS

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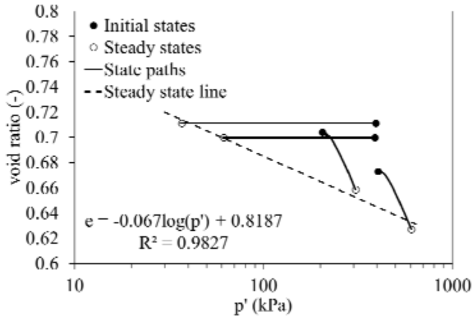

Figure 6. State paths and steady state line for H1

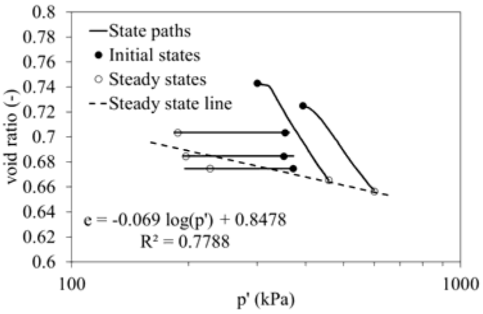

Figure 7. State paths and steady state line for L1

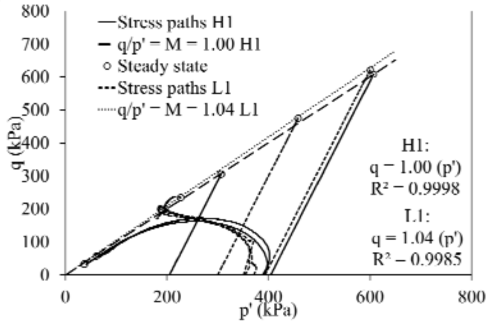

Figure 8. Stress paths for H1 and L1

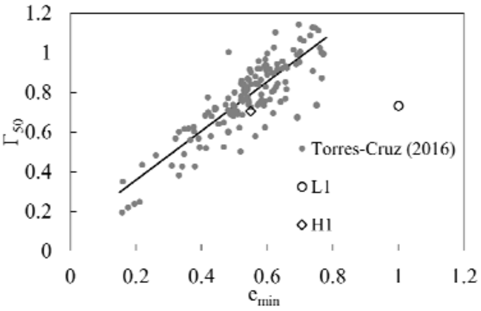

Figure 9. Current work data plotted with correlation between Γ_{50} and e_{min} (Torres-Cruz 2016)

6 REFERENCES

Carrera A., Coop M. and Lancellotta R. 2011. Influence of grading on the mechanical behaviour of Stava tailings. *Géotechnique* 61 (11), 935-946.

Cubrinovski M. and Ishihara K. 2002. Maximum and minimum void ratio characteristics of sands. *Soils and Foundations* 42 (6), 65-78.

Feng T.-W. 2001. A linear log d – log w model for the determination of consistency limits of soils. *Canadian Geotechnical Journal* 38, 1335–1342.

Hemer J.C., Mincione N.L.M and Torres-Cruz L.A. 2016. Determination of steady state lines for non-plastic platinum tailings. *Proceedings of the first Southern African Geotechnical Conference*. Sun City, South Africa.

Jefferies M. and Been K. 2006. *Soil liquefaction: A critical state approach*, Oxon: Taylor and Francis.

Morgenstern NR.,Vick SG., van Zyl D. 2015. *Report on Mount Polley Tailings Storage Facility Breach.*

Schofield AN. and Wroth P. 1968. Critical state soil mechanics. McGraw-Hill.

Torres-Cruz LA. 2016. *Use of the cone penetration test to assess the liquefaction potential of tailings storage facilities*. PhD Thesis. Faculty of Engineering and the Built Environment. University of the Witwatersrand. South Africa.

Verdugo R. and Ishihara K. 1996. The steady state of sandy soils. *Soils and Foundations* 36 (2), 81-91.

Yu HS. 1998. CASM: A unified state parameter model for clay and sand. *International Journal for Numerical and Analytical Methods in Geomechanics* 22, 621—653.