ARTICLE

Characterization of unsaturated mine waste: a case history

P.K. Robertson, A. Viana da Fonseca, B. Ulrich, and J. Coffin

Abstract: It is becoming increasingly common in the mining industry for either crushed ore or filtered mine waste to be stacked to a significant height (>100 m) in a moist state with little compaction, resulting in deposits that can be potentially loose and unsaturated. This paper presents a case history describing the characterization of stacked filtered tailings at a mine site in South America. Cone penetration tests with pore pressure and seismic velocity measurements (SCPTu) were carried out along with selected drilling, sampling, and laboratory testing. Compression wave velocity (V_p) and shear wave velocity (V_s) profiles were obtained and compared with laboratory values on reconstituted saturated and unsaturated samples. Results indicate that shear wave velocity is sensitive to suction hardening effects and appears to capture the correct unsaturated in situ behavior. The cone resistance, which is a large strain measurement, can destroy the beneficial effects of suction hardening and appears to be insensitive to the unsaturated in situ behavior, but may capture the correct behavior after the beneficial effects of suction are removed if the soil becomes saturated.

Key words: tailings, unsaturated, cone penetration test (CPT), seismic, case history.

Résumé : Il est de plus en plus courant dans l'industrie minière d'empiler soit le minerai concassé ou les résidus miniers filtrés à une hauteur significative (>100 m) dans un état humide avec peu de compaction entraînant des dépôts qui peuvent être potentiellement lâches et non saturés. Cet article présente une étude de cas décrivant la caractérisation des résidus filtrés empilés sur un site minier en Amérique du Sud. Des essais de pénétration au cône de la pression interstitielle et avec des mesures de vitesse sismique (« SCPTu ») ont été effectués ainsi que certains forages, échantillonnages et essais en laboratoire. Les profils de la vitesse de l'onde de compression (V_p) et la vitesse de l'onde de cisaillement (V_s) ont été obtenus et comparés aux valeurs obtenues en laboratoire sur des échantillons saturés et insaturés reconstitués. Les résultats indiquent que la vitesse de l'onde de cisaillement est sensible aux effets de durcissement par succion et semble capter le comportement correct in situ non saturé. La résistance du cône, qui est une mesure de grande déformation, peut détruire les effets bénéfiques du durcissement par succion et ne semble pas sensible au comportement in situ insaturé, mais peut capturer le comportement correct après les effets bénéfiques de la succion sont supprimés si le sol se sature. [Traduit par la Rédaction]

Mots-clés : résidus, non saturé, essai de pénétration au cône (« CPT »), sismique, histoire de cas.

Introduction

In the mining industry, it is becoming more common for either crushed ore or filtered mine waste to be stacked to a significant height (>100 m) in a moist state, often with little compaction. The resulting deposit can be potentially loose and unsaturated. Characterization of these stacked deposits for stability under both static and seismic loading can be challenging due, in part, to the potentially unsaturated state. This paper presents a case history describing the characterization for stacked filtered tailings in South America.

The tailings storage facility is composed of filtered tailings placed via conveyor and radial arm stacker within a valley. The materials have been placed in lifts of about 20 to 30 m thickness during previous mine operations with minimal compaction and currently have an approximate overall downstream slope of 4H:1V (horizontal to vertical). Lifts have been placed at slopes of approximately 1.5H:1V to 2.5H:1V with each lift offset by either 40 to 60 m to create benches.

At the time of the investigation the maximum height from toe to crest was about 200 m with a maximum thickness of tailings of about 125 m, due to the sloping natural ground. The total surface area of the facility is about 282 000 m² with an estimated contents of about 100×10^6 t. One of the main design issues is the stability of the tailings facility under both static and seismic loading. Hence, detailed characterization is important to understand the behavior of the tailings under both static and seismic loading conditions. A major design issue is to determine if the tailings could experience any strength loss and hence, possible instability (i.e., flow liquefaction).

Given the dry climate in the region, the placement of the tailings in a moist loose state, and the relatively low rate of irrigation, the tailings are expected to be predominately unsaturated. In unsaturated soils the voids are filled with a mixture of fluid and air resulting in suction forces. In general, unsaturated soils have a higher resistance to cyclic loading, but may experience some strength loss if the degree of saturation is relatively high and the soils very loose (Grozic et al. 2000).

A review of the literature (e.g., Leroueil and Hight 2003) on unsaturated soil behavior provides the following additional observations:

- Soil suctions increase the effective stresses (σ') in the soil compared to saturated soils.

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Fig. 1. Typical seismic cone penetration test with pore pressure measurements (SCPTu) profile showing basic cone penetration tests with pore pressure measurements (CPTu) parameters (cone tip resistance, q_t; sleeve friction, f_s; penetration pore pressure, u_2). Diss., dissipation test. [Color online.]
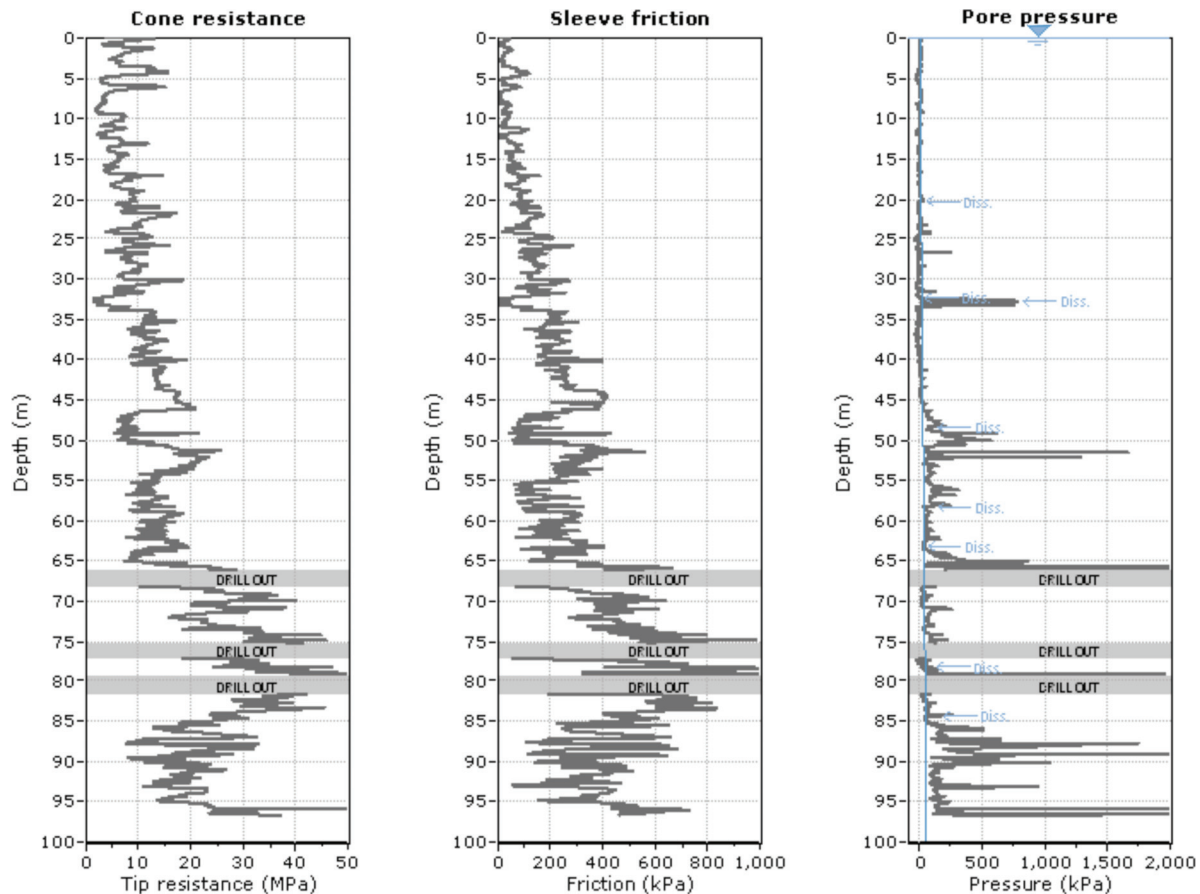
- Suction also increases the size of the yield surface for soils, such that unsaturated soils tend to behave more like an overconsolidated soil (i.e., respond inside the yield surface).
- The size of the yield surface is a function of the amount of suction (e.g., higher suction values produce larger yield surface and more dilatant response).
- Suction appears to move the critical state line (CSL) that is also a function of the amount of suction.
- The movement of the CSL produces a cohesion intercept in terms of strength (due to the higher yield surface and CSL).

The objective of this paper is to present a summary of a recent tailings characterization program and to describe the interpretation and implications for design. The recent site investigation included seismic cone penetration tests with pore pressure measurements (SCPTu). Based on accepted current practice there was a significant difference in the interpretation of soil behavior based on either cone resistance or shear wave velocity. Hence, much of this paper investigates and attempts to explain this difference.

Site investigation program

Since the start of mine operations at the site in 1990, there have been several geotechnical studies to characterize the tailings deposit. This paper will focus only on the most recent study that started in 2014 and was composed of SCPTu, drilling, sampling, and installation of piezometers. Limited seismic profiling was also carried out using multichannel analysis of surface waves (MASW) at the downstream toe of the tailings facility. Laboratory testing was also carried out on selected and representative reconstituted samples tested in either a saturated or unsaturated state.

Based on grain-size distribution curves, the tailings are classified as predominately silty sand to sandy silt with a mean grain size (D_{50}) of about 0.065 mm. The grain-size distribution curve for the tested tailings is similar to other poorly graded silty tailings reported by Jefferies and Been (2006). The average specific gravity of the tailings is 2.73 and the tailings are predominately nonplastic.

The SCPTu program was carried out using a portable hydraulic ram mounted on to a drill rig. A total of 12 SCPTu locations were advanced in the tailings facility described in this paper. Compression wave velocity (V_p) and shear wave velocity (V_s) measurements were made using a geophone in the 15 cm² cross-sectional area cone using the down-hole method (e.g., Robertson et al. 1986). Pore pressures were measured in the u_2 location behind the cone tip. Twenty-three vibrating wire piezometers were also installed in cased boreholes at six locations to record and monitor the long-term piezometric pressures. At each location, several piezometers were installed at different depths in a nested array to monitor the piezometric pressures (u_o) over time.

Figure 1 shows a typical SCPTu profile at the deepest section of the facility where the SCPTu profile extended to a depth of 96.6 m. Figure 1 shows the profile of corrected cone tip resistance (q_t), corrected for unequal end area (Campanella et al. 1982), sleeve friction (f_s), and penetration pore pressure (u_2). Several zones required a drill-out due to the limited reaction capacity of the anchored drill rig and are identified in the profile as gaps in the SCPTu data. The SCPTu data suggest that the tailings are mostly composed of loose sandy silt with some zones that appear to have slightly higher fines content where some excess penetration pore pressures are recorded.

Fig. 2. Normalized CPT profile showing normalized parameters (Q_{tn}, F_r, B_q, I_c). [Color online.]
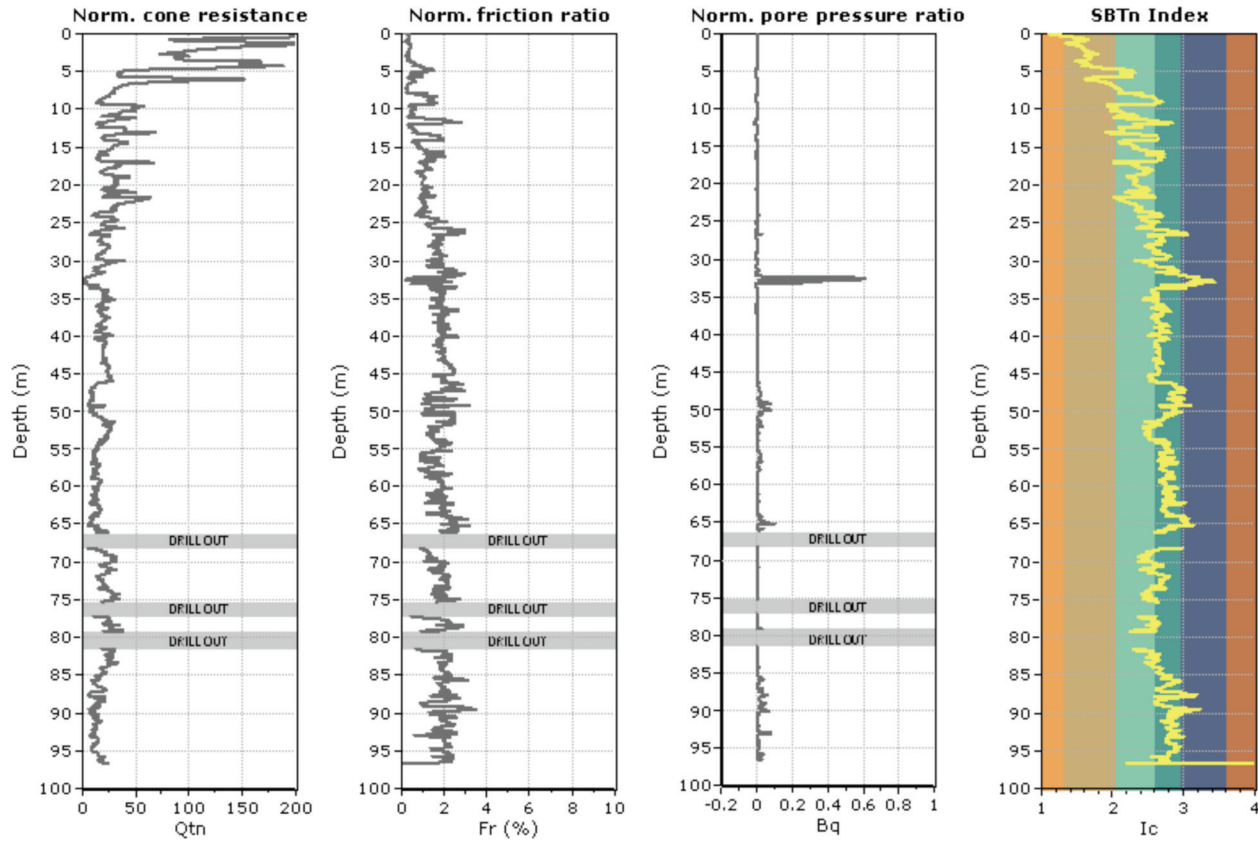
Dissipation tests were carried out at frequent depth intervals to estimate the equilibrium piezometric pressure (u_o) at the time of the investigation. The time taken to monitor the dissipation of any excess penetration pore pressures varied from a few seconds up to 3600 s. The time required to reach 50% dissipation (t_{50}) varied from essentially zero (i.e., essentially drained penetration) up to 100 s with an average t_{50} of about 50 s. In general, the equilibrium pore pressures measured by the SCPTu (u_o) were close to zero over much of the profile. The very low piezometric profile was generally confirmed by the data from the vibrating wire piezometers monitored over a much longer time period. The maximum value for u_o measured in the SCPTu profile shown in Fig. 1 was about 50 kPa at a depth of 84.3 m.

Figure 2 shows the same SCPTu profile, but in terms of normalized cone penetration test (CPT) parameters (normalized cone resistance (Q_{tn}), normalized friction ratio (F_r), normalized pore pressure ratio (B_q), and soil behavior type index (I_c)) suggested by Robertson (2009). The SCPTu data were normalized assuming an average total unit weight of 16 kN/m³ and a piezometric profile (u_o) based on the dissipation tests and nearby piezometers. It is useful to note that the vertical effective stress near the base of the tailings is very high ($\sigma'_{vo} > 15$ atm), due to the predominately unsaturated nature of the materials (i.e., $u_o \sim 0$) and significant depth. The soil behavior type index (I_c) is close to 2.6 over much of the profile suggesting that the soils are transitional in behavior between either more sand-like or more clay-like (Robertson 2009). This is consistent with the measured grain-size distribution of silty sand to sandy silt and the partial drainage conditions during CPT with average t_{50} values close to 50 s, that was suggested as the boundary between fully undrained cone penetration and partially drained penetration (DeJong and Randolph 2012). Given the high overburden stresses with depth, the grain-size distribution is expected to become slightly finer with depth due to some grain

crushing. The relatively low average normalized cone resistance value ($Q_{tn} \sim 20$) suggests that the tailings would have a cyclic resistance ratio (CRR) of around 0.1 and would be expected to be generally contractive in shear at large strains (Robertson and Wride 1998; Robertson 2009).

Figure 3 shows the same SCPTu profile (as shown in Figs. 1 and 2) in terms of the measured seismic compression wave velocity (V_p) and shear wave velocity (V_s). The measured compression wave velocity (V_p) varies from about 350 up to 1100 m/s, with values generally increasing with depth. The measured shear wave velocity (V_s) varies from about 225 up to 560 m/s with values increasing with depth, as shown in Fig. 3. As V_p for most saturated soils is about 1500 m/s, the measured values confirm that the deposit is mostly unsaturated. Studies have shown that V_p is very sensitive to degree of saturation and can show a significant drop below 1500 m/s for a very small change in degree of saturation of 1% or 2% (Jamiolkowski 2012). However, V_p cannot be used to estimate degree of saturation because the value tends to be insensitive to degree of saturation below values of around 98% (Jamiolkowski 2012). The combined normalized CPT and V_s data suggest that much of the tailings have little microstructure, i.e., very young and uncemented (Robertson 2016).

Figure 4 shows the same SCPTu profile in terms of normalized shear wave velocity (V_{s1}), defined as follows:

$$(1) \qquad V_{s1} = V_s \left(p_a / \sigma'_{vo} \right)^{0.25}$$

where p_a is reference pressure (= 100 kPa) and σ'_{vo} is in situ vertical effective stress.

The vertical effective stress was based on assumed dry soil (i.e., no suction) with a soil unit weight of 16 kN/m³. The average normalized shear wave velocity is 225 m/s. Although accuracy is re-

Fig. 3. Typical seismic velocity profile in terms of compression (V_p) and shear wave velocity (V_s) measured using SCPTu. [Color online.]
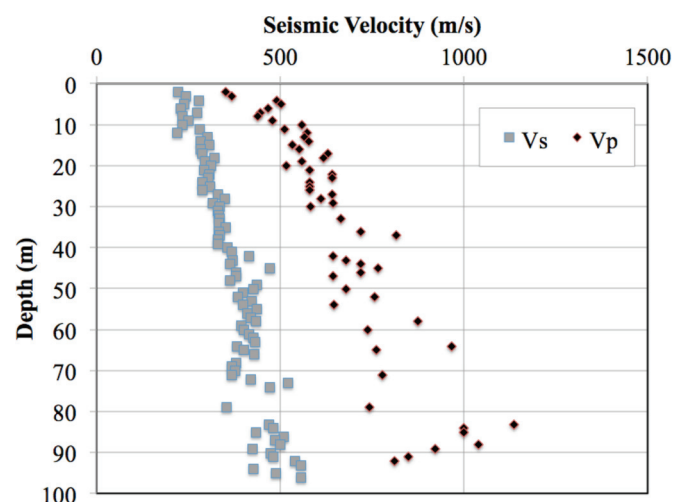
Fig. 4. Typical normalized shear wave velocity (V_{s1}) profile. [Color online.]
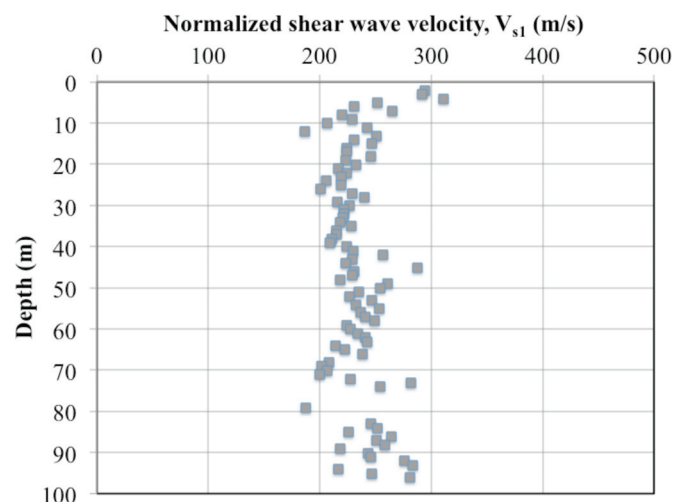
duced with depth using the down-hole method, as reflected in the increased scatter with depth, the seismic measurements show a consistent trend of approximately constant normalized values with depth. The SCPTu measured shear wave velocity values also agree with the limited available MASW values. As will be shown subsequently, the assumption of zero suction to normalize the CPT and seismic velocities is reasonable given the relatively small in situ suction values compared to the very high total overburden stresses below a depth of about 10 m. The high value of normalized shear wave velocity ($V_{s1} \sim 225$ m/s) suggests that the tailings would have a CRR around 0.4 (Kayen et al. 2013) and would be expected to be generally dilative in shear at large strains (Robertson and Fear 1995). Hence, there appears to be inconsistency in the interpretation of behavior under both cyclic and monotonic shear between the normalized cone resistance and the normalized shear wave velocity. This difference may, in part, be due to the lack of saturation and was investigated through laboratory testing.

Laboratory testing

The tailings are derived from crushed Cenozoic volcanic and Triassic sedimentary rocks from the adjacent mine. The tailings are filtered and placed uncompacted to form a generally loose unsaturated deposit. Surface irrigation is carried out resulting in

Table 1. Summary of isotropically consolidated triaxial compression tests on saturated reconstituted samples.

Test	Test type	End of consolidation		End of shearing or critical state (CS)			
		e_c	p'_c (kPa)	e_f	p'_{cs} (kPa)	q_{cs} (kPa)	ε_{cs} (%)
1	CIU	0.80	20	0.80	0	0	1.92
2	CIU	0.76	60	0.76	0	0	2.09
3	CIU	0.75	100	0.75	0	0	4.89
4	CIU	0.71	199	0.71	2	0	5.95
5	CIU	0.67	601	0.67	10	10	23.35
6	CIU	0.63	1200	0.63	94	127	4.30
7	CID	0.79	20	0.66	33	43	27.61
8	CID	0.77	59	0.64	109	150	42.12
9	CID	0.77	101	0.64	186	257	28.61
10	CIU*	0.77	20	0.77	0	0	2.5
11	CIU*	0.74	100	0.74	0	0	11.10
12	CID*	0.67	601	0.54	1083	1455	45.2

Note: CIU, isotropically consolidated undrained compression; CID, isotropically consolidated drained compression; e_c, void ratio at end of consolidation; p'_c, mean effective stress at end of consolidation; e_f, void ratio at end of shear or critical state (CS); p'_{cs}, mean effective stress at end of shear or CS; q_{cs}, deviator stress at end of shear or CS; ε_{cs}, axial strain at end of shear or CS.

*No seismic measurements and samples frozen to determine void ratio.

some fluid percolating through the tailings. Based on samples, the in situ water content varies between 2% and 15% and the degree of saturation between 5% and 50%, depending on depth, location, and localized irrigation.

Saturated samples

Laboratory testing was carried out on reconstituted samples to identify critical state (CS) parameters. A series of isotropically consolidated drained and undrained triaxial tests were carried out on reconstituted samples with approximate dimensions of 72 mm diameter and 144 mm height prepared loose by moist tamping at an initial moisture content of about 11.5%. Triaxial tests were conducted in axial compression until either CS was reached or about 20% axial strain. The triaxial equipment was fitted with piezoelectric elements to measure both compression (V_p) and shear wave velocity (V_s). Testing was carried out on saturated samples that were saturated using a combined CO_2 percolation and backpressure method. Saturation was achieved when a measured Skempton's pore pressure parameter B of 0.98 or higher was reached along with a measured compression wave velocity of about 1500 m/s. The saturation process was conducted under an effective confining stress of 10 kPa according to Fonseca et al. (2015). The saturation process causes a slight collapse of the very loose samples resulting in slightly lower void ratios during consolidation. During the consolidation and shearing phases, the seismic velocities (V_p and V_s) were measured using bender–extender elements, incorporated in the triaxial equipment. The interpretation of velocities was carried out in the time and frequency domain (e.g., Fonseca et al. 2009).

Table 1 shows a summary of the test program on the saturated samples in terms of void ratio (e_c) and mean effective stress (p'_c) at end of consolidation, and void ratio (e_f), mean effective stress (p'_{cs}), deviator stress (q_{cs}), and axial strain at end of shear or CS (ε_{cs}). Table 2 shows a summary of the test program on the saturated samples in terms of the measured seismic velocities at end of consolidation.

As sandy soils can be sensitive to small changes in void ratio (e), a series of three tests (tests 10, 11, and 12 in Table 1) were carried out without bender–extender elements so that the samples could be frozen after shearing to accurately measure the final void ratio (e_f), as suggested by Sladen and Handford (1987) with details in Soares and Fonseca (2016). Volume change during consolidation

Table 2. Summary of seismic velocity measurements in isotropically consolidated triaxial compression tests on saturated reconstituted samples.

Test	Test type	End of consolidation			
		e_c	p'_c (kPa)	V_p (m/s)	V_s (m/s)
1	CIU	0.80	20	1483	64
2	CIU	0.76	60	1493	94
3	CIU	0.75	100	1480	111
4	CIU	0.71	199	1513	138
5	CIU	0.67	601	1523	200
6	CIU	0.63	1200	1587	232
7	CID	0.79	20	1527	72
8	CID	0.77	59	1226	99
9	CID	0.77	101	1534	112

Note: e_c, void ratio at end of consolidation; p'_c, mean effective stress at end of consolidation; V_p, compression wave velocity; V_s, shear wave velocity.

and shearing was measured using an automatic volume gauge with electronic displacement transducer.

Figure 5 shows a summary of the triaxial test results on saturated samples in terms of void ratio (e) and effective mean stress (p') for end of consolidation and at CS. The CSL is also identified as a locus of points at CS. The end-of-consolidation points represent an approximate isotropic limiting compression curve (LCC) for very loose saturated samples (e.g., Pestana and Whittle 1995).

All the samples tested had very loose states at the end of consolidation relative to CS, with an average state parameter of around $\psi \sim +0.1$. The loose samples tested in undrained compression at effective confining stresses less than 200 kPa showed complete strength loss with a deviator stress at failure (q_f) close to zero. All samples were contractive at large strains and either showed an increase in pore pressures when sheared undrained or compressive volumetric strains when sheared drained. The CSL appears to bend downward at mean effective stresses greater than about 500 kPa. The CSL for the tested tailings is similar to other silty tailings reported by Jefferies and Been (2016), Bedin et al. (2012), and Schnaid et al. (2013). Based on the tests in this study on saturated tailings, the critical friction ratio, $M = 1.34$ ($\phi' = 33.5°$, where ϕ' is the friction angle).

Cunning et al. (1995) had proposed a linear relationship between normalized shear wave velocity (V_{s1}) and void ratio (e) for young, uncemented sands and Fig. 6 shows the measured relationship between V_{s1} and e for the end of consolidation conditions for the saturated tailings in this study. For these tailings in a saturated state the linear relationship, similar to that proposed by Cunning et al. (1995), is

(2) $\qquad V_{s1} = 220 - 145e \qquad$ (m/s)

Based on this relationship combined with eq. (1), it is possible to show contours of V_s on the e–p' plot, as shown in Fig. 7 compared to the measured CSL. Jefferies and Been (2016) have suggested that the separation between a dilative and contractive response at large strains occurs at a state parameter of about $\psi = -0.05$. At a mean effective reference stress of 100 kPa, this would represent a consolidated void ratio of about $e_c = 0.59$. Based on Fig. 6, this contractive–dilative boundary can be represented by $V_{s1} = 135$ m/s. This is similar to the values indicated by Cunning et al. (1995) of 130 to 150 m/s for a range of saturated young, uncemented clean sands. The laboratory data also show that when $V_{s1} < 115$ m/s (i.e., when $e_c > 0.72$), the saturated tailings samples in this study will essentially collapse (i.e., $q_{cs} \sim 0$) in undrained shear.

Based on the laboratory tests on saturated samples, the average measured in situ normalized shear wave velocity of 225 m/s indi-

Fig. 5. Summary of isotropically consolidated triaxial compression tests on saturated reconstituted tailings samples showing critical state line (CSL) and limiting compression curve (LCC). [Color online.]
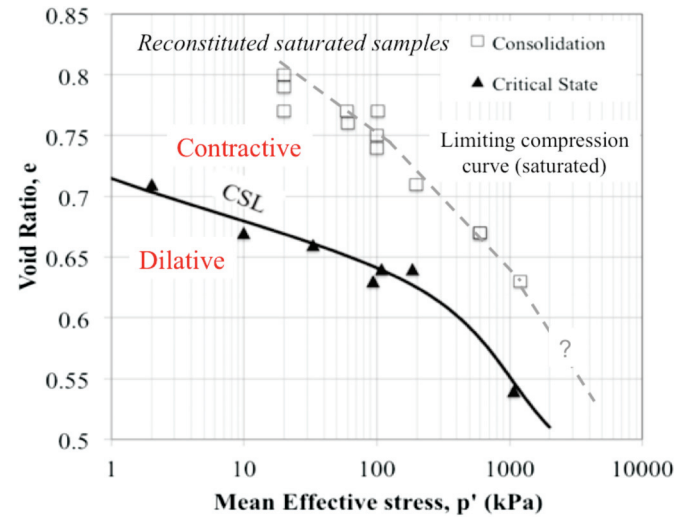
Fig. 6. Normalized shear wave velocity (V_{s1}) as a function of void ratio at the end of consolidation (e_c) for saturated samples. [Color online.]
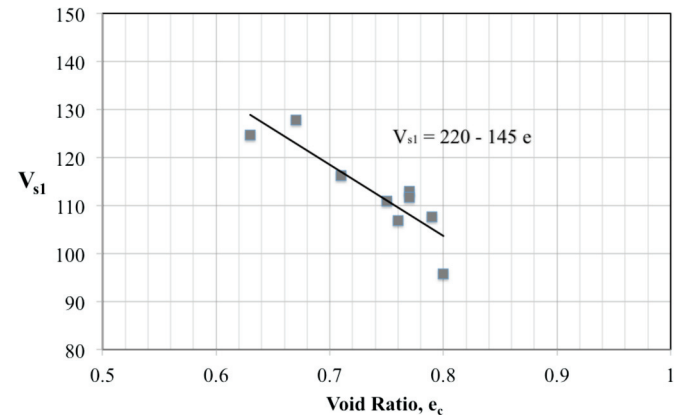
cate that the tailings would be expected to be strongly dilative at large strains, if saturated. Hence, there is a difference between predicted behavior under saturated conditions based on either CPT penetration resistance, which indicates a contractive behavior, or shear wave velocity, which indicates a dilative behavior at large strains. However, the measured in situ compression wave velocity values and samples confirm that the tailings are predominately unsaturated and in situ suctions may influence the behavior and resulting interpretation. To investigate further, a series of laboratory tests were performed on similar reconstituted samples, but tested unsaturated.

Soil-water characteristic curve (SWCC)

For unsaturated soils, the suction can be represented by a soil-water characteristic curve (SWCC) that defines the relationship between soil matric suction ($u_a - u_w$) and degree of saturation, S (%). The SWCC is also a function of grain-size distribution, with larger suctions in more fine-grained soils.

Suction tests to determine the SWCC were performed in two Richards' chambers, one for lower pressures and one for high pressures (Richards and Fireman 1943). Circular specimens were molded inside steel rings, using the moist tamping technique, with 11.5% water content and initial void ratio of 1.2 (the same void ratio values used for the triaxial tests). The specimens were placed on a

Fig. 7. Summary of isotropically consolidated triaxial compression tests on saturated reconstituted tailings samples with contours of shear wave velocity (V_s).
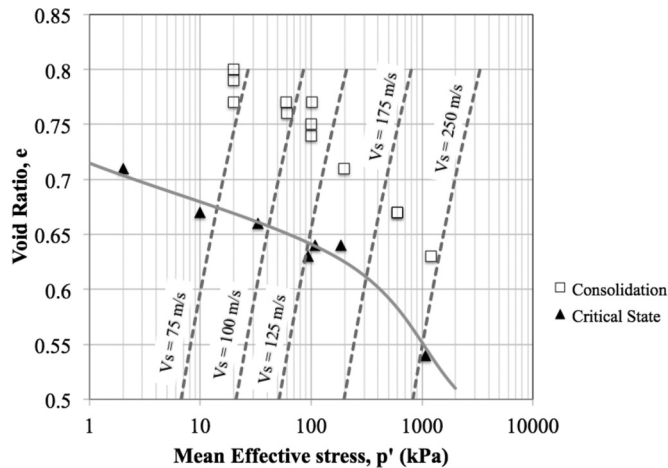
porous stone inside the chamber and saturated. The samples stayed inside the chamber at constant differential pressure (i.e., suction) for 7 days, then the water content determined for the specific pressure (suction). This process was restarted for the different pressures (suctions) applied, always starting from the same initial water content and initial void ratio. For each pressure, four specimens were molded and the values considered are the mean of the four values obtained. The suction pressures were 4, 8, 20, 32, 60, 100, 200, 400, 600, and 700 kPa. Figure 8 shows the resulting SWCC in terms of degree of saturation (S) versus suction (s). The measured SWCC is consistent with other silty sands to sandy silts (e.g., Leroueil and Hight 2003). Given the nonplastic nature of these soils, volume changes were very small during the suction tests to determine the SWCC and the results adjusted accordingly. The in situ degree of saturation varies between 5% and 50%, which indicates that the in situ suctions range from around 5 to 300 kPa.

Soil suctions increase the effective stresses (σ') in the soil compared to saturated soils, as follows:

$$(3) \qquad \sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$

where σ is total stress, u_a is pore-air pressure, $(\sigma - u_a)$ is net total stress, χ is effective stress parameter that has a value of 1 for saturated soils and 0 for dry soil, u_w is soil-water pressure, and $(u_a - u_w)$ is matric suction ($= s$).

The change in effective stress increases the strength and stiffness of an unsaturated soil. Hence, unsaturated soils tend to be stronger and stiffer than identical saturated soils. The effective stress parameter (χ) varies with degree of saturation (S). Several approaches have been introduced for estimating the χ parameter, such as utilizing the air entry value (e.g., Khalili and Khabbaz 1998; Khalili et al. 2004), and the effective degree of saturation (e.g., Lu and Likos 2006; Lu et al. 2010). For practical purposes, it is common to assume that the variation of the χ parameter is assumed to be linear with the degree of saturation, S (i.e., from 0 to 1) (Leroueil and Hight 2003).

Unsaturated samples with known suction

A series of isotropically consolidated triaxial compression tests were performed on similar reconstituted samples of tailings under different known suction conditions. Sample preparation was identical for the saturated samples, but strain and volume changes were measured using axial and radial transducers (Hall-effect calipers). As tests were performed under unsaturated conditions, there was no percolation and saturation phase. Two tests were

carried out using a triaxial cell (TX) that can control the suction using a high air entry porous stone. Five tests were carried out using a Bishop-Wesley cell (BW) modified to measure seismic velocities using bender elements under constant-water-content conditions with a suction probe to measure suction within the sample. In the Bishop-Wesley cell (BW), the suction cannot be imposed so, to have the required suction, the samples were molded with specific initial water content, corresponding to the desired suction according to the measured SWCC. The moisture content was checked before and after the test and did not vary significantly. The suction was also measured using a suction probe and confirmed agreement between the expected suction based on the SWCC and measured suctions. According to the SWCC, a suction of 20 kPa corresponds to water content of 11.5% and a suction of 200 kPa corresponds to water content of 4.0%. The tests performed are presented in Table 3, where the type of cell, total confining stress, and suction are summarized along with values of the void ratio and water content measured before and after testing.

A challenge when testing unsaturated samples is the ability to track volume changes. Radial (Hall-effect) calipers were used to track changes in sample diameter. Because the samples bulged during shearing, the sample volume change was based on an assumed parabolic shape of the deformed specimen. The samples were contractive and strain hardening during shear although the volumetric strains were generally small, with changes in void ratio generally less than 0.1. The contractive behavior was primarily due to compression of air voids during shear.

Table 4 presents a summary of the measured seismic velocities on the unsaturated samples at the end of consolidation. An additional test (T9-600S20) was performed on a similar unsaturated sample to measure seismic wave velocities at different total consolidation stresses with a controlled suction of 20 kPa. The velocity measurements on unsaturated samples with known suction provide an opportunity to determine the relationship between normalized shear wave velocity (V_{s1}) and void ratio for unsaturated samples based on the effective stress values that incorporate suction using eq. (3).

The in situ degree of saturation of the tailings is in the range of 5% to 50%. The average insitu degree of saturation is around 10% to 20% that would indicate an average in situ suction of around 50 to 100 kPa based on the SWCC. Based on a range of methods, the χ parameter would vary from 0.1 to 0.2, for S from 0.1 to 0.2. An average χ parameter of 0.1 was applied, although the results are not overly sensitive to the exact value selected based on number of different methods. The results of normalized shear wave velocity versus void ratio as a function of suction are shown in Fig. 9 that shows that V_{s1} increases significantly with suction. This increase appears to be primarily due to suction hardening effects and not the change in effective stress from the suction. The suction hardening effects are similar to interparticle cementation where suction hardening is an isotropic hardening phenomenon that controls the size of the yield surface in addition to plastic volumetric strains, and therefore the location of the CSL (Loret and Khalili 2002; Arroyo et al. 2013). The change in small strain stiffness reflected by V_{s1} is significant for a small amount of suction. For example, V_{s1} increases by 58% with only 20 kPa suction. That is equivalent to an approximately 150% increase in small strain shear modulus (G_o) for a small change in effective stress.

A summary of the triaxial tests in terms of the CSL for both saturated and unsaturated samples is shown in Fig. 10. The tests on the unsaturated tailings showed that the CSL was located at higher values of void ratio (for similar confining stress) compared to the saturated samples. The CSL for unsaturated samples appears to be independent of the magnitude of the suction. Fern et al. (2016) reported no change in CSL due to suction hardening in clean sands whereas others (e.g., Russell and Khalili 2006) reported a significant change in CSL in clays. It appears that the influence of suction hardening on small strain stiffness and the

Fig. 8. SWCC in terms of degree of saturation versus matric suction for silty tailings. [Color online.]
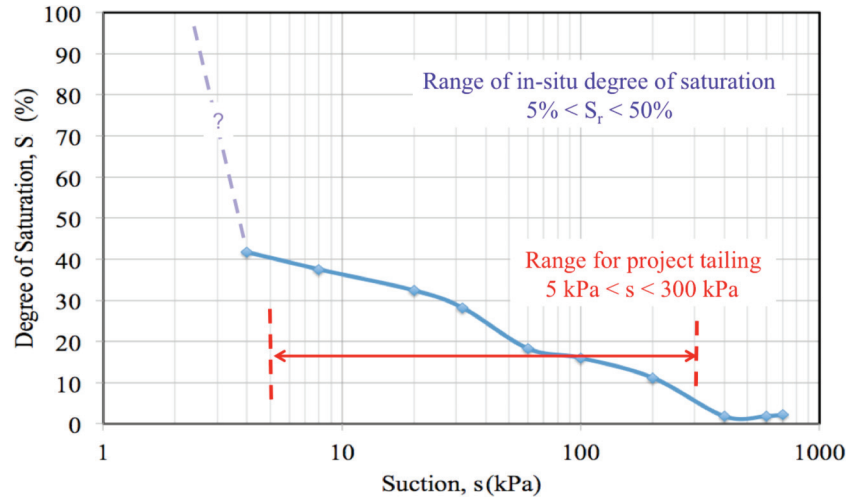
Table 3. Summary of isotropically consolidated drained triaxial compression tests on unsaturated reconstituted samples with known suction.

Test	Confining stress, p_c (kPa)	Suction, s (kPa)	Initial void ratio, e_0	Initial water content, w_0 (%)	Final water content, w_f (%)
T1-50S20TX	50	20	0.94	11.72	9.95
T2-600S20TX	600	20	0.83	15.27	9.70
T3-600S20BW	600	20	0.81	11.15	12.30
T4-600S200BW	600	200	0.86	3.80	3.79
T5-50S200BW	50	200	0.86	3.90	3.92
T6-400S200BW	400	200	0.85	4.01	3.94
T7-200S20BW	200	20	0.85	11.36	11.30

Table 4. Summary of seismic velocities measured on unsaturated samples with controlled suction values.

Test	Total confining stress, p_c (kPa)	Suction, s (kPa)	Void ratio, e	Effective confining stress, p' (kPa)	Seismic velocities at end of consolidation (m/s) V_p	V_s
T4-600S200	600	200	0.86	620	669	328
T5-50S20	50	200	0.86	70	460	192
T6-400S200	400	200	0.85	420	528	316
T7-200S20	200	20	0.85	202	550	211
T9-600S20	50	20	0.674	52	736	178
	200	20	0.653	202	738	234
	400	20	0.635	402	728	275
	600	20	0.624	602	745	299

location of the CSL maybe a function of grain-size distribution and soil plasticity, where more fine-grained soils show a larger influence due to suction hardening.

Discussion

As stated earlier, the in-situ degree of saturation of the tailings is in the range of 5% to 50% with an average value around 10% to 20%. This would suggest an average in situ suction of around 50 to 100 kPa based on the SWCC. Based on a range of methods, the χ parameter would vary from 0.1 to 0.2, for S from 0.1 to 0.2. Hence, the additional effective stress due to suction (χs) is only around 10 kPa. Given the significant depth profile of the tailings with resulting high total overburden stress, the additional effective

stress from suction is very small at depths greater than around 10 m. Hence, any error in calculated in situ vertical effective stress ignoring suction is small for depth greater than 10 m.

Figure 9 shows that the large change in V_{s1} when the soil is unsaturated is not due to the small change in effective stress, but due to suction hardening effects and that the hardening itself appears to be a function of suction. The suction hardening is similar to cementation in that the small strain stiffness (via shear wave velocity) is not controlled primarily by effective stress. Cementation and suction hardening appears to reinforce the links between particles, and increases the small strain stiffness, even at the same void ratio. It appears that because shear wave velocity is a small strain measurement, it is sensitive to suction hardening

Fig. 9. Normalized shear wave velocity (V_{s1}) as a function of void ratio at the end of consolidation (e_c) for saturated ($s = 0$) and unsaturated samples with suction of $s = 20$ and 200 kPa of silty tailings. σ_c, total confining stress. [Color online.]
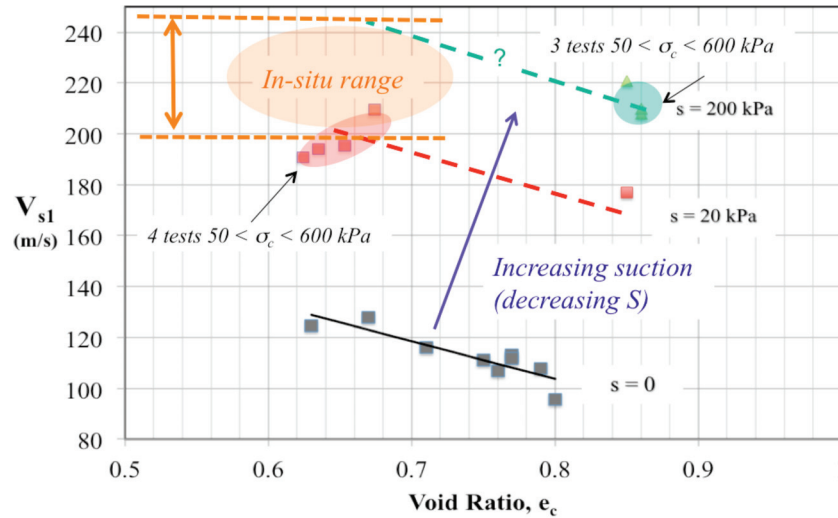
Fig. 10. CSL for both saturated ($s = 0$) and unsaturated samples ($s = 20$ and 200 kPa) of silty tailings. [Color online.]
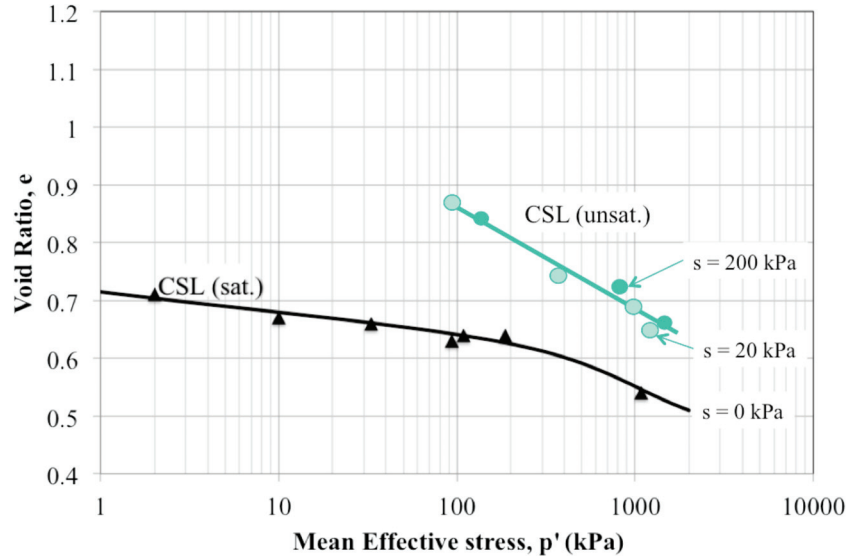
and captures the correct in situ unsaturated behavior. The cone resistance is a large strain measurement that can destroy the beneficial effects of suction hardening and appears to be insensitive to the unsaturated in situ behavior. This may explain why the normalized cone resistance values are relatively small compared to the relatively higher normalized shear wave velocity values. The process of cone penetration may decrease the beneficial effects of suction on the yield surface and CSL, which may explain the perceived looser state from the CPT. It appears that the shear wave velocity is more sensitive to the suction hardening from lack of saturation whereas the cone resistance destroys the beneficial effects of suction hardening and provides a measure of the soil behavior closer to what would exist if the soil became fully saturated when the suction hardening effects become removed.

The in situ normalized shear wave velocity values are predominately between 200 and 250 m/s. These values are not significantly changed when accounting for in situ suctions from 20 to 200 kPa at the high in situ overburden stresses. Taking this range of in situ suction values combined with the measured normalized shear wave velocity values it is possible to estimate the in situ void ratio using Fig. 9. Using this approach, the estimated in situ void ratio is

between 0.58 and 0.72, as shown schematically in Fig. 9. The average in situ void ratio is estimated to be about 0.65. It is interesting to note that the seismic velocity values (both V_s and V_p) measured on the unsaturated sample with a void ratio of 0.65 (test T9-600S20) are close to those measured in situ at similar values of total overburden stress.

Taking this range of estimated void ratio combined with the estimated range of in situ mean effective stress, it is possible to plot the in situ state relative to the various CSLs, as shown schematically in Fig. 11. Based on Fig. 11, the in situ void ratio values of between 0.58 and 0.72 for in situ effective stress levels of between 100 and 1000 kPa suggest that the soils are on the dilative side of the unsaturated CSL. Hence, based on the in situ shear wave velocity measurements and laboratory testing, the in situ tailings are expected to behave in a dilative manner in shear at large strains when unsaturated. If the soils were to become saturated, the range of estimated in situ void ratio and stress levels would suggest that the soils could be more contractive, as shown schematically in Fig. 11. However, it is uncertain what effect, if any, suction hardening may have on the soil behavior after saturation, although the CPT data suggest that almost all beneficial effects

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