Characterization of Unsaturated Tailings & its Effects on Liquefaction

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ABSTRACT: In the mining industry, it is becoming relatively common for filtered mine tailings to be stacked to a significant height (>100m) with little to no compaction. The resulting deposit can be loose and potentially unsaturated. Characterization of these filtered tailings facilities for slope stability and deformation under earthquake loading conditions can be complex due to the potentially unsaturated state. This paper presents a summary of test results from the assessment of a filtered tailings facility which is located in Latin America. Cone penetration tests (CPTs) and seismic velocity measurements (SCPTu) were carried out along with selected drilling, sampling and laboratory testing. The results of laboratory testing utilizing bender element testing indicate that the CPT-based liquefaction analysis could not be relied upon due to suction-hardening of the unsaturated tailings, and that the seismic wave tests were the more applicable approach to assessing the potential for liquefaction in this case. The paper presents the results of the characterization and the interpretation of the test data.

1 BACKGROUND

1.1 *Basic Project Information*

The project under discussion is an inactive filtered tailings facility located in an arid and high-altitude region of Latin America. To gain an understanding of the liquefaction potential of the deposited tailings, a series of in-situ tests was carried out during a large-scale site investigation completed to characterize the deposited tailings. Due to the high seismicity project setting and nature of the tailings, seismic cone penetration tests with pore pressure measurements (SCPTu) were utilized with the intention of characterizing the liquefaction susceptibility of the tailings. Additionally, due to the arid project setting and elapsed time from previous operations, seismic wave measurements were obtained during probing to provide insight into the saturation of the tailings.

The CPT-based liquefaction analysis, following the Robertson approach (e.g., Robertson and Wride, 1997, Robertson, 2015), indicated that the tailings were likely contractive and susceptible to liquefaction during the design earthquake event, even at significant depth. The shear-wave-based liquefaction approach, following the methodology described by Kayen et al. (2013), indicated that the tailings were dilative and therefore not susceptible to liquefaction during the design earthquake event.

Given this vast disparity in results, an additional step was made to improve the understanding of those test results. Included in the additional work was a series of triaxial shear strength tests, with bender element excitation during consolidation and during shear, to confirm that testing was conducted under in-situ conditions, which will be described in a later section of this paper.

1.2 *Filtered Tailings and the Tailings Continuum*

Filtered tailings reside at the higher solids content end of the tailings thickening continuum. The thickened tailings continuum has been presented numerous times elsewhere (e.g., Ulrich and Coffin, 2013, Kerr and Ulrich, 2011, Ulrich and Kerr 2011)). The continuum simply represents the nature and behavior of tailings at various degrees of thickening, as follows:

- Conventional slurry tailings
- Conventionally thickened tailings
- High density tailings
- Paste tailings
- Filtered tailings

Yield stress is often employed as a distinct boundary to help define these transitions within the continuum. According to Ulrich and Kerr (2011), the yield stress separating conventional slurry tailings and thickened tailings tends to range between 5 and 20 Pascals (Pa) [1 lb/ft^2 is approximately 48 Pa]. The boundary between thickened and paste tailings is approximately 100 Pa, and 800 Pa is the boundary between paste tailings and filtered tailings. Some practitioners prefer to think of the thickened tailings continuum in terms of solids content rather than using yield stress as the reference condition. While convenient, it may not be entirely meaningful in understanding material behavior. For example, consider two tailings slurry samples. One has a high magnetite content. The other sample is "exactly the same", but without the magnetite component (the magnetite is "replaced" instead with the ordinary host rock, thus the volume of solids is identical for both samples, as is the volume of water). The difference in average particle specific gravity between the two samples is the only difference, but the two samples would have different solids contents. It isn't altogether satisfying to place these two materials at different positions on the thickened tailings continuum based simply on their different magnetite content (or more generally, specific gravity). A similar comparison could be made for otherwise identical samples containing different amounts of clay minerals. In this case, they may indeed have quite different yield stresses, but identical solids content. So, although conceptually less intuitive for many people, yield stress is the author's preferred reference for the thickened tailings continuum rather than solids content, due to the direct evaluation of material behavior.

Ulrich and Kerr (2011) indicate that some of the key drivers for selecting thickened, paste or filtered tailings pertain to social acceptance, ease of permitting, and water savings. Especially potential fresh water consumption savings. In very arid regions, water can come at a considerable cost and even more so if population centers are situated near the mining area who also rely on the resource. Accordingly, finding a means of reducing fresh water consumption can come to the forefront in tailings management planning. Social acceptance and ease of permitting fall right in line with the water savings considerations. Other drivers include:

- Water recovery prior to deposition
- Avoidance of evaporative losses
- Topographic constraints
- Land constraints
- Regulatory restrictions
- Closure implications
- Draindown considerations
- Corporate decision making

One advantage of reducing the moisture content of the tailings before sending it to the disposal area is that there is a potential to reduce seepage that may be released into the environment. Another advantage is the reduced amount of consolidation the tailings will experience (including post-closure consolidation) should be reduced in most cases. This is also an advantage of subaerial tailings (refer to Knight and Haile, 1983 and Ulrich, East and Gorman, 2000), although this achievement is accomplished differently with the two methodologies. The first process (filtered tailings) recovers water in the mill and the latter process (subaerial tailings) recovers water via an underdrain and decant pond, but also water lost to evaporation is promoted to increase

desiccation of the tailings. Compared to conventional slurry, either process helps to reduce the magnitude of consolidation by removing water from the tailings. The possible disadvantage of subaerial tailings is that some of the moisture may be lost to evaporation (although if water does not come at a premium price, this may not be a disadvantage).

1.3 *Filtered Tailings*

While the use of the filtering process in tailings management has been growing rapidly over the past several years, there are a disproportionately meager number of publications regarding this topic compared to other tailings preparation methodologies. Davies et al. (2010) indicate that there are approximately triple the number of filtered tailings facilities as there are surface paste tailings facilities, but the number of publications for surface paste facilities far outweigh the number of publications for filtered tailings facilities. This disparity is primarily due to the perceived relative ease of the design and operation of a filtered tailings facility compared to a surface paste facility, but also the uniqueness, complexity and idiosyncrasy of surface paste facilities. In fact, the industry 'go-to' handbook on the topic, 'Paste and Thickened Tailings – A Guide' (Jewell and Fourie, 2006) discusses the topic of surface filtered tailings facilities only in passing, although there is a good discussion on the filtering process itself.

Filtered tailings facilities may be perceived as being very ordinary and somewhat undeserving of extensive coverage in the literature. This perception is somewhat true as there are many ordinary filtered tailings facilities which have been constructed and operated; however, as the filtering technologies continue to develop in the efficiency of filter plants, very significant facilities (i.e., high throughput) are now being designed that will bring this application to ever greater importance. In fact, USFS (2010) reports on an operation that will be producing filtered tailings at a rate of approximately 70,000 tonnes per day with a facility that will ultimately store 300 million tonnes of tailings to a height of 150 meters (Ulrich and Coffin, 2013).

It has been said elsewhere (e.g., Davies and Rice, 2001, Ulrich and Coffin, 2013), but it bears repeating here. There is no one-size-fit-all tailings panacea, and no single tailings preparation method should be considered a cure-all. This includes filtered tailings. For example, Wilson and Robertson (2015) wrote:

> "The writer's note that in the specific case of 'dry stacking of filtered tailings' this method should not be considered a panacea for the elimination of failure potential. One of the writers is currently reviewing two such dry stacks where the design, operating and site conditions have [led] to an urgent need for remedial modifications to avoid failure conditions".

Filtered tailings facilities are often referred to as 'dry stacks' (e.g. Davies and Rice, 2001; USFS, 2010; Davies et al., 2010; Lupo and Hall, 2010), while contradictory terms are also used for certain portions or aspects of the deposit such as 'wet cake' (Davies and Rice, 2001; Davies et al., 2010; Newman et al., 2010), and zones of the dry stack that may be 'overly wet' (Lupo and Hall, 2010). Davies and Rice (2001) indicate that the term dry stack has been adopted by designers and regulatory authorities for filtered tailings facilities, admitting that the facilities are not truly dry, but that if practitioners bear in mind that this is a somewhat misused term, it is acceptable to continue using this terminology. This understanding was a focus of the research presented herein as liquefaction is a phenomenon associated with saturated, or nearly saturated, materials and not generally considered a risk for 'dry' materials.

Regarding terminology, the rather misleading term dry stack is generally not a good engineering term since the target moisture content coming from the filter plant is typically desired to be somewhere around the optimum moisture content based on the Proctor compaction procedure (either the standard or modified test, as determined by the design engineer). Geotechnical engineers associate the optimum moisture content with moisture levels just below full saturation after compaction, thus terming such a facility as a dry stack is a misnomer. The present authors would encourage practitioners to abandon the use of the term dry stacking in favor of the more straightforward term, 'filtered tailings'. It is not desirable to unintentionally mislead the public at large with an industry term that is noticeably misused (Ulrich and Coffin 2013).

1.4 *Liquefaction and In Situ Testing*

A good discussion of liquefaction is provided by Robertson and Wride (1998). They indicate that during cyclic undrained loading, almost all saturated, frictional soils develop positive pore pressures due to the contractive response of the soil at small shear strains. If there is shear stress reversal, the effective stress state can advance to the point of momentary zero effective stress. When frictional soil reaches the condition of essentially zero effective stress, the soil has very little stiffness/shear strength and large deformations can occur during, or immediately after, cyclic loading. When cyclic shaking stops, those deformations essentially stop, except for deformation due to pore-pressure redistribution, which may still be significant.

Significant developments have taken place in recent decades in evaluating the liquefaction potential of soils. The cone penetration test is now commonly used to evaluate liquefaction potential due to the ability to conduct the testing on in-situ materials at in-situ states of stress, thus, removing the complication of undisturbed soil sampling or sample remolding in the laboratory (Robertson et al., 1992; Robertson and Wride, 1997; Robertson, 2015). Additionally, liquefaction assessments using the CPT have the advantage of producing nearly continuous, repeatable measurements that provide a detailed profile of the soil.

There have also been significant developments in evaluating liquefaction potential based on in-situ shear wave velocity (V_s) measurements (Kayen et al., 2013). Potential liquefaction assessment methods based on shear wave velocity have the advantage that they are essentially independent of intrinsic soil characteristics, such as fines content, as they only measure the bulk response of a soil mass. However, this approach usually lacks the stratigraphic information provided by the CPT (Robertson, 2015) due to the practical resolution of the testing interval in-situ.

2 THE PROJECT

2.1 *Facility Description*

The filtered tailings facility that is the subject of this paper is located in a very arid, high-seismicity, and high-altitude site in Latin America. The facility is composed of filtered tailings that were placed via conveyor and radial arm stacker. The material was placed in lifts of approximately 20 to 30m thickness during the mining operations with minimal compaction. Lifts were placed at individual slopes ranging from approximately 1.5H:1V (horizontal to vertical) to 2.5H:1V with each lift offset by either 40 to 60m to create benches, resulting in an approximate overall downstream slope of 4H:1V. At the time of the investigation, the maximum height from toe to crest was about 200m with a maximum thickness of tailings of approximately 125m. The total surface area of the facility is about 30 hectares with an estimated storage of 100 million tonnes of filtered tailings.

One of the main design objectives of the assessment was the stability of the tailings facility under static and seismic loading conditions; therefore, detailed characterization of the shearing behavior of the tailings under both static and seismic loading conditions was important. This included establishing whether the tailings could experience strength loss and related instability (Robertson et al., 2017) due to the occurrence of the design earthquake event.

Given the dry climate of the region and the placement of the tailings in a moist, loose state, the tailings were expected to be predominately unsaturated. In unsaturated soils the voids are filled with a mixture of fluid and air, which can result in the development of 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 site-specific seismic hazard assessment was completed to characterize the potential seismic loading conditions to be used in the design and operation of the filtered tailings facility. The maximum design earthquake (MDE) was defined as the event with a recurrence interval of 2,475 years considering the Significant Hazard Class (Canadian Dam Association, 2014) assigned to the facility and the owner's corporate design requirements. This event corresponds to a subduction zone type earthquake event of moment magnitude 9.0 producing a peak horizontal ground acceleration (PHGA) of 0.45g.

2.2 Site Investigation

Since the onset of mine operations in the 1990s there have been several geotechnical studies to characterize the tailings deposit. This current paper focuses on the most recent study that began in 2014 and included SCPTu probes, drilling, sampling (both disturbed and undisturbed sample recovery) and the installation of piezometers. Laboratory testing was carried 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 0.065mm. The grain size distribution curve for the tested tailings is similar to other poorly graded silty tailings reported by Jefferies and Been (2016) based on classification under the Unified Soil Classification System (USCS) and visual comparison. The average specific gravity of the tailings is 2.73 and the tailings are predominately non-plastic.

The SCPTu program was carried out in accordance with ASTM D5778 using a portable hydraulic ram mounted on to a drill rig. A total of 12 SCPTu probes were advanced in the tailings facility. Compression wave (V_p) and V_s measurements were made using a geophone and the down-hole method (e.g., Robertson et al, 1986). The intention was to use the V_p data to identify the depth at which materials become saturated (generally, an estimated V_p equal to 1,500 meters per second [m/s] indicates a material is saturated) and the V_s data as both a liquefaction potential indicator (generally, a V_s less than 200 meters per second indicates potentially liquefiable materials [Robertson et al., 1992]) and to estimate small strain behavior of the tailings for seismic deformation analyses. Pore pressures were measured behind the cone tip continuously during probe advancement. Additionally, pore pressure dissipation (PPD) testing was conducted by halting advancement at various depths to allow the penetration induced pore pressure to equilibrate to the in-situ ambient condition. PPDs that did not stabilize sufficiently during the test were extrapolated using the method discussed by Scheremeta (2014). Numerous vibrating wire piezometers were also installed at six locations. At each location, several piezometers were installed at different depths in a nested array to monitor the piezometric pressures over time.

The measured V_s data varied between 200 and 500 m/s (with an average normalized shear wave velocity [V_{s1}] of approximately 225 m/s) over the depth of tailings tested. The measured V_p data was consistently less than 1,500 m/s with an average of approximately 800 m/s. Over significant continuous intervals, the penetration induced pore pressure measured at or near zero (regularly slightly negative), indicating that the materials are sufficiently unsaturated that both volumetric and shear induced volumetric strain were insufficient to cause saturation and positive pore pressure development. The results of the PPD and piezometer readings estimated zero, or slightly negative, ambient pore pressures, with the exception of the bottom several meters of the deposit which indicated a nominal positive pore pressure in both the PPD results and piezometer readings.

2.3 Liquefaction Analyses

While the CPT data suggests that the materials are likely unsaturated, potentially precluding the occurrence of liquefaction, sufficiently undisturbed samples could not be obtained to estimate the in-situ degree of saturation. Due to this uncertainty, the extreme seismicity of the region, and the hazard class of the facility, it was deemed prudent to conduct a thorough liquefaction assessment. Liquefaction analyses were completed using the CPT-based approach following the Robertson methodology (e.g., Robertson and Wride, 1997, Robertson, 2015), and the shear-wave-based approach, following the methodology described by Kayen et al. (2013).

The two methodologies indicated different results, where liquefaction potential was predicted using the CPT approach, but it was not predicted by the shear wave velocity approach. Refer to Figure 1 for a typical example of contradictory results from field data. Given this contradiction, additional laboratory testing was conducted to attempt to resolve this apparent discrepancy.
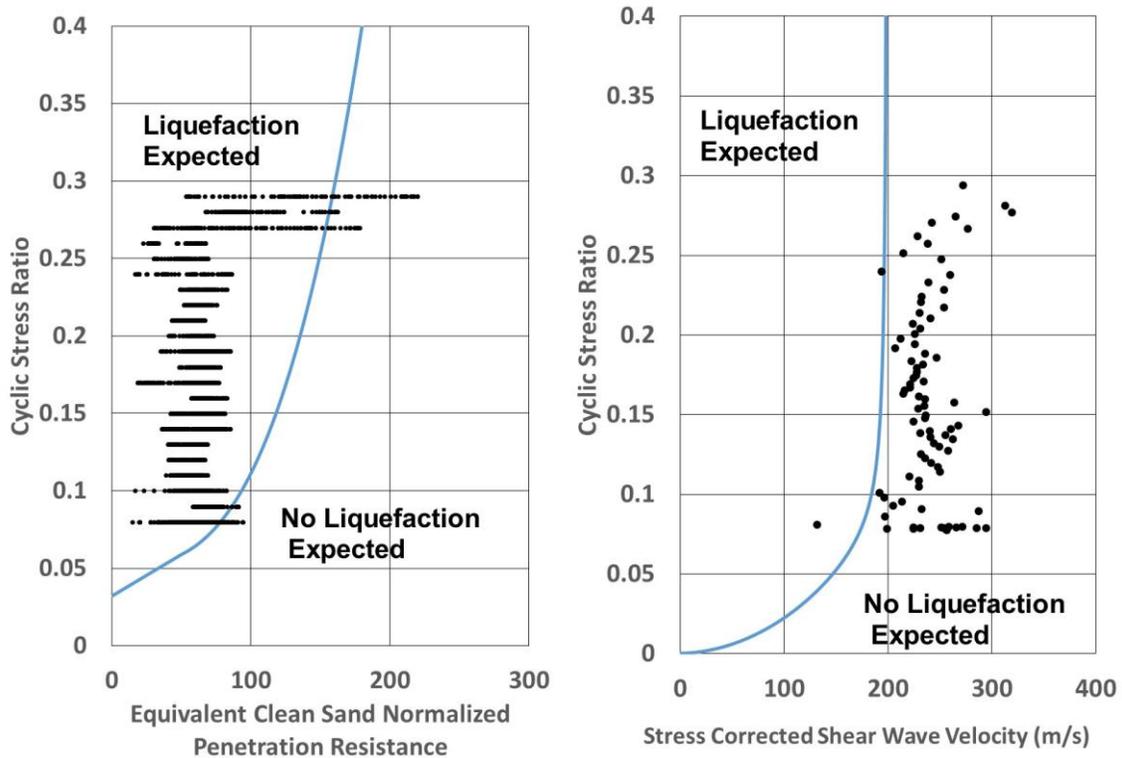
Figure 1 – Typical Example of Contradicting Results from Field Data

The laboratory testing program consisted of a suite of triaxial shear strength testing on saturated and unsaturated samples under drained and undrained conditions. Additionally, bender element testing was conducted during the consolidation phase and during the shearing phase of the triaxial testing to gain additional insight and for comparison with the in-situ test data.

3 BENDER ELEMENT AND TRIAXIAL SHEAR STRENGTH TESTING

3.1 *General*

Bender elements provide a simple means of determining the elastic (very small-strain) shear stiffness of a soil sample. Bender elements are shear wave transducers for instrumenting soil cells due to soil–transducer coupling and compatible operating frequency (Lee & Santamarina, 2005). Bender elements, in which an elastic modulus is derived based on the wave propagation theory, enhance the capabilities of triaxial testing devices such that one can measure both dynamic and static parameters of soils subjected to axisymmetric stress conditions. Because the bender elements induce very small strains which keep the specimen intact during loading, measurement of elastic and elastic-plastic responses may be made simultaneously during monotonic loading (Leong, 2009). Kim et al. (2015) provide a good description of bender element testing:

> "Bender elements are thin piezoceramic electro-mechanical transducers capable of transmitting and receiving signals; when installed on both ends [of a test apparatus], they can be used to measure wave velocities in a sample. Bender elements consist of two piezoceramic plates bonded together in series or parallel with an electrode plate in between. They convert electrical energy into mechanical movement and vice versa. Bender elements are typically mounted in the base pedestal and top cap of a triaxial cell. When excited by an input voltage, the source element bends, emitting a horizontally polarized wave that travels through the soil sample. In response, the wave motion causes the receiver element to mechanically vibrate, which is captured by a high-speed digital data acquisition system. The shear wave velocity is calculated by determining the travel distance and the travel time".

For this project, bender element tests were carried out on reconstituted, representative saturated and unsaturated samples of filtered tailings collected at the project site. The reason that reconstituted samples were tested was due to the difficulty of obtaining high-quality, undisturbed samples during the site investigation. It also allowed for variance in the degree of saturation and initial sample density to readily represent the range of conditions anticipated in-situ.

Samples were prepared by remolding using the moist tamping technique (Vaid et al., 1999) with an initial moisture content of 11.5 percent that resulted in loose samples (i.e., samples prepared at as low an initial dry density as practical) prior to consolidation and shearing. A series of triaxial shear tests was performed on samples saturated using percolation and backpressure, according to the procedure proposed by Viana da Fonseca et al (2015). Upon achieving saturation, the samples typically collapsed slightly resulting in slightly lower void ratios at the onset of the consolidation phase. Seismic velocities (both V_s and V_p) were measured using the bender elements during consolidation and the shearing phase of the testing. Triaxial shearing (drained and undrained) was carried out to determine the critical state conditions of the samples and the Critical State Line (CSL) of the material (Jefferies and Been, 2006). Additionally, a similar series of tests was conducted on unsaturated samples to measure the behavior of the material more representative of the in-situ conditions. Those samples were subject to suction measurement using a suction probe, and volume change was tracked using radial calipers. Seismic wave velocity measurements on unsaturated samples with known suction provide an opportunity to determine the relationship between V_{s1} and void ratio based on effective stress values that incorporate suction.

3.2 Results

The results of the saturated suite of tests are consistent with previous published work for similar materials (Cunning et al, 1995; Jefferies and Been, 2014) in terms of the shape and location of the CSL and V_s contours at the end of isotropic consolidation. The in-situ and laboratory testing results at a mean effective reference stress of 100 kPa indicate that a V_s between 115 and 135 m/s would represent the contractive-dilative boundary; while Cunning et al. (1995), indicated a V_s as high as 150 m/s for young, uncemented sands under these conditions. Based on these results and the in-situ measured V_s of 225 m/s, the project tailings would be expected to dilate under shear if the materials were saturated.

The results of the unsaturated suite of tests (refer to Figure 2) indicated that V_{s1} values significantly increase with suction; this appears to be primarily due to suction hardening rather than from the change in effective stress due to suction (Robertson et al., 2017). In addition, the CSL is located at higher values of void ratio (for similar confining stress) compared to the saturated samples. Also shown on Figure 2 are approximate contours for shear wave velocity (V_s). These contours were established based on the project-specific relationship:

$$V_{s1} = 220 - 145e$$

Where e is the void ratio at the end of consolidation for saturated samples, and V_{s1} are from the Bender testing. The normalized shear wave velocity was reverted to shear wave velocity assuming a $K_o = 0.50$ condition.

The shift in the unsaturated CLS line is as expected and previously described by Leroueil and Hight (2003). The reason for this shift is due to the development of matric suction within the unsaturated matrix which generally increases the effectives stress and causes a stronger and stiffer response to loading than identical materials under saturated conditions. The position of the CSL for the unsaturated samples appears to be independent of the magnitude of suction, at least within the range of suction carried out in these tests. Leroueil and Hight (2003) proposed that this suction hardening can be described by the following:

- Suction increases the size of the yield surface for soils, such that unsaturated soils tend to behave more like over-consolidation 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 a more dilatant response)

- Suction appears to move the CSL and is also a function of the magnitude of suction
- The movement of the CSL produces an apparent 'cohesion' in terms of strength (due to the higher yield surface and CSL)
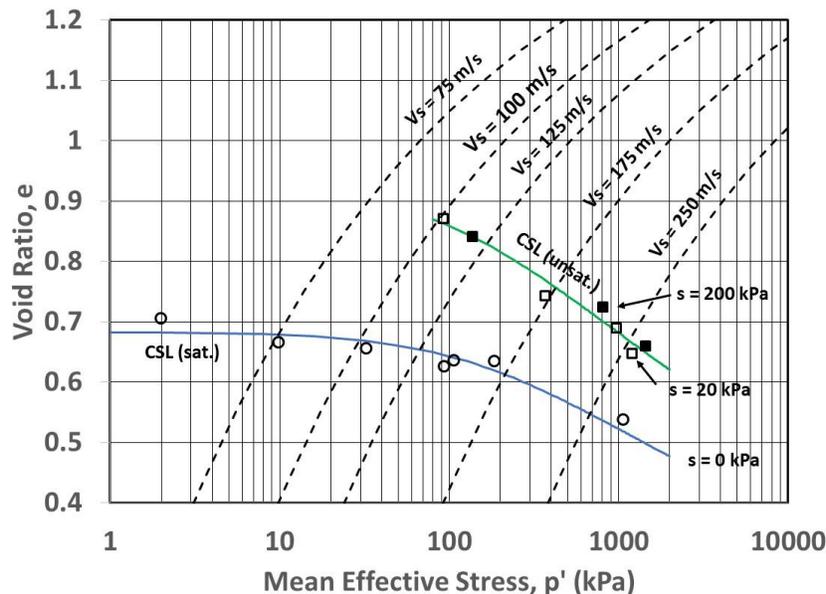

Figure 2 – Summary of Bender Element Test Results

The unsaturated triaxial testing of the project tailings was conducted at V_s and V_p values (180 to 330 and 460 to 740 m/s, respectively) generally within the range of those measured on site (200 to 550 and 350 to 1150 m/s, respectively) to confirm that testing would be representative of the in-situ conditions. While the suctions anticipated under these in-situ conditions (likely between 50 and 100 kiloPascal (kPa) based on the project specific soil water characteristic curves) are relatively small, the effect of suction hardening is significant in terms of soil behavior under shear.

Based on the results of both the saturated and unsaturated triaxial testing, it was concluded that the tailings are expected to be dilative under large strain, even if the materials were to become saturated in the future. This is consistent with the shear wave liquefaction assessment methodology, but at odds with the CPT based assessment. The unsaturated nature of the tailings would lead to a higher compressibility due to the entrained air within the voids which would appear as a lower measured cone resistance during CPT probing. This lower penetration resistance will increase the estimated liquefaction potential of the materials, and in this instance, the CPT-based liquefaction assessment provided an inaccurate indication that the materials would likely liquefy due to the occurrence of the design earthquake.

4   CONCLUSIONS

The filtered tailings facility that is the subject of this paper is an example of a well-operated facility. This is not always the case for filtered tailings facilities. When designing a filtered tailings facility, the designer should duly consider the site topography, climate, operational practice and the intended geotechnical characteristics of the filtered tailings. The inclusion of drainage features should be considered, as should cold/wet season operation and/or storage areas within the facility. The designer should consider the potential of upset conditions to occur as well as variation of the geotechnical characteristics of the tailings over time. There is no panacea for tailings deposition, and filtered tailings is but one option that designers have in their toolbox.

The results of the project site investigation provided conflicting liquefaction potential indicators. The degree of saturation and V_s were consistent with materials which are not expected to liquefy under shear. However, the industry standard practice considering the CPT cone re-

sistance methodology indicated that the materials were likely to liquefy if saturated, or nearly saturated. Upon additional investigation using drained and undrained triaxial shear strength testing, with bender element testing to confirm samples are prepared at the measured in-situ seismic wave velocities, it was determined that the materials present within the project facility are expected to dilate under large strain. The "false positive" indicated by the CPT results is likely due to the higher compressibility of air in the voids of the unsaturated tailings artificially reducing the cone resistance during probing and decreasing the beneficial effects of suction hardening which is present in unsaturated soils.

The results of the triaxial shear strength testing were consistent with previous research and provided a suitable alternative to understanding the tailings behavior under shear. When industry standard approaches seemed to provide insufficient understanding of the materials the more sophisticated, less common approach provided suitable reconciliation of the entire data set for use in the design and engineering analyses.

5 ACKNOWLEDGEMENTS

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