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A Comparison of Different Laboratory Techniques to Simulate Stress and Moisture History of Hard Rock Mine Tailings

Farzad Daliri, Paul Simms and Siva Sivathayalan

Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada

Abstract

In thickened tailings technology, tailings are deposited at solids concentrations sufficient to prevent segregation and allow for formation of gently sloped stacks. Post-deposition, thickened tailings are known to gain strength through a combination of hindered settling, desiccation, and consolidation. Recently, it is understood that the shear strength and geotechnical stability of the stack is dependent on the degree of desiccation or drying time for a given layer, as well as consolidation history during subsequent deposition. This paper presents some preliminary investigations into how best to reproduce this stress history for element testing. Three laboratory methods for simulating stress history of thickened tailings layers are introduced for preparing samples for testing in an NGI type simple shear apparatus. In the first method, tailings are reconstituted in the simple shear mold, desiccated to different degrees, and re-wetted before shearing. The second method consists of simulating the thickened tailings deposition in a column, followed by sample extraction using a shearing thin-wall sampler. In the third method, a flume is employed to simulate the movement of thickened tailings layers from the deposition point down the beach. The third method is intended to assess whether the movement of tailings down the beach constitutes an important part of stress history, and influences the evolution of the fabric. This paper recommends the most appropriate method for preparing samples to assess the geotechnical behaviour of thickened tailings. It is concluded that desiccation to the shrinkage limit could significantly increase the monotonic shear strength of hard rock mine tailings; however, with continuing desiccation beyond the shrinkage limit, additional monotonic strength gain is minimal.

Introduction

From the early 1970's when thickened tailings technology was first proposed by Robinsky (1970), the technology has been increasingly used for a variety of types of mining. Thickened tailings are deposited at a density sufficient to allow for the formation of gently sloped stacks, therefore avoiding reducing reliance on dams for containment and the associated risk of catastrophic failure. However, many regulators are concerned with remobilization of these unbounded tailings stacks due to cyclic loading or heavy rains. Therefore, the monotonic and cyclic behaviour of these tailings stacks are of significant interest to mining operators.

Thickened tailings gain shear strength post-deposition through a combination of settling,desiccation, and self-weight consolidation under subsequent layers of deposition (Simms et al 2007, Simms and Grabinsky, 2004) . Figure 1 presents a possible volume stress history of a thickened tailings layer, which initially shrinks due to drying and increasing matric suction, is subsequently rewetted by an additional layer, and then undergoes consolidation as deposition continues. In order to accurately investigate the monotonic or cyclic behaviour of thickened tailings layers, an appropriate method to simulate the stress history experienced in the field is needed. This paper investigates three laboratory methods to simulate tailings deposition and associated stress history, and compare the thickened tailings monotonic response between these three methods. The effect of the over consolidation ratio induced by desiccation history on the monotonic response of thickened tailings layers is also presented. It should be noted that this paper continues the line of study performed by Al-Tarhouni et al. (2011) and Kim et al. (2011).

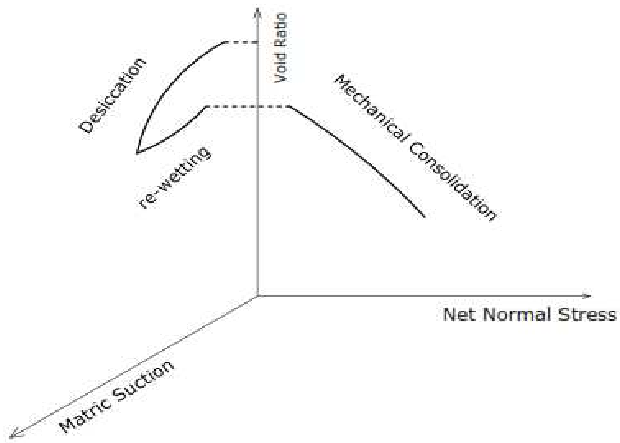

Figure 1: Volume-stress history of a thickened tailings layer

Suction Stress Charactristics Curve (SSCC)

For investigating the stress history of thickened tailings stack deposition, it is required to utilize a method explaining the stress conditions in unsaturated soils.

There are a number of recognized approaches for describing the state of stress in unsaturated soil, including:

- The modified effective stress approach, which is attributed to the work of Bishop (1959)
- The independent stress state variable approach, which is attributed to the work of Fredlund and Morgenstern (1977);
- Modified stress variable approaches adopted by a number of researchers for stress–strain analyses.

Bishop's effective stress approach contains a modified form of the saturated effective stress equation: (Bishop, 1959)

$$\sigma' = (\sigma - u_a) + \chi (u_a - u_w) \qquad \textbf{(1)}$$

The "effective stress parameter "χ" is generally considered to vary between zero and unity as a function of the degree of saturation. The difference between σ and u_a is the net normal stress and the difference between u_a and u_w is matric suction (Bishop, 1959). Experiments show that for a variety of soils there is a relationship between the soil water characteristic curve (SWCC), plotting suction versus saturation, and the suction stress characteristic curve (SSCC), plotting the equivalent effective stress versus saturation (Lu et al., 2010). Lu and Likos (2006) proposed a form of suction stress that is consistent with Terzaghi's effective stress:

$$\sigma' = (\sigma - u_a) - \sigma^s \qquad \textbf{(2)}$$

Where $\sigma^s = -(u_a - u_w) \times S$, where S is degree of saturation.

Lu et al. (2010) also used the same approach to represent the suction stress based on Van-Genuthcan parameters. Figure 2 shows a typical comparison of SWCC and SSCC for a typical soil.

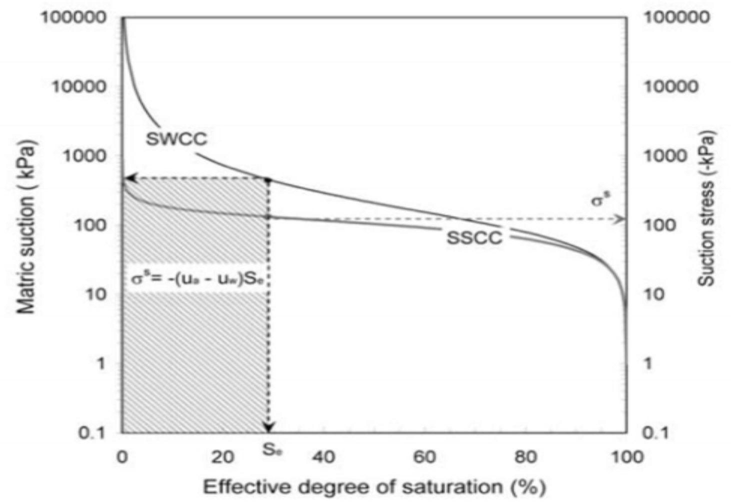

Figure 2: A typical comparison of SWCC and SSCC (after Ning Lu et al., 2010)

The method proposed by Lu et al. (2010) is employed in this research to obtain the SSCC for gold tailings in order to investigate the stress-history of the thickened tailings stacks.

Materials

The tested tailings were collected from the Bulyanhulu gold mine located in Tanzania. The tailings were transported from the mine submerged in water-filled plastic bags, in order to minimize oxidation of the minerals and acid rock drainage. Although the tailings were shipped at the pumping water content (38%), it was found that due to settling during transport, the water content reduced to around 30% and it was necessary to remix the tailings with the bleed water produced by settling in order to re-produce tailings with a water content of 38%. The specific gravity of the tailings was 2.89; the Liquid Limit (LL), Plastic Limit (PL), and shrinkage limit were 22.5%, 20%, and 18% respectively. According to Unified Soil Classification System, the tailings were classified as silt with low plasticity (ML).

Fisseha et al. (2010) used a variety of methods in order to obtain the soil water charactristics curve (water retention curve) of Bulyanhulu gold tailings. Figure 3 presents the SWCC of Bulyanhulu gold tailings based on gravimetric water content (GWC) and degree of saturation obtained by Fisseha et al. (2010).

In order to determine the stress history of the gold tailings stack, the equivalent effective stress of the tested tailings during desiccation is required. Using equation 2, the SSCC of the gold tailings is obtained and compared with SWCC in Figure 4. It is clear that with decreasing the degree of saturation during desiccation, both matric suction and suction stress increase. However, the amount of increase is not equivalent below Sr = 0.8 (GWC = 22%). In fact, between Sr = 0.8 and Sr = 0.42 (GWC = 22% and GWC = 11%), the suction stress does not increase as the matric suction increases. As expected, the trend in the suction stress after the AEV (air entry value) is not the same as the suction stress before the AEV. In other words, before the AEV (~80kPa) the suction stress is almost equal to matric suction; while after the AEV, it is lower than the matric suction. However, the suction stress continues to increase despite the decrease in degree of saturation.

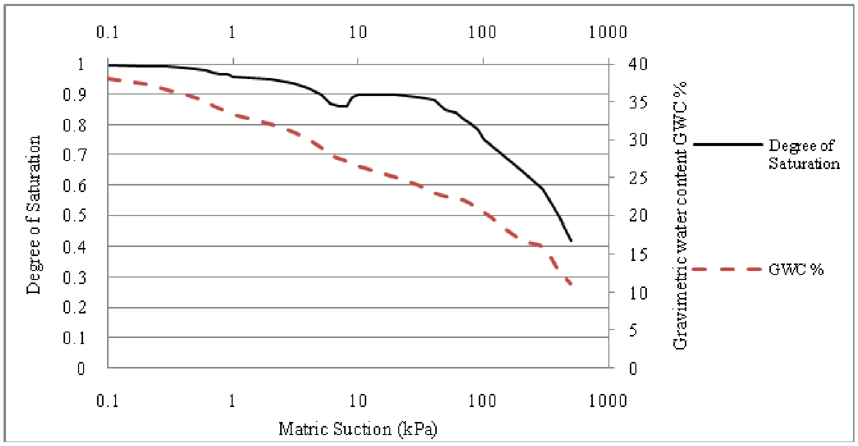

Figure 3: Measured Soil water charactristics curve of gold tailings (Fisseha et al., 2010)

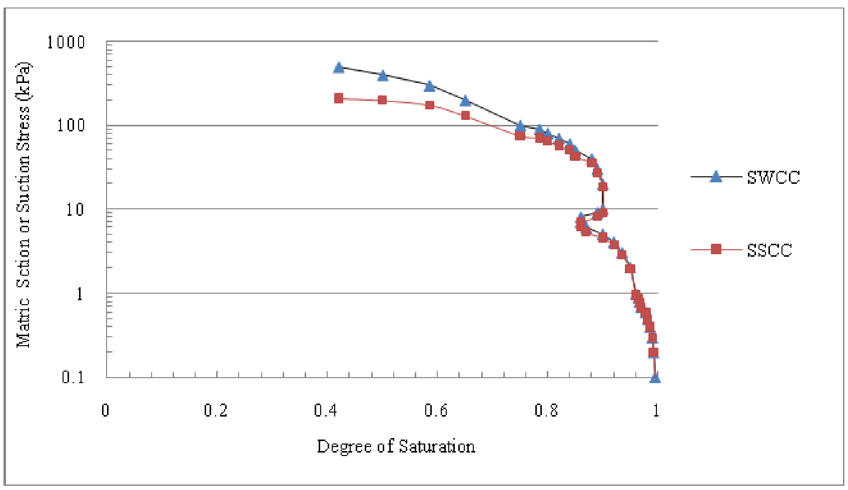

Figure 4: The comparison of SWCC and SSCC for gold tailingsMethdology

Methdology

Three different sample preperation methods are proposed in this paper. The first method is simply to reconstite samples at the pumping water content in the simple shear test mold, before drying and consolidation. The second method involves sampling small-scale simulations of multilayer deposition. In the third method, a flume test is performed to consider the effect of thickened tailings deposition movement on the montonic response of thickened tailings. In other words, the third method is focused on whether the movement of tailings down the beach constitutes an important role in the shear strength of thickened tailings layers.

The reconstituted samples and samples extracted from deposition simulation are tested using a simple shear apparatus. The simple shear apparatus employed in this study was the NGI (Norwegian Geotechnical Institute) type. The apparatus consists of a shear load frame, a vertical single acting air piston, a horizontal double acting air piston, a constant speed motor drive, load cells, Electronic-Pneumatic Transducer (EPT), and Linear Variable Displacement Transducers (LVDT). In the apparatus the sample is contained within a steel wire reinforced rubber membrane in order to constrain the lateral deformation. The constant volume condition is obtained during shear loading by keeping the height of the sample constant using a clamping mechanism. In order to achieve the constant volume condition, the specimen diameter is kept constant by the reinforced membrane and any vertical displacement is restricted by clamping the top and bottom loading cap against vertical movement. Figure 5 shows a schematic diagram of the simple shear apparatus used in this study. It has been illustrated that the decrease or increase of vertical stress in a constant volume simple shear test is typically equivalent to the increase (or decrease) of excess pore water pressures in an undrained test. In this case, the change in applied vertical stress has been shown to be equivalent to the excess pore pressure ($\Delta u = \sigma'_{vc} - \sigma'_{v}$), which would have been measured in a truly undrained test (Dyvik et al., 1987). Al-Tarhouni et al. (2011) showed that tailings in the pseudo-saturated range, in which the matric suction is zero but the sample contains an occluded air phase, show similar behaviour with fully saturated tailings. In other words, whether they are tested in this pseudo-saturated state, or tested after their degree of saturation has increased by connecting the sample to a water reservoir, they exhibit essentially identical response to shearing.

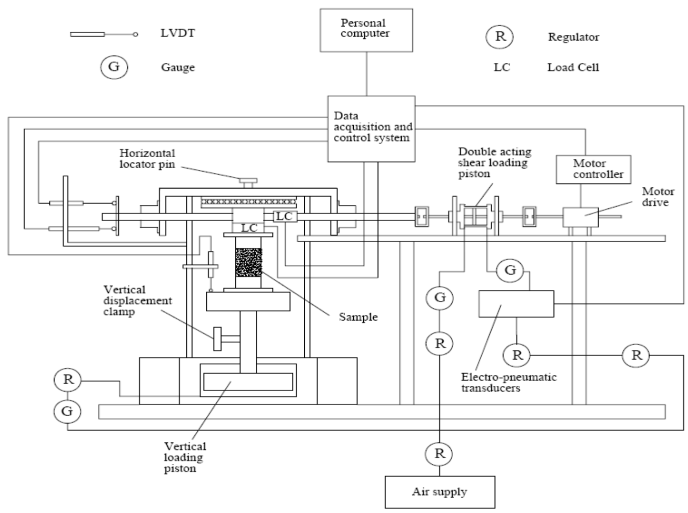

Figure 5: A schematic diagram of the simple shear apparatus (Al-Tarhouni, 2008)

First method: reconstituted samples

In the first method, tailings at the pumping water content (38%) were reconstituted in a simple shear mold and allowed to desiccate to different water content values. Samples were taken from buckets in which their water content was less than 30% (post-settling), and submerged in process water. Process water was mixed with the tailings to increase the water content before placement of the tailings in the mold. Desiccated samples were allowed to dry to 25%, 18% (the shrinkage limit) and 13% water content (corresponding to ~ 400 kPa matric suction). W_d is introduced to show the water content to which the samples are desiccated. The samples with W_d = 18% and W_d = 13% were rewetted with tailings bleed water. After reaching desired water content, water was added slowly in order to resaturate the sample. The water content of the desiccated tailings after rewetting but before consolidation was always between 21 and 22%, although the degree of saturation varied between 0.96 and 0.88 due to different obtained void ratios after re-wetting. In order to simplify comparisons among specimens desiccated to different water content (matric suction), the over consolidation ratio of desiccated specimens (OCR_D) is introduced. The overconsolidation ratio is normally defined as the highest stress experienced divided by the current stress (Das, 1997). As previously discussed, during the desiccation soil samples are subjected to an equivalent effective stress (suction stress) depending on the matric suction and degree of saturation. As a result, the over-consolidation ratio in this case is defined by the ratio of maximum suction stress achieved during drying, and the consolidation pressure applied after rewetting. It should be noted that if the suction stress is lower than the consolidation pressure, the sample is considered normally consolidated and OCR_D is equal to one.

$$\begin{cases} OCR_D = \dfrac{\text{Suction Stress}}{\sigma'_{vc}} & \text{suction stress} > \sigma'_{vc} \\ OCR_D = 1 & \text{suction stress} < \sigma'_{vc} \end{cases} \qquad \textbf{(3)}$$

Where σ'_{vc} is the consolidation pressure applied to the sample after resaturation.

All resaturated samples were consolidated under 50 kPa consolidation pressure before shearing.

Second method:

The second method consisted of successively depositing two layers of tailings of thickness of about 10 cm in a cylindrical column with a 25 cm diameter. In this method, thickened tailings were deposited in the column at the pumping water content (38%) and allowed to desiccate to different values of water content above and below the shrinkage limit (e.g. 30, 28, 25, 23, 19, 17, 12 and 4%). Fans were located on top of the columns in order to accelerate desiccation. Continuing desiccation to lower water contents generates higher suction stress in the tailings. These tailings were then overlaid with fresh tailings, which led to resaturation of the underlying tailings by capillary action. Samples were obtained from the bottom layer after about 12 hours. Similar to the first method, the water content of the samples before extraction was measured at around 21 ~ 22%. Degree of saturations after sampling ranged from 0.86 to 0.90. For sampling, some thin wall tubes with a length-diameter ratio of 1.42 were employed. It should be mentioned that for fine grained soils, it is recommended to use a thin, sharp edged tube with the length-diameter ratio of 1.4 and area ratio less than 15 for sampling method (Wijewickreme, Sanin 2004). Figure 6 shows typical extracted samples from the column.

Figure 6: Typical extracted samples using second method of deposition

Extracted samples were placed in a simple shear device and consolidated under 50 kPa, 100 kPa and 200 kPa consolidation pressures. Based on definition of OCR_D, the amount of OCR_D is a function of consolidation pressure. Table 1 shows the values of OCR_D for different water contents and consolidation pressures calculated using equation 3.

Table 1: The values of OCR_D for different water contents and consolidation pressures

W_d (Water Content) %	Consolidation Pressure		
	50	100	200
30	1	1	1
28	1	1	1
25	1	1	1
23	1	1	1
19	1.7	1	1
17	2.6	1.3	1
12	4.1	2.1	1
4	8	4	2

Third method:

In the third method, a 200 × 10 cm flume was used to simulate the movement of thickened tailings layers from the deposition point down the beach. Tailings at the pumping water content were pumped with a centrifugal pump and deposited at the edge of the flume. The pumping rate was such that movement of the tailings front along the bottom of the flume was between 0.1 and 0.2 cm/s. After reaching 15 cm thickness, the flow was stopped and tailings were allowed to desiccate to reach 30% and 25% water content. Samples were extracted from the deposition point (L=0 cm) and 200 cm away from the deposition point (L=2 m) using a shear thin wall sampler. Extracted samples were placed in a simple shear test for strength measurement. Figure 7 shows the flume test process.

Figure 7: Flume test process

Results:

First method results:

Figure 8 presents the results of the first method of deposition simulation. All samples were consolidated under 50 kPa vertical stress after rewetting and before shearing. It is clearly shown that the sample desiccated to water content above the shrinkage limit (W_d=25%) had a reduced response. Continuing desiccation to W_d = 18% and 13 % (OCR_D = 2.3, OCR_D = 4) increases the dilative response. However, the rate of increasing dilative behaviour by desiccation to the shrinkage limit (18%) is not the same as desiccation beyond the shrinkage limit. In other words, the rate of dilation increases sharply as OCR_D increases from 1 to 2.3, but increasing OCR_D from 2.3 to 4 does not lead to a tangible increase in the dilation. It should be noted that samples with higher OCR_D show stronger response in spite of the higher void ratio after consolidation.

Kim et al. (2011) employed this method to compare the behaviour of desiccated samples with OCR_D and mechanically overconsolidated samples. Figure 9 demonstrates that the effect of OCR_D on the monotonic response is qualitatively different from the effect of mechanical overconsolidation. Mechanical overconsolidation produces a pronounced peak stress, while overconsolidation by desiccation does not, but rather increases strain hardening past the phase transformation point.

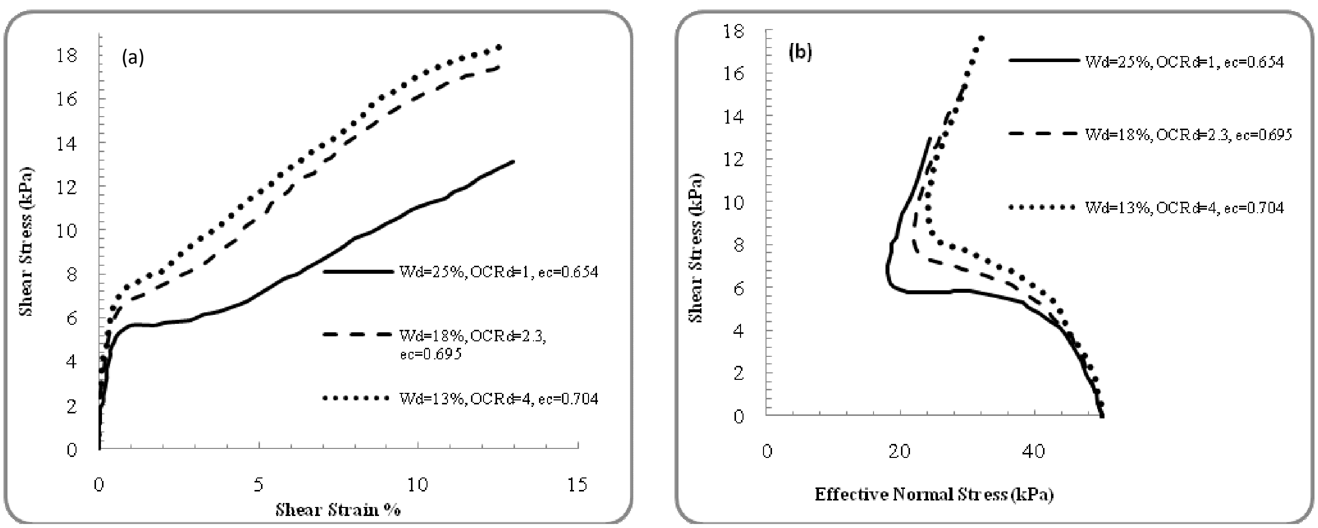

Figure 8: The effect of desiccation on monotonic response of thickened tailings based on the first method

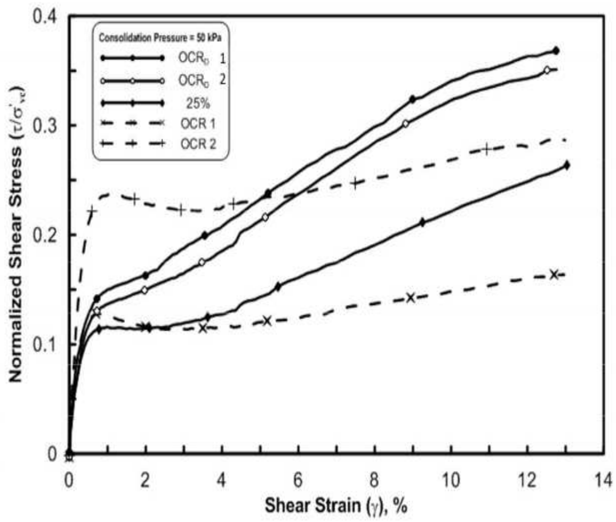

Figure 9: The comparison of overconsolidation ratio derived by desiccation (OCR_D) and mechanical loading (OCR_M) (after Kim et al., 2011)

Second method results:

Figure 10 and Figure 11 present the results of the second method under 50 kPa consolidation pressure after extraction. It is clear that samples desiccated to Wd= 30% have a contractive response. The phase transformation point appears for tailings dried to Wd=28% and lower and the dilative response is increased with continuing desiccation. With contining desiccation to the shrinkage limit (AEV at SWCC, OCR_D = 1.7), the dilative response becomes more pronounced. Desiccation beyond the AEV also increases the dilative response; however, the rate of increase is significantly lower in comparison to samples desiccated to the AEV. In other words, after the shrinkage limit, although the OCR_D increases from 1.7 to 4.1, the shear strength does not increase in the same proportion as before the AEV.

Figure 12 shows the comaprison of the normalized shear stress at phase transformation (PT) points (τ_{PT}/σ'_{vc}) for different consolidation pressures. As with the relative degree of dilation, with increasing the desiccation to AEV, the shear stress at PT increases rapidly; however, the rate of increase in shear stress at PT is not as rapid for samples desiccated past the AEV. It should be noted that samples with higher consolidation pressures had higher shear stress at PT.

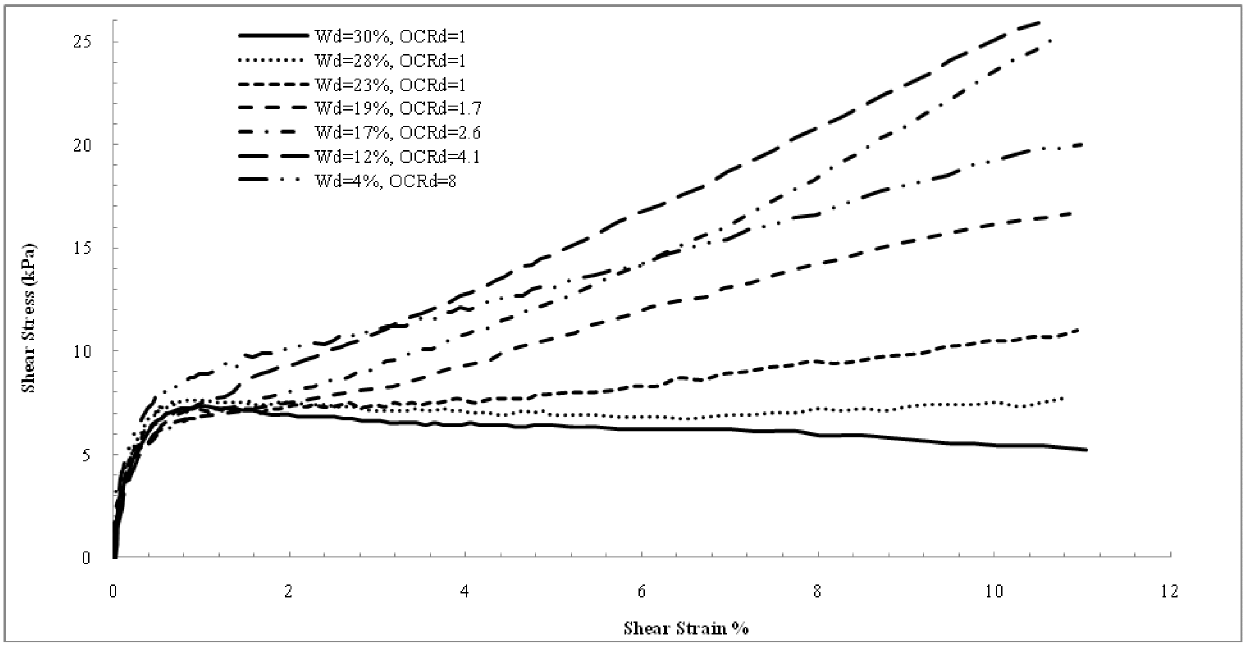

Figure 10: The effect of desiccation on stress-strain response of thickened tailings (CP = 50 kPa)

Third method results:

Figure 13a and 13b show the result of samples extratced from deposition point and 2 m away from the deposition point with the flow velocity of 0.1 cm/s and 0.2 cm/s respectively. Based on Figure 13a, it is clear that the sample extracted from L = 2 m from the deposition point is less dilative than the sample extracted from the deposition point. However, the difference is almost negligible. According to Figure 13b, both samples have same response before the phase tranformation point. After PT, samples extracted from L= 200 cm have less dilative response.

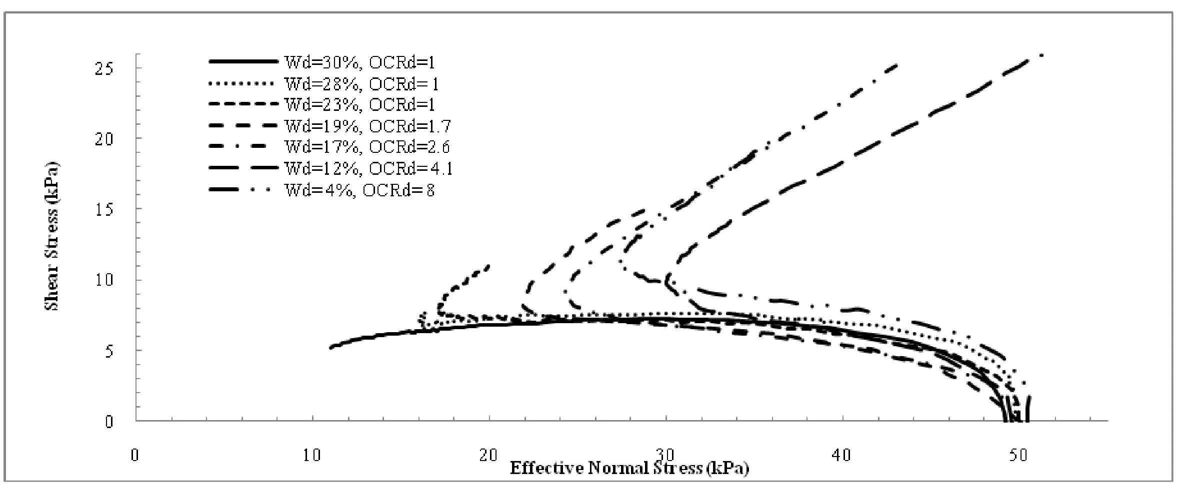

Figure 11: The effect of desiccation on stress path response of thickened tailings (CP = 50 kPa)

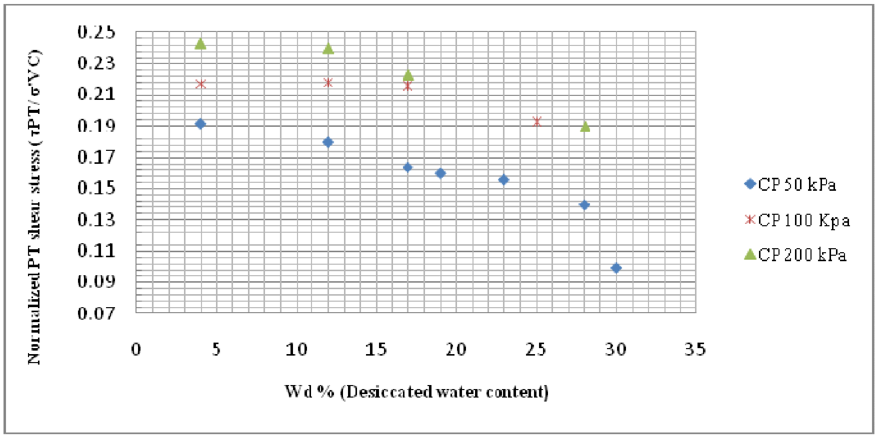

Figure 12: The comparison of the value of normalized shear stress at phase tranformation points with the desiccation history

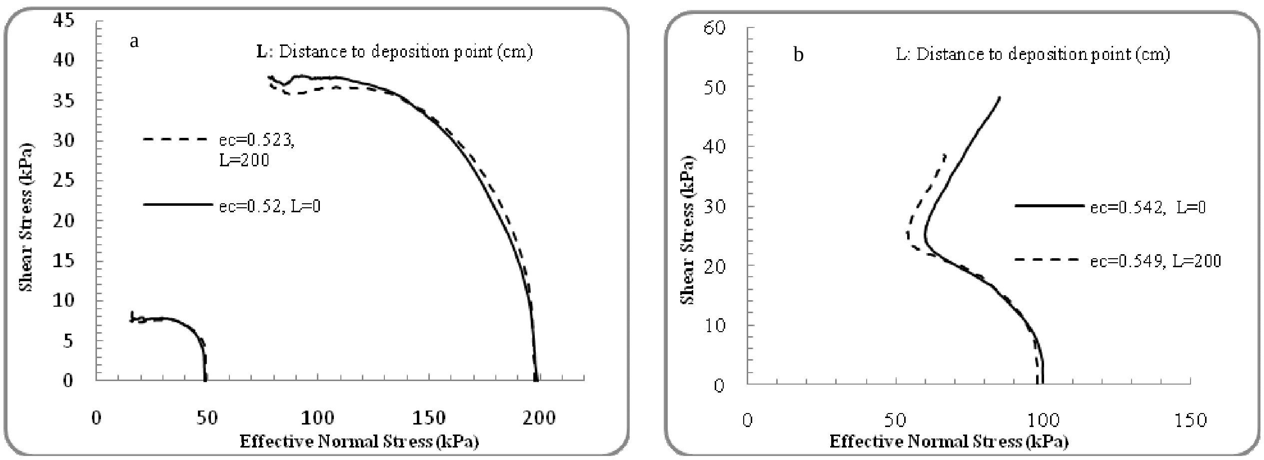

Figure 13: Response of tailings near the deposition point and at the toe (2 m away) in a flume simulation of desposition

Discussion

Three different laboratory techniques are proposed to simulate the deposition of hard rock thickened tailings as a stack. In both the first and second methods higher OCR_D (higher desiccation history) leads to higher monotonic shear strength. The rate of strength increase is higher as the material dessicates to the shrinkage limit, but additional strength gain is minimal with subsequent drying beyond the shrinkage limit. This is perhaps due to the higher post-consolidation void ratios of the highly desiccated samples. Figure 14 shows the comparison of the first and second methods considering the variation of normalized shear stress at PT and void ratio with desiccated water content (W_d). It is obvious from Figure 14b that for both methods, the void ratio obtained after consolidation increases with increasing the desiccation history. In other words, samples with higher OCR_D (lower W_d) have higher void ratio after consolidation. Figure 14a demonstrates that the higher void ratio does not affect the normalized shear stress at PT significantly.However, the first method of deposition could lead to higher void ratios and therefore lower shear strength in comparison to the second method. In other words, although the second method could simulate the field deposition more appropriately, the result of the first method could be safer for static design due to the lower shear strength. It is also shown that for both methods with increasing desiccation history (increasing OCR_D or decreasing W_d), the monotonic shear strength increases. However, the rate of increase is more significant for samples desiccated to AEV.

For the third method, it should be noted that samples extracted from the deposition point have slightly higher strength. However, this slight difference is almost negligible. It is proposed to develop the experiment to longer lengths of deposition for more accurate simulation.

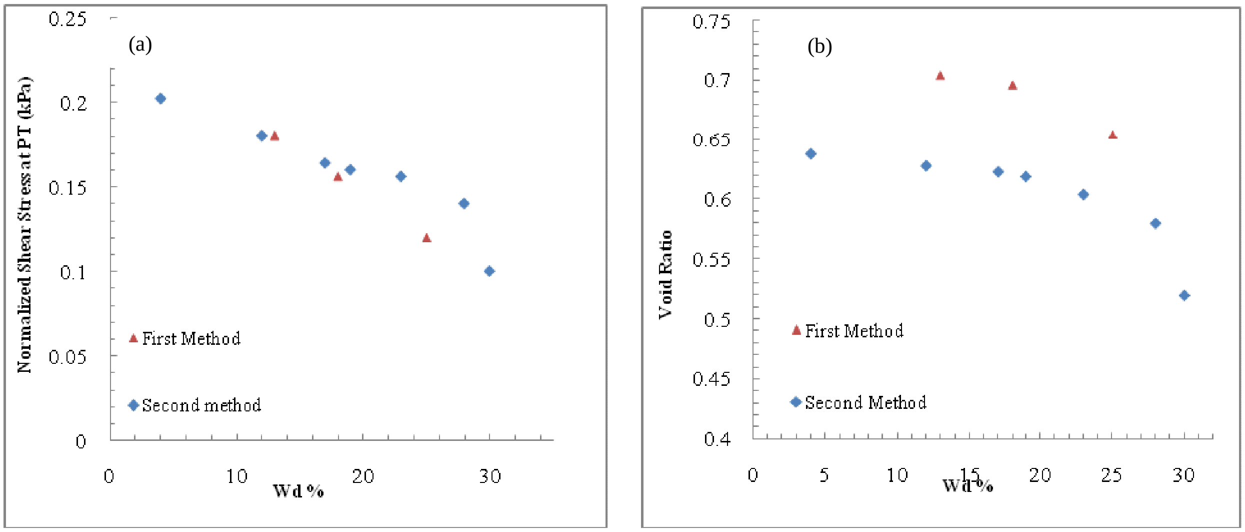

Figure 14: A comparison of the first and second methods

Conclusions

Three different laboratory methods for simulating stress history of thickened tailings layers were used in order to determine the best method to reproduce the stress history of thickened tailings stack layers for element testing. Based on the simple shear test results, the following can be concluded:

1. Thickened tailings at high water content (more than 30%) have a contractive response.
2. Desiccation to shrinkage limit could significantly increase the monotonic shear strength of hard rock mine tailings; however, desiccation beyond the shrinkage limit would not be as beneficial as desiccation to the shrinkage limit.
3. The second method could simulate the field deposition more appropriately; however, due to the lower void ratio in comparison to the first method, the results of the second method are more dilative.
4. The movement of thickened tailings during deposition could slightly decrease the strength. However, this decrease could be negligible for short deposition lengths. More research is required for longer deposition lengths of deposition.

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