The influence of desiccation and overconsolidation on monotonic and cyclic shear response of thickened gold tailings

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ABSTRACT:
Regulators are naturally concerned with remobilization of unbounded deposits of mine waste residuals, such as thickened tailings stacks. Consequently, the monotonic and cyclic behaviour of thickened tailings is of significant interest to practitioners of mine waste geotechnique. Thickened tailings are known to gain strength through a combination of hindered settling, desiccation, and consolidation post-deposition. This paper reports on the effects of over-consolidation ratio (OCR) and desiccation, using a simple shear apparatus (NGI type). Samples were alternately overconsolidated by either mechanical loading, or by desiccation followed by rewetting and consolidation. Mechanical overconsolidation highly influenced the monotonic and cyclic resistance of thickened tailings specimens and both monotonic and cyclic resistance exponentially and continuously increased with increasing OCR for desiccated tailings, the relationship between increasing OCR and increasing cyclic resistance is more complicated and, surprisingly, could be converse with excessive desiccation beyond the shrinkage limit.

RÉSUMÉ
Des régulateurs sont naturellement concernés par la remobilisation des dépôts illimités des résidus miniers, tels que les piles des résidus épaissies. En conséquence, le comportement monotone et cyclique des résidus épaissis est intérêt significatif aux praticiens du geotechnique. Des résidus miniers épaissis sont gagner la puissance par une combinaison de sédimentation, de la dessiccation, et de consolidation. Ce document rend compte des effets du rapport d'au-dessus-consolidation (OCR) et de la dessiccation, utilisant un appareil de cisaillement simple (type de NGI). Des échantillons sur-consolidés alternativement par le chargement mécanique, ou par la dessiccation suivie de ré-humidification et de consolidation. OCR mécanique influence fortement la résistance monotones et cyclique des spécimens et résistance monotones et cyclique exponentiellement augmentation avec l'augmentation d'OCR mécanique. Pour les résidus miniers, le rapport entre augmenter OCR par dessiccation, et augmenter la résistance cyclique est plus compliqué et, étonnant, pourrait être inverse avec la dessiccation excessive au delà de la limite de retrait.

Key words: Thickened tailings, cyclic resistance ratio, desiccation, overconsolidation, simple shear test

1 INTRODUCTION

To remove or reduce reliance on dams and minimize the risk of dam failure, an increasing number of mines are employing thickened tailings technology. This technology dewaters the tailings to the point where they exhibit a yield stress, which allows the tailings to form gently sloping deposits. Thickened tailings deposition has been increasingly used since 1970's (Robinsky, 1999).

It is known that thickened tailings may gain shear strength through desiccation and self-weight consolidation under subsequent layers of deposition (Simms et al. 2007, Simms and Grabinsky, 2004). The increase in density due to desiccation not only decreases the total volume of the stack layers, but also likely increases the resistance of tailings stack to earthquake loading. Therefore, stress history in terms of matric suction as well as mechanical loading may influence the cyclic resistance of the tailings. Figure 1 shows a possible volume-stress history of a thickened tailings layer in a cyclic deposition scheme, which initially shrinks due to drying by matric suction, is subsequently rewetted by the placement of an additional layer, and then undergoes consolidation as deposition continues.

It has been suggested that if thickened tailings are dried to their shrinkage limit, that they will not exhibit flow liquefaction, and so pose minimal risk of significant deformation during seismic events (UNEP and ICOLD 2001). However, there has been only limited experimental evidence to back up this supposition. Al-Tarhouni et al. (2011) investigated the influence of desiccation on cyclic behaviour of thickened gold tailings. In their study, samples were allowed to desiccate to various water contents at and below the shrinkage limit. The samples were then rewetted to near saturation before consolidation to a relatively low confining stress (50 kPa) and cyclic testing in a simple shear device. When compared to samples that were normally consolidated to 50 kPa, the desiccated samples did show a substantial increase in cyclic resistance. Nevertheless, sizable deformations would still be possible through cyclic mobility and post-cyclic strains, for a sufficiently strong earthquake.

The present paper continues the line of investigation started in Al-Tarhouni et al. (2011). In this paper, a comparison is made between monotonic and cyclic behaviour of tailings mechanically overconsolidated and tailings overconsolidated by desiccation. This is of interest as i) Many practitioners believe that desiccated tailings will behave as mechanically overconsolidated tailings and ii) If this is true, it will simplify testing procedures needed to evaluate the behaviour of desiccated tailings. Samples are evaluated under monotonic and cyclic loading using a direct simple shear apparatus (NGI type).

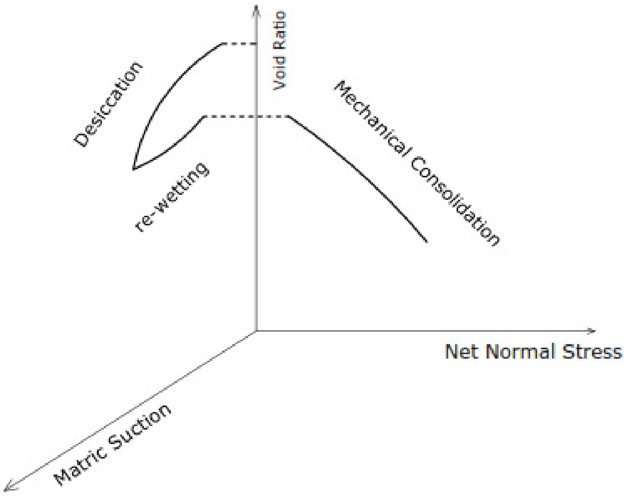

Figure 1. A possible volume-stress history of a thickened tailings layer

2 MATERIAL AND METHODOLOGY

The tested tailings were from a gold mine. The specific gravity was 2.89; the Liquid Limit (LL), Plastic Limit (PL), and shrinkage limit were 22.5%, 20%, and 18% respectively. The tailings are potentially acid generating, and contain 11% pyrite. Figure 2 presents the particle size distribution of tested materials. According to Unified Soil Classification System, tailings were classified as silt with low plasticity (ML). The tailings were transported from the mine submerged in water-filled plastic bags, in order to minimize oxidation of the sulphide minerals. Though the tailings were shipped at the pumping water content (38%), it was noted that due to settling during transport, the water content decreased to around 22% and it was necessary to remix the tailings with the bleed water produced by settling in order to re-produce the tailings with w=38%.

Mechanically overconsolidated samples were prepared at the pumping water content, deposited and consolidated to 100, 200, or 400 kPa in the simple shear device, and then unloaded to 50 kPa before shearing. Desiccated samples were allowed to settle and dry in duplicate sample moulds to 25%, 18% (the shrinkage limit), or 13% (corresponding to ~60% degree of saturation) water content. The samples desiccated to 18% and 13% were resaturated with tailings bleed water. Water was added in steps of mass to both moulds: one mould was instrumented with a tensiometer to check that matric suction reduced to near zero. The other mould was used in the shearing apparatus. The water content of the desiccated tailings after rewetting but before consolidation was always between 21 and 22%, though the degree of saturation varied between 0.96 and 0.88. In order to simplify comparisons among specimens desiccated below the shrinkage limit, the over consolidation ratio of desiccated specimens is defined by the ratio of maximum matric suction achieved during drying and the consolidation pressure applied after rewetting. This ratio is termed OCR_D, while OCR_M will refer to the mechanical overconsolidation ratio. It should be noted that this ratio is simplistic, in the sense that the contribution of matric suction to the stress state decreases as degree of saturation decreases. The ratio is used merely for comparison. OCR_D and OCR_M having the same value should not be taken to imply similar behaviour.

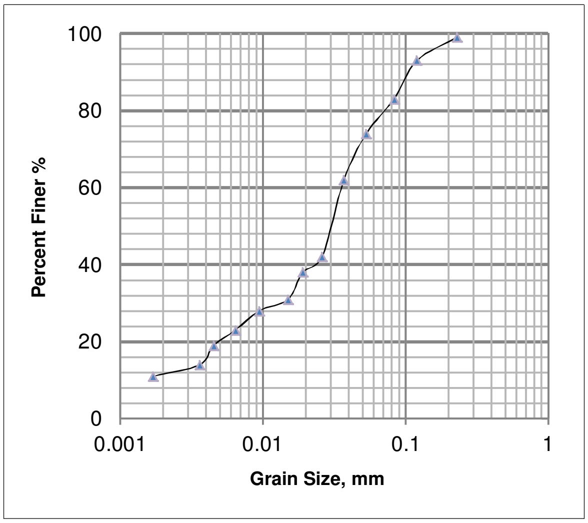

Figure 2. Grain size distribution of examined tailings

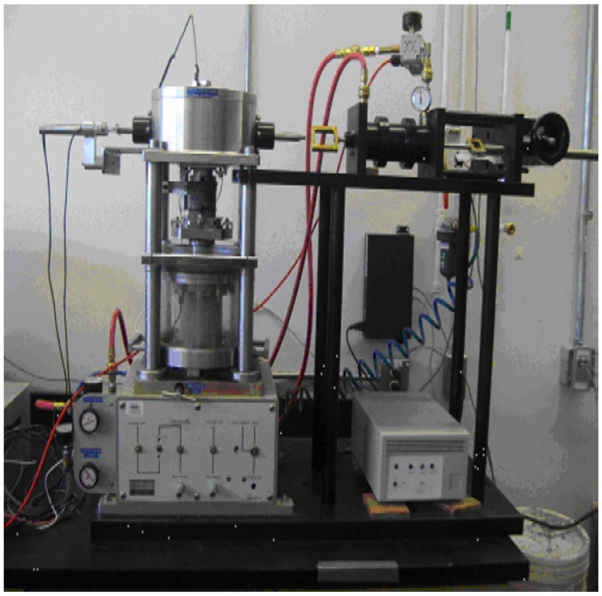

Figure 3. A photograph of simple shear apparatus

The direct simple shear apparatus employed in this study was a NGI (Norwegian Geotechnical Institute) apparatus. A photograph of this device is shown in Figure 3. 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).

The sample is contained within a steel wire reinforced rubber membrane in order to constrain its lateral deformation. The constant volume condition is achieved during shear loading by keeping the height of the sample constant. A clamping mechanism is used to facilitate this. In a constant volume test, the specimen diameter is constrained by the reinforced membrane and any vertical displacement is restricted by clamping the top and bottom loading cap against vertical movement. It has been demonstrated that the decrease or increase of vertical stress in a constant volume simple shear test is essentially 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). It has been shown that the material response of a dry sand, and the same dry sand saturated by connection of the sample to a water reservoir, exhibit identical behaviour in this apparatus. Al-Tarhouni et al. (2011) also showed that tailings in the pseudo-saturated range, in which the matric suction is zero but the sample contains an occluded air phase, likewise show similar behaviour. 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 an identical response to shearing.

US National Research Council (NRC 1985) suggested that the development of 3.75 % single amplitude shear strain should be regarded as the triggering of liquefaction under cyclic loading. The same criterion is used in this study to define the initiation of liquefaction.

3 RESULTS

3.1 Monotonic Results

3.1.1 The effect of mechanical OCR

Samples with similar void ratios after consolidation (±0.01) and with OCR_M = 1, 2, 4, 8 were loaded under monotonic loading with loading rate of 20 %/h. Figure 4 shows the effect of mechanical overconsolidation on stress-strain response, stress paths and excess pore pressure generation. Figure 4 clearly shows that normally consolidated tailings and tailings with OCR_M = 2 generally exhibit a limited liquefaction type of response, with essentially identical effective stress ratios at phase transformation. In other words, normally consolidated tailings and mechanically over-consolidated tailings with low OCR might exhibit marginal strain softening, or sudden strain development at constant shear stress. The initial contractive behaviour transforms into dilative response upon reaching the phase transformation state. On the other hand, for highly over-consolidated specimens, the response is strain hardening and there is negative excess pore pressure during monotonic loading. It must be mentioned that the range of void ratio after consolidation for all compared specimens varied between 0.6 and 0.65, even though all these specimens were deposited at fairly similar initial void ratios. Such variations are expected on account of the different compressibility during loading and unloading.

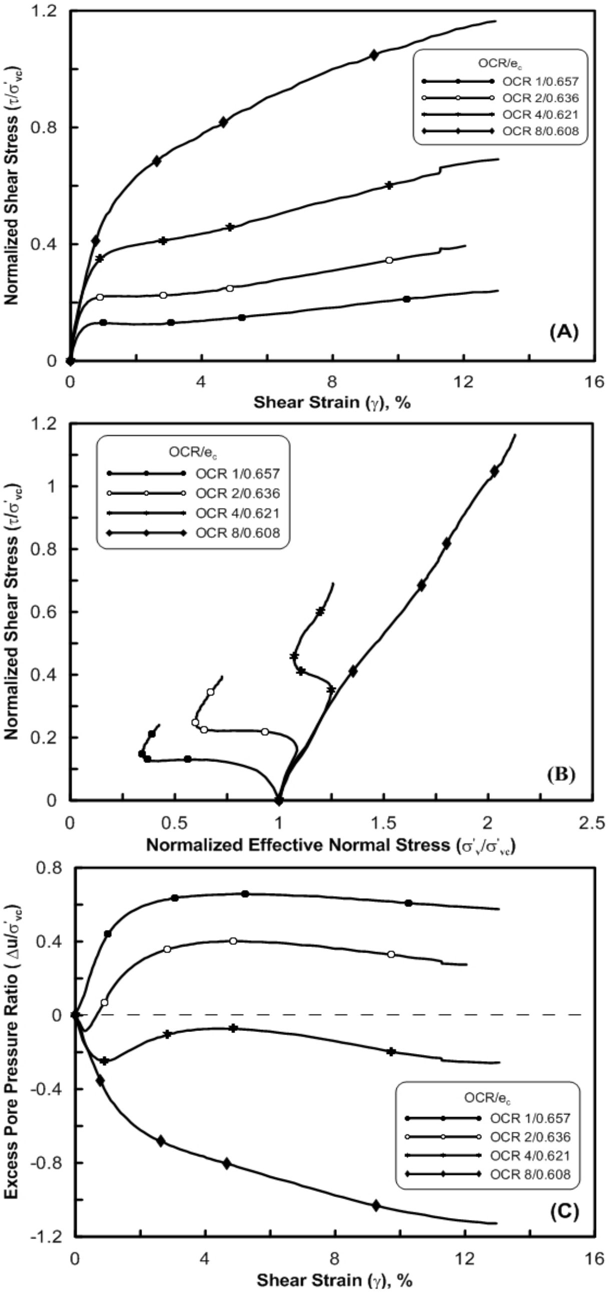

Figure 4. The effect of OCR_M on monotonic response of thickened gold tailings

3.1.2 The effect of OCR derived by desiccation

Tailings were desiccated to 25%, 18% and 13% and re-wetted gradually to reach the water content 21%. Figure 5 shows the water-retention curve of gold mine tailings. According to Figure 5A, for tailings desiccated to 18% and 13% water contents, the corresponding matric suctions are 150 kPa and 400 kPa matric suction respectively. Specimens after desiccation and re-wetting were consolidated to 50 kPa. As a result, specimens desiccated to 18% and 13% water contents correspond to $\text{OCR}_\text{D} = 3$ and $\text{ORC}_\text{D} = 8$.

Figure 6 shows the monotonic shear response of desiccated tailings and its comparison with mechanically over-consolidated tailings.

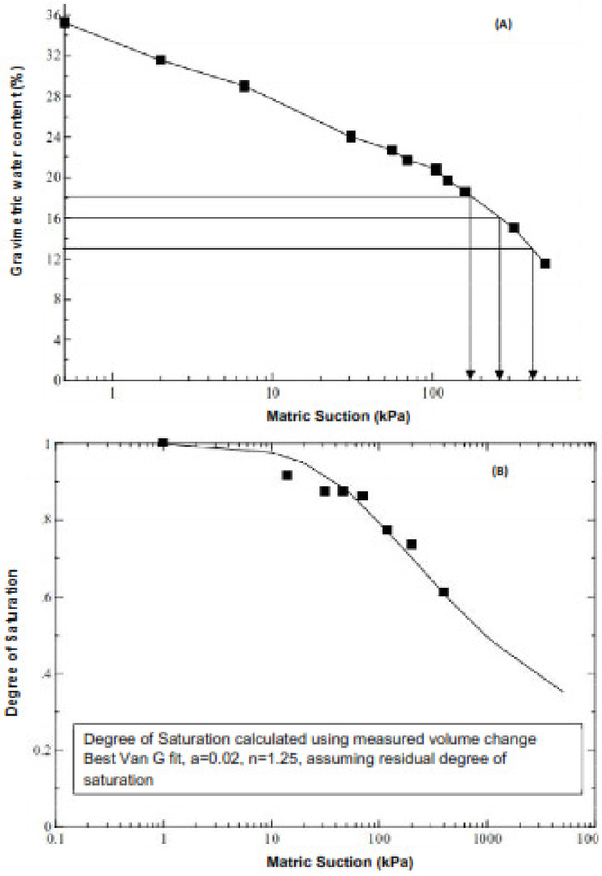

Figure 5. Soil water characteristic of gold mine tailings (Fisseha et al, (2010); Simms et al, (2007))

It is clear that desiccated tailings exhibit more strain-hardening in comparison to normally consolidated tailings with no desiccation. Interestingly, it is also demonstrated that although desiccation increases the shear strength of thickened gold tailings, the differences in shear strength between desiccated tailings of $\text{OCR}_\text{D} = 8$ & $\text{OCR}_\text{D} = 3$ is fairly small compared to the significant difference in matric suction (i.e. 250 kPa). This is not completely unexpected, as the degree of saturation is 60% for the sample dried to 13% (400 kPa) suction. Figure 6 also demonstrates that the effect of OCR_D on monotonic response is not as influential as OCR_M.

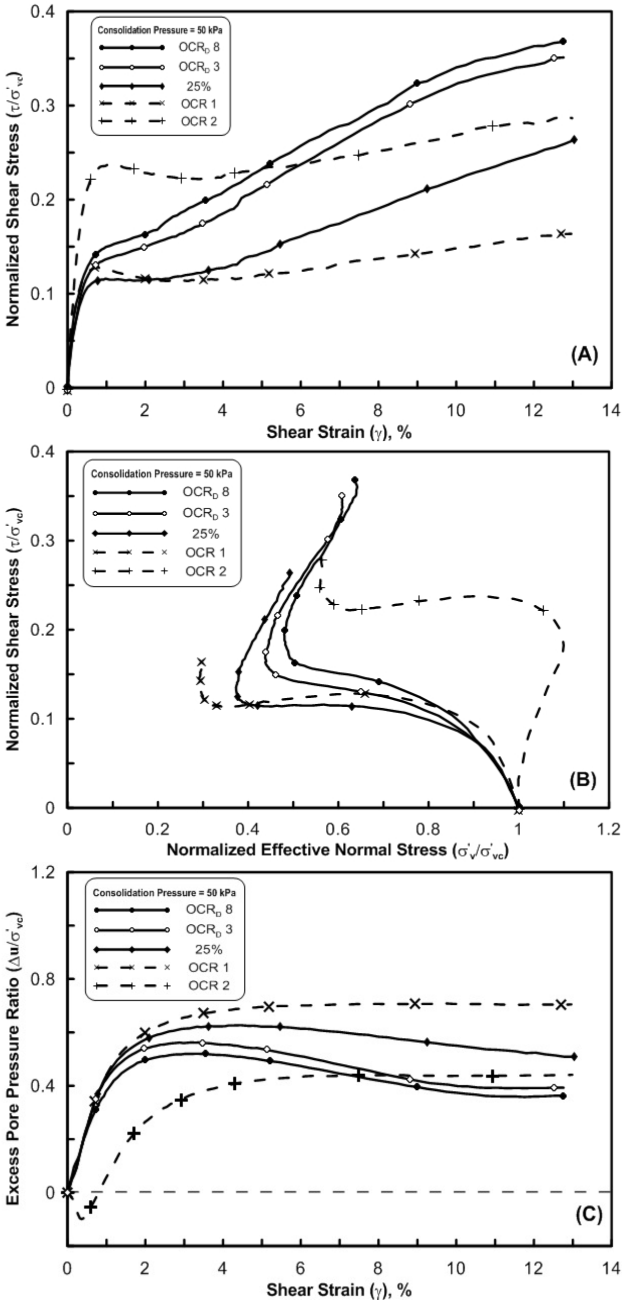

Figure 6. The effect of OCR derived by desiccation on monotonic response of thickened gold tailings

Table 1 shows the value of void ratio after consolidation for both mechanically overconsolidated and desiccated samples under monotonic loading. While the variations in void ratio make exact comparisons not possible, the data clearly show the trends that can be expected.

Table 1. The void ratio after consolidation for mechanical and desiccated overconsolidation ratios for monotonic tests

OCR_M	e_c[1]	OCR_D	e_c
1	0.657	1	0.654
2	0.636	3	0.704
4	0.621	3	0.707
8	0.608	8	0.695

[1] Void ratio after consolidation

3.2 Cyclic Results

3.2.1 The effect of mechanical OCR

Figure 7 shows the cyclic stress-strain response of thickened gold tailings subjected to the same level of cyclic shear (CSR = 0.2) but under different mechanical OCRs. It is clearly shown that the stress-strain response of thickened gold tailings is highly influenced by increasing mechanical OCR. At OCR_M = 1 & 2, the specimens liquefies within a few stress cycles (1 for OCR_M = 1, and 3 for OCR_M = 2). On the other hand, for OCR_M = 4 & 8, the specimen requires a fairly large number of cycles to mobilize the required strain levels, and to reach liquefaction. Number of cycles to reach liquefaction is noted to exponentially increase with increasing mechanical OCR.

Figure 8 shows the excess pore pressure generation versus number of cycles for CSR = 0.2 and OCR_M = 8. It should be pointed out for fine grained soils including tailings, the development 100 % pore pressure ratio might not occur even at high shear strain levels, and so the criteria based on the 100% pore pressure ratio is not valid (Singh, 1996), and the strain based criteria used herein is the only logical approach to define the triggering of liquefaction.

Figure 9 presents the cyclic stress ratio versus number of cycles at different mechanical OCRs. Samples with a specific OCR and different CSRs with the fairly same void ratio after consolidation were selected in order to make identical samples. It is clearly observed that number of cycles to reach liquefaction (N_L) is dramatically higher in higher OCR_M. In other words, higher mechanical over-consolidated specimens are remarkably more resistant to liquefaction in comparison to samples with lower OCR or normally consolidated specimens. For instance, samples with OCR_M = 4 needs around 2500 cycles to reach liquefaction under CSR = 0.075, and that at OCR_M = 8 requires 66 cycles at a CSR of 0.20. The equivalent stress cycles produced by earthquakes are typically in the range of 5 to 25 (depending on the magnitude of the earthquake). As a result, mechanically over-consolidated specimens are highly resistant to liquefaction in comparison to normally consolidated specimens.

Figure 10 presents the influence of overconsolidation ratio on cyclic resistance ratio (CRR) for 15 number of cycles, which corresponds to an earthquake with M = 7.5 magnitude.

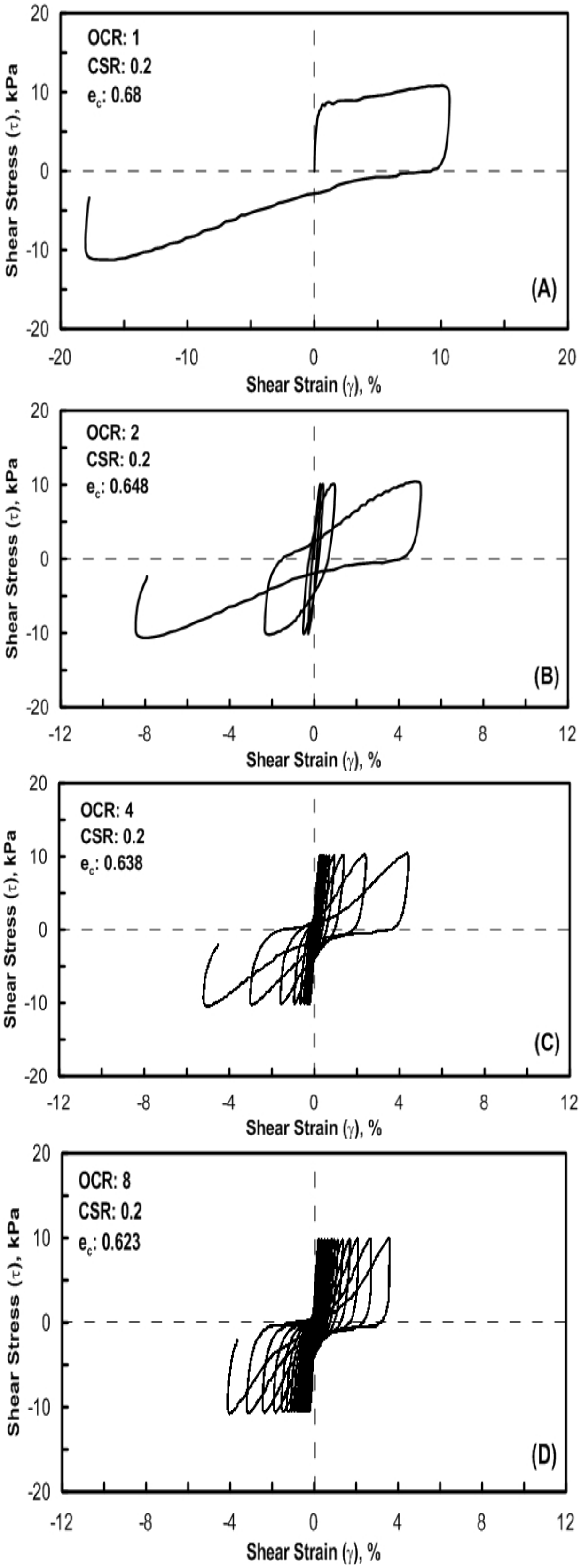

Figure 7. The influence of mechanical OCR on stress-strain response of thickened gold tailings

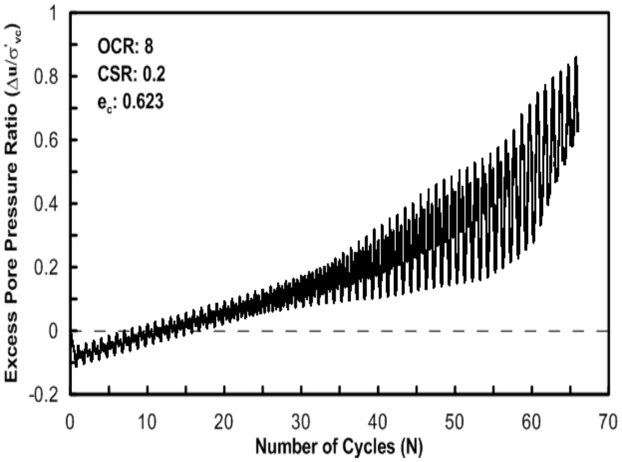

Figure 8. The Excess pore pressure generation for $OCR_M = 8$

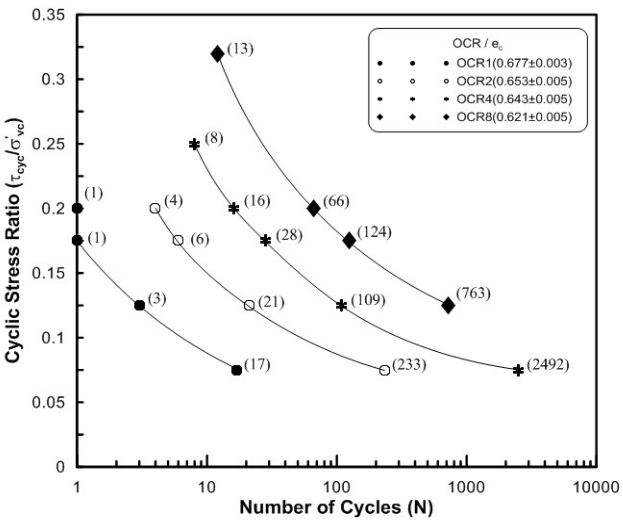

Figure 9. Cyclic Stress Ratio versus number of cycles (N_L) for different mechanical OCR

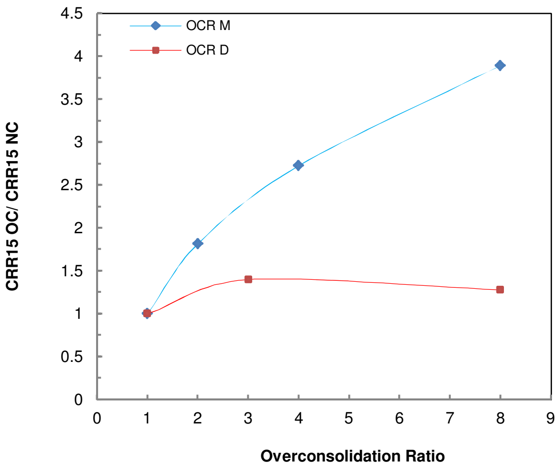

Figure 10. The influence of overconsolidation ratio on CRR15

3.2.2 The effect of OCR derived by desiccation

Figure 11 shows the excess pore pressure ratio versus number of cycles for different desiccated tailings. According to Figure 11, pore pressure generation is slower in desiccated samples in comparison to samples without desiccation. In other words, samples with higher OCR_D have more cyclic resistance than samples with no desiccation history. However, interestingly, although samples with $OCR_D = 3$ have lower degree of desiccation, they needed more cycles to reach liquefaction in comparison to samples with $OCR_D = 8$ which have higher degree of desiccation, but somewhat looser void ratio (0.700 vs. 0.655). It is not clear at this time whether this difference in response is the true response representing the effect of OCR_D, or due to the differences in void ratio, or any other unknown experimental artefact. If this is actual material behaviour effect of OCR_D, it would suggest that even though desiccation could increase cyclic strength, excessive desiccation might decrease the cyclic shear strength. In any event, desiccation does increase CRR compared to the normally consolidated sample, but the increase is much less than by mechanical overconsolidation. This is true even for samples desiccated to water contents above the shrinkage limit. Therefore, the kind of stress history experienced by the tailings is a factor in its mechanical response.

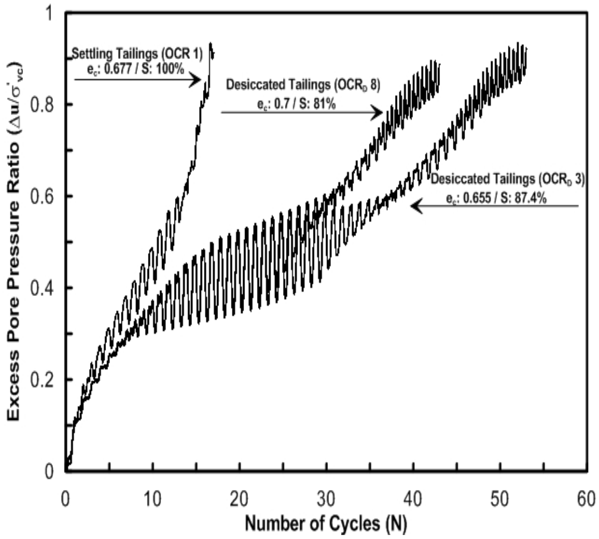

Figure 11. The excess pore pressure generation for different overconsolidation ratio derived by desiccation

The influence of OCR derived by desiccation on cyclic stress ratio is presented in Figure 12. It is obvious that specimens with desiccation history are more resistant to liquefaction during earthquake. However, the cyclic resistance of desiccated specimens at different OCR_D values are significantly lower than the resistance curves for $OCR_M = 2$. This observation is consistent with the observations under monotonic loading.

Table 2 shows the values of void ratio after consolidation for mechanical and desiccated overconsolidation ratios during cyclic tests.

Table 2. The void ratio after consolidation for mechanical and desiccated overconsolidation ratios for cyclic tests

OCR_M	CSR[1]	e_c	N_L[2]	OCR_D	CSR	e_c	N_L
1	0.2	0.68	1	1	0.2	0.655	1
1	0.175	0.675	1	1	0.175	0.659	1
1	0.125	0.676	3	1	0.125	0.651	4
1	0.075	0.674	17	1	0.1	0.646	8
2	0.2	0.648	4	1	0.075	0.654	28
2	0.175	0.65	6	3	0.2	0.659	2
2	0.125	0.648	21	3	0.175	0.653	2
2	0.075	0.658	233	3	0.125	0.657	7
4	0.2	0.638	16	3	0.1	0.656	19
4	0.175	0.648	28	3	0.075	0.651	53
4	0.125	0.645	109	8	0.2	0.7	1
4	0.075	0.646	2492	8	0.175	0.699	2
8	0.32	0.623	13	8	0.125	0.697	5
8	0.2	0.615	66	8	0.15	0.695	7
8	0.175	0.626	124	8	0.1	0.709	14
8	0.125	0.634	763	8	0.075	0.692	43

[1] Cyclic Stress Ratio

[2] Number of cycles to reach liquefaction

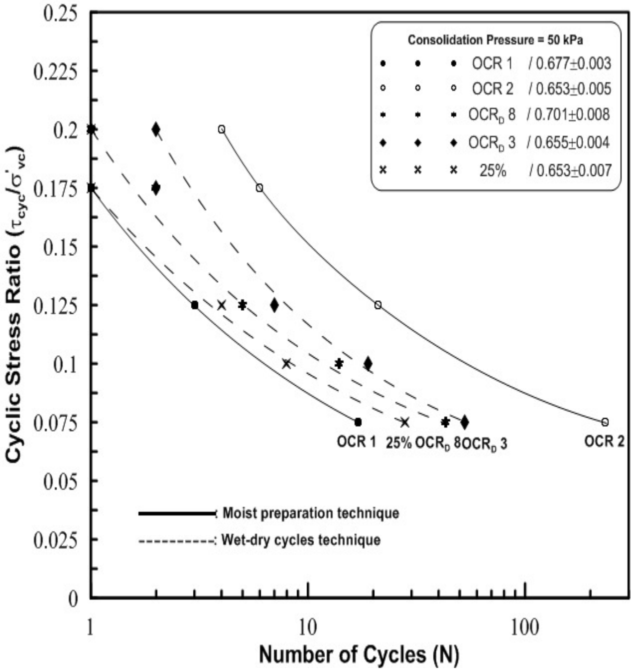

Figure 12. The comparison of the influence of mechanical OCR_M and OCR_D derived by desiccation on cyclic shear response of thickened gold tailings

4 DISCUSSION

Monotonic and cyclic resistance of tailings are markedly influenced by mechanical over-consolidation. Higher mechanical OCRs correspond to significantly higher monotonic shear strength, and exponentially higher numbers of stress cycles were required to trigger liquefaction under cyclic loading. This suggests that the degree of dependency of cyclic resistance on OCR_M is at least equally, or more profound in tailings compared to sands. In addition, excess pore pressure does not reach 100% in both normally consolidated and over-consolidated tailings. The peak excess pore pressure recorded was typically about 0.8 in most tests.

Both monotonic and cyclic shear strength increase with desiccation. However, the rate of strength increase with OCR_D is not as significant as that with OCR_M. The behaviour of desiccated tailings under cyclic loading is not as simple as mechanical over-consolidated tailings. Essentially, samples with OCR_D have more resistance than normally consolidated specimens. With increasing OCR_D and desiccation to the shrinkage limit cyclic resistance increases. Desiccation beyond the shrinkage limit may actually reduce the cyclic resistance due to the higher post-consolidation void ratios of the highly desiccated samples.

5 SUMMARY AND CONCLUSIONS

Based upon the limited set of simple shear tests presented on tailings from a particular mine, the following can be concluded:

1. Mechanical overconsolidation substantially increases monotonic and cyclic strength. Increasing OCR lead to higher strengths at phase transformation, a strain hardening response at higher strains, and higher CRR values.
2. Samples overconsolidated by desiccation also showed increases in monotonic and cyclic strength, but the magnitude of the strength increases were substantially less than for mechanical overconsolidation for a given OCR.
3. Monotonic behaviour of desiccated samples was qualitatively different from the mechanically overconsolidated samples. Desiccated samples exhibited much less of an increase in strength at the phase transformation point, but a higher degree of strain hardening at higher strains.
4. Desiccated samples showed less of an increase in CRR than did mechanically overconsolidated samples. For samples dried to water contents below the shrinkage limit, CRR decreased somewhat compared to CRR at the shrinkage limit. This may be due to higher post-consolidation void ratios exhibited by the heavily desiccated samples.

In summary, desiccation does provide benefits in terms of strength and CRR, but not to the same degree as mechanical overconsolidation. Desiccated tailings also behave qualitatively different from mechanically overconsolidated tailings. Therefore, the type of stress history experienced during thickened tailings deposition will influence the response of the stack during seismic events.

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