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Seismic Behaviour of Thickened Gold Tailings

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Abstract

A simple shear apparatus (Norwegian Geotechnical Institute type) has been used to investigate the liquefaction behaviour of gold tailings over a range of confining stresses and void ratios, including monotonic and cyclic loading. The tested samples were prepared by either simply reconstituting the sample at a given water content or by employing a "dry-wet" preparation technique. The latter technique involved drying the sample to the shrinkage limit, re-saturating the sample, and then consolidating it, in order to simulate the stress history that might be experienced in the field. Cyclic resistance ratios for samples prepared by using the dry-wet preparation technique were considerably higher than those of samples prepared by using the standard technique. In general, the tailings could experience significant deformation during cyclic loading irrespective of whether the monotonic response was contractive or dilative. It is recommended that a strain criterion be adopted to design thickened tailings stacks to resist earthquake loading.

1 Introduction

The resistance of surface deposited thickened tailings to cyclic loading is an important issue in regions of seismic risk. Regulators and the public are naturally concerned with the risk of mobilisation of an unbounded deposit of sloped tailings A report by ICOLD and UNEP (2001) stated that in thickened tailings, the possibility of liquefaction would be eliminated by drying the tailings layers to the water content near their shrinkage limit; as a result, tailings would experience a dilative response under dynamic shaking. The belief of many practitioners is that this would prevent catastrophic deformations occurring during or after an earthquake. This claim has, however, not been proved to be general to all tailings. Even if it is possible to eliminate the risk of flow liquefaction, tailings may still have the capacity for significant deformation under cyclic loading.

The present paper summarises the results of the response of gold tailings to monotonic and cyclic loading using a direct simple shear apparatus. The effect of desiccation is examined using a special preparation technique designed to simulate the drying-wetting behaviour that occurs in the field.

2 Background

Tailings dam failures associated with earthquakes have been reported since the first quarter of the last century. The Barahona tailings dam failure, which occurred at El Teniente copper mine in Chile on 1 October 1928, was one of the oldest flow failures in a tailings dam to have been recorded. Following the earthquake, 4 million tonnes of material flowed along the valley and killed 54 people (Dobry and Alvarez, 1967). Another catastrophic failure of a tailings dam in Chile occurred on 28 March, 1965, at the El Cobre copper mine. The cause of failure of the tailings has been attributed to the triggering of liquefaction. On 14 January 1978 in Japan, the failure of Mockikoshi storage pond during the Near Izu-Oshiam earthquake was induced by liquefaction (Ishihara et al., 1980). Davies et al. (1998) described a static liquefaction event that occurred in the Active Iron Pond tailings impoundment at the Sullivan Mine (Canada) in August 1991. It was reported that the failure of the upstream constructed facility was triggered by the initiation of shear stresses in the foundation tailings in excess of their shear strength. More recently (1994), the Merriespruit gold tailings dam failure in South Africa was an interesting historical case on the liquefaction of mine tailings. The failure occurred a few hours after high rains due to thunderstorm. The liquefaction phenomenon has been attributed as being the cause of the dam failure (Fourie and Papageorgiou, 2001).

Knowledge about liquefaction and consequences of liquefaction (and post-liquefaction) of mine tailings is of prime importance for any tailings dam stability analysis. Unfortunately, little systematic research has been carried out to investigate the influence of the initial conditions and consolidation pressure on the liquefaction behaviour of tailings especially for tailings classified as low plastic silt. It was reported that the cyclic loading resistance is nearly independent of the void ratio for mine tailings classified as silt (Ishihara et al., 1981). The development of excess pore pressure ratio in silt during cyclic loading is different than for sand. For silt, experimental results have shown that the development of strain is much more gradual than in sands, often with significant deformations occurring for pore-water pressure ratios well below 100% (Singh, 1996; Hyde et al., 2004; 2007).

As stated in the introduction, it is the belief of many that desiccation of tailings to the shrinkage limit will render the tailings immune to liquefaction, by achieving a void ratio and state of stress inducing a dilative response under undrained loading. While flow liquefaction (also called Type I liquefaction), may not occur, certainly significant loss in strength and significant deformation may indeed occur. This paper quantifies the monotonic and cyclic behaviour of a gold tailings using a direct simple shear apparatus. The effect of drying to the shrinkage limit is evaluated by drying tailings in the sample mould prior to resaturation and testing.

3 Materials and methods

The tailings examined in this study were gold tailings of very low plasticity. These tailings are predominantly silt-sized, and have a specific gravity of 2.9. The major minerals are: Silicates (80%), Pyrite (11%), Calcite (5%), and Ankerite (4%). The particle size distribution of tailings was established by the combination of sieve (wet technique) and hydrometer analyses results based on ASTM D 422-63 (2002). Figure 1 shows the grain size distribution of the tailings. The liquid limit (LL), and plastic limit (PL) were 22.5%, 20% respectively (ASTM D4318, 2000). The shrinkage limit was 18%. Based on Unified Soil Classification Systems (USCS), tailings are classified as low-plastic silt (ML).

The tailings were shipped from the mine in 20 l pails, and would arrive at a water content between 22-24%, having settled from the pumping water content of 38% during transport. To prepare the samples for shear strength testing, the settled tailings (tailings in pail, w = 22-24%) were mixed with the bleed water by using a mixer and spatula. Two different preparation methods were employed, the moist preparation method and the dry-wet method. For the moist method, the pre-shear water content of the tailings was controlled simply by remixing the tailings with the necessary amount of bleed water, before pouring the sample into the mould. However, for the dry-wet cycle method, the water content was increased to the pumping water content (w = 38%). Once in the mould, the sample was allowed to dry to 18%. Before initial consolidation, an amount of water was added to bring the degree of saturation close to 1. The water was added slowly in duplicate 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.

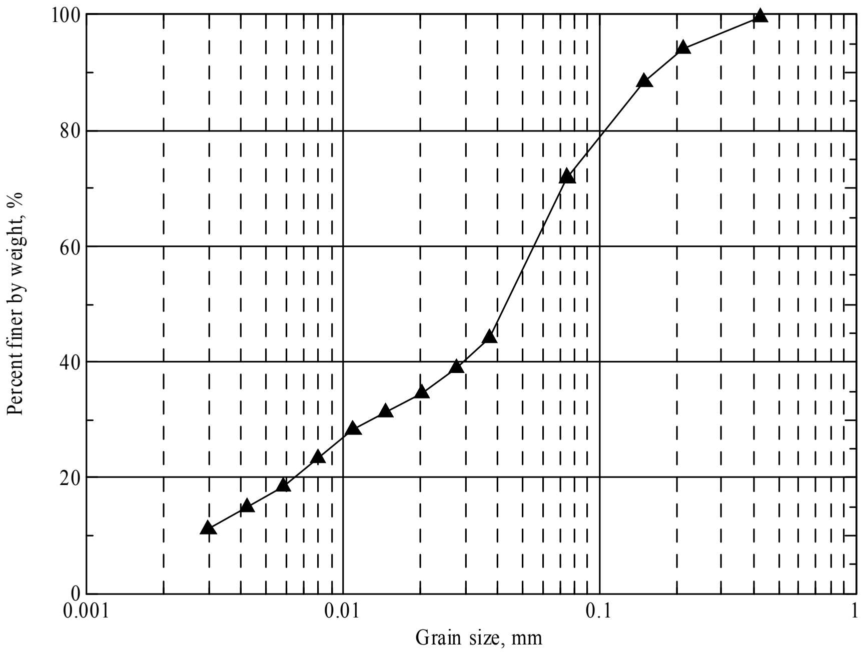

Figure 1 Grain size distribution of tailings

The direct simple shear apparatus used in this study was similar to the one originally developed at Norwegian Geotechnical Institute (NGI) (Bjerrum and Landva, 1966). The commercially available apparatus was extended in-house to permit both stress and strain controlled loading. A schematic diagram of the specific apparatus used in this study is shown in Figure 2. The apparatus consists of a simple shear load frame, a vertical single acting air piston, a horizontal double acting frictionless air piston, a constant speed motor drive, load cells, Electronic-Pneumatic Transducer (EPT), and Linear Variable Displacement Transducers (LVDT).

In this apparatus, the sample is placed into a reinforced rubber membrane to constrain its lateral deformation. Therefore, the lateral strain components (ε_x and ε_y) become zero. The constant volume condition is achieved during shear loading by keeping the height of the sample constant. A clamping mechanism is used to fix the height of the sample when needed. As a result, no volume change of the sample during the shear loading is allowed and the undrained shear condition is then simulated (Bjerrum and Landva, 1966). 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).

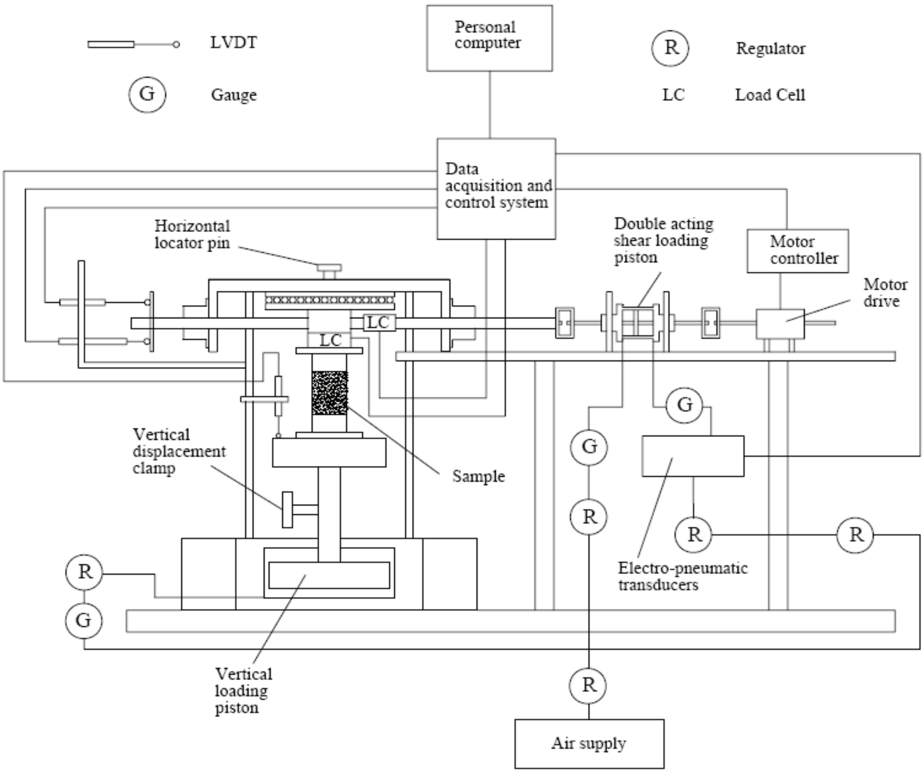

Figure 2 Direct simple shear apparatus

4 Results

4.1 Monotonic and cyclic loading, moist preparation method

Monotonic shear loading was applied at a constant rate of strain (20% per hour). Samples were tested after consolidation under loads of 50 to 400 kPa. Shown in Figure 3 are the results for a variety of void ratios achieved by consolidation to 100 kPa. The void ratio after consolidation strongly depended on the initial preparation water content. The samples in all of these tests were prepared by the moist preparation method.

It can be seen that for a given consolidation pressure, as expected, there is either a contractive or dilative response, dependant on the void ratio. Dilative behaviour becomes suppressed at higher consolidation pressures. For example, for the same range of post-consolidation void ratios shown in Figure 3, no dilative behaviour was exhibited after consolidation to 400 kPa.

In the cyclic tests, the samples were tested at constant cyclic stress ratios (CSR - the ratio between the maximum applied shear stress and the consolidation pressure) ranging from 0.075 to 0.15. The tests were terminated after a shear strain of 3.75% was reached in the last cycle. The US National Research Council (NRC, 1985) suggested that the development of 3.75% shear strain should be regarded as the triggering of liquefaction under cyclic loading. This shear strain often corresponds to the development of 100% pore pressure ratio for contractive sands where no static shear stress exists on the sample. Though this criterion has also been used also to investigate different types of fine-grained mine tailings by simple shear apparatus (Wijewickreme et al., 2005), it should be pointed out for fine grained soils including tailings, the development 100% pore pressure ratio may not occur even at high shear strain levels (Singh, 1996). However, using the shear strain level as a criterion provides for consistent comparison of cyclic shear resistance data.

An example of the cyclic response is shown in Figure 4. Excess pore-water pressure ratios achieved by the maximum strain criteria ranged from 0.8 to 0.96. Therefore there was never a total loss of strength. There was considerable variation in the number of cycles required to reach the maximum strain criterion, ranging from 2 to 110.

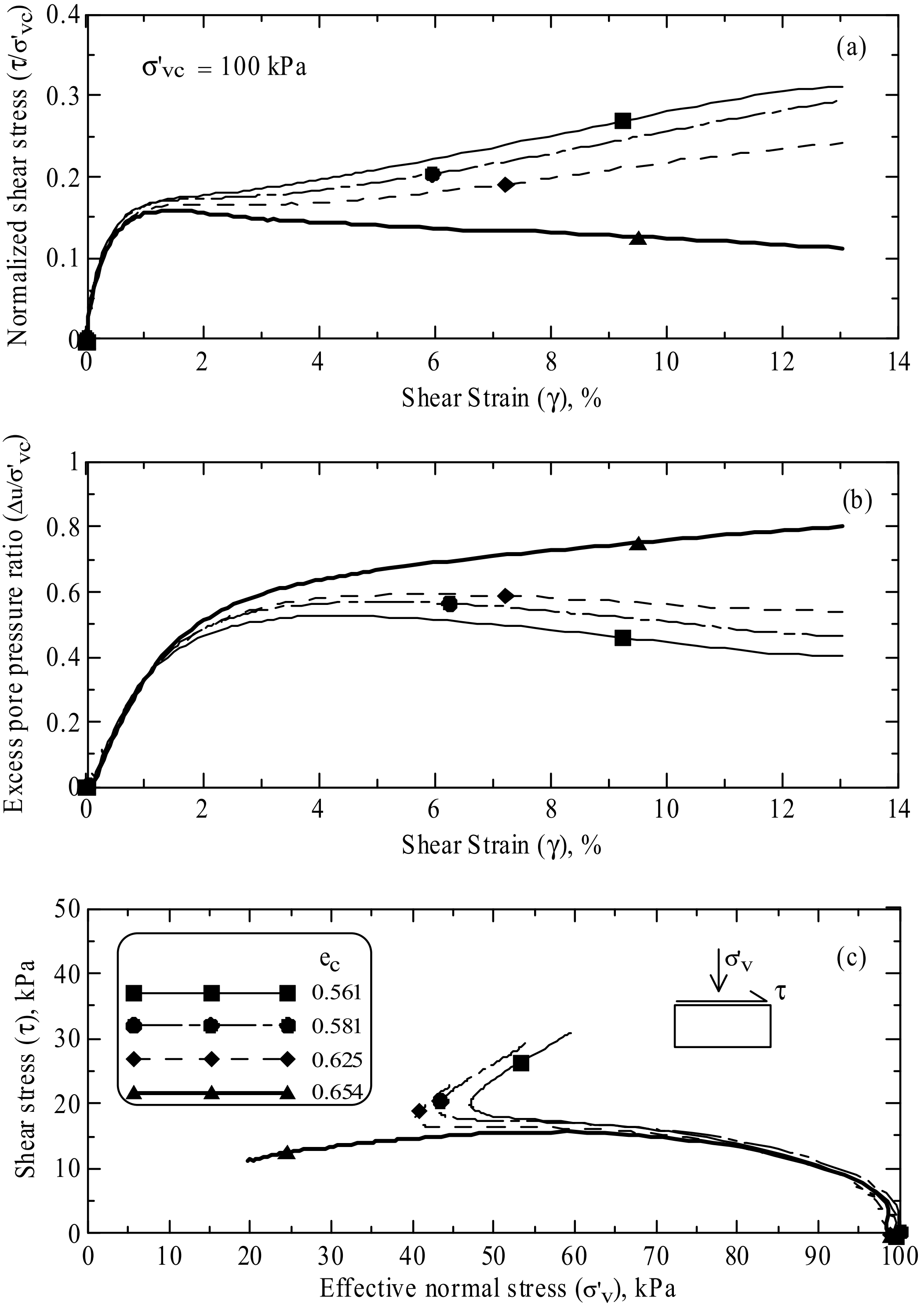

Figure 3 **Monotonic loading for a range of initial void ratios at 100 kPa consolidation pressure**

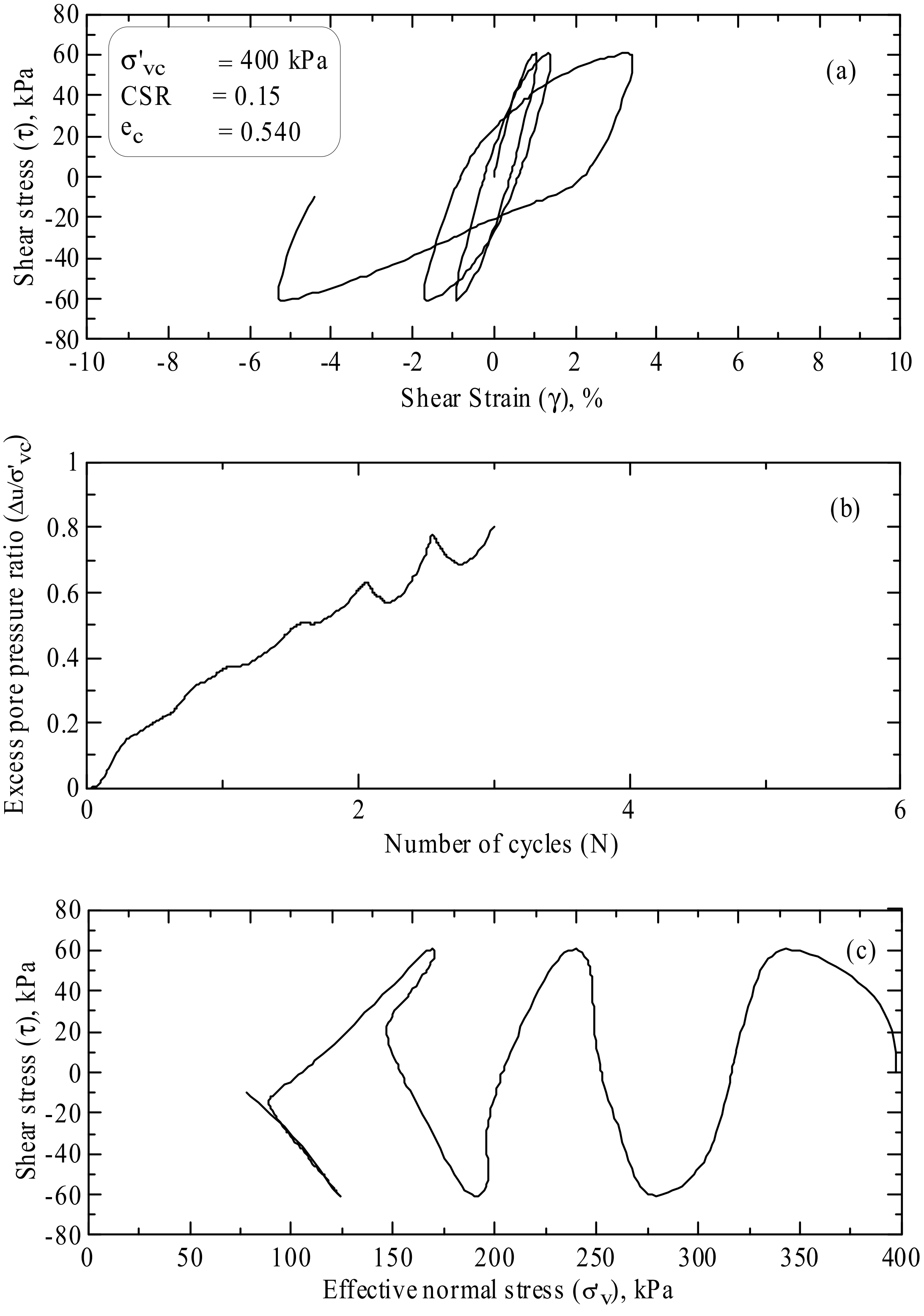

Figure 4 Example of cyclic response for the tailings after consolidation to 400 kPa and using a cyclic stress ratio of 0.15

For a given void ratio, the cyclic tests can be summarised in terms of the number of cycles required to reach the strain criterion, as shown in Figure 5. Notably, the influence of consolidation pressure is rather small. All of the tests can be summarised in terms of the CSR required to fail the tailings within ten cycles, termed the cyclic resistance ratio (CRR), as in Figure 6. This type of chart is commonly used to evaluate factor of safety in resistance to earthquake loading in geotechnical engineering.

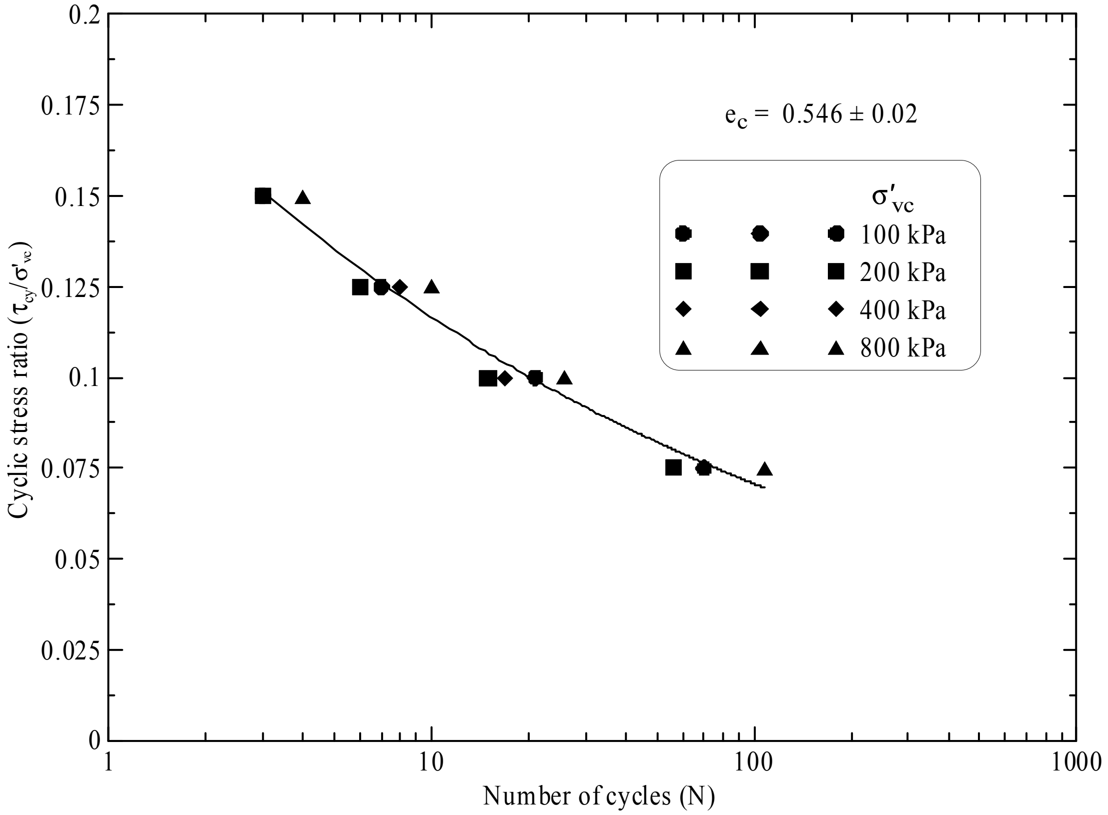

Figure 5 Cyclic response summarised for a range of consolidation pressures at a given void ratio

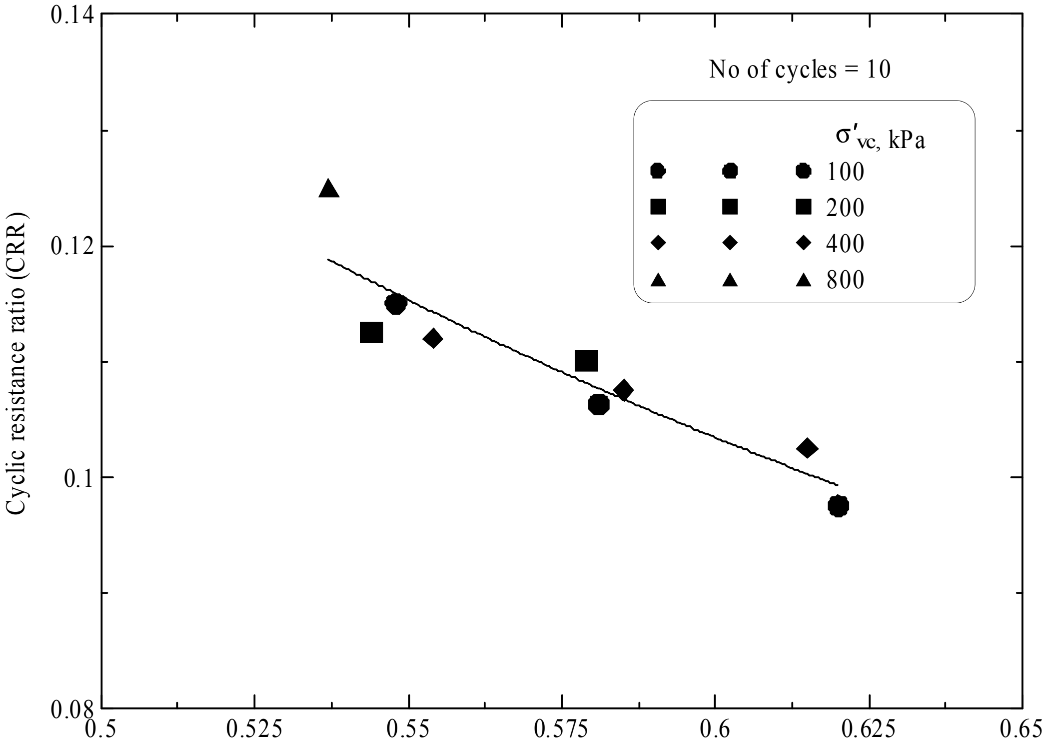

Figure 6 Cyclic results expressed as a design chart, to give the CRR necessary to induce liquefaction (3.75% shear strain) within 10 cycles

4.2 Influence of desiccation

Figure 7 compares samples prepared to the same post-consolidation water content and void ratio using the two different sample preparation methods. The dry-wet method attempts to simulate desiccation. The samples were desiccated down to 18% before being rewetted back to approximately 21% gravimetric water content, prior to consolidation at 50 kPa. The 18% gravimetric water content was chosen as it conforms to the shrinkage limit of the tailings. The 18% gravimetric water content corresponds to a matric suction of approximately 150 kPa, as determined from the water retention curve of the tailings (Simms et al., 2007). It can be seen that desiccation does substantially increase the CSR required to fail the tailings when compared to samples prepared using the moist preparation technique and consolidated to the same moisture content and void ratio. Therefore cyclic deposition of thickened tailings does hold out the potential of additional resistance to earthquake loading.

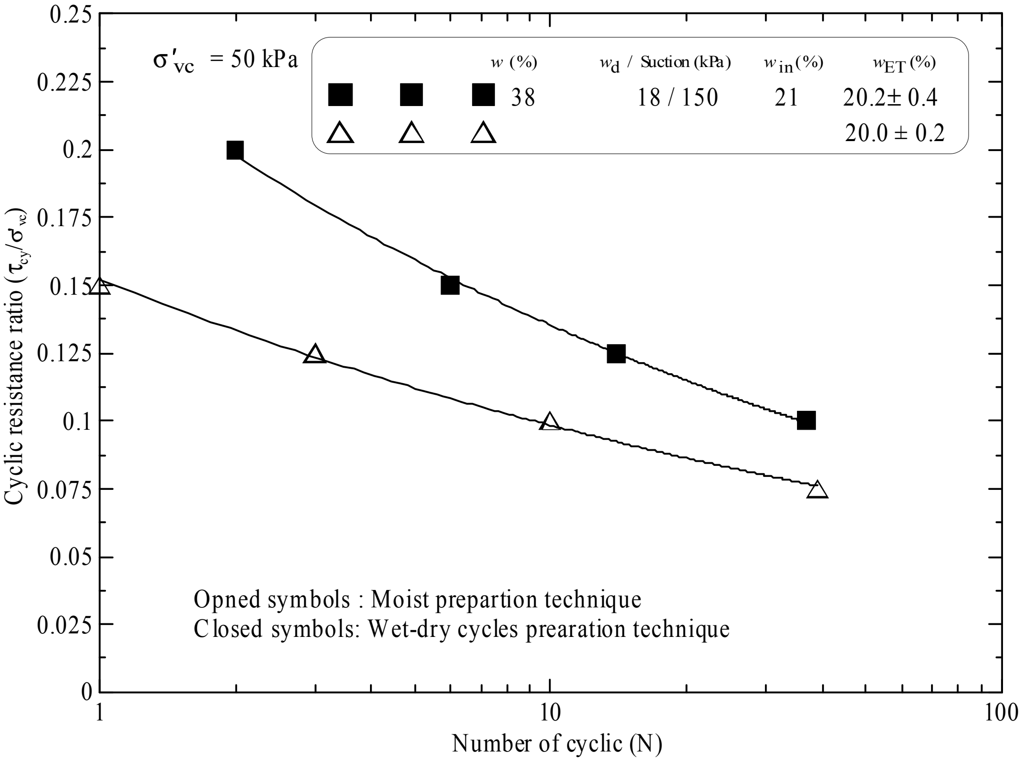

Figure 7 Effect of dry-wet cycle on cyclic resistance ratio – tailings are dried to 18% gravimetric water content (corresponding to 150 kPa matric suction) before being rewetted to 21% prior to consolidation

5 Discussion

The use of the strain level criterion of 3.75% for liquefaction may be overly conservative for these predominantly silt-size tailings. Silts tend to produce deformation and build up excess pore pressure at a much more gradual rate than sands during cyclic loading (Singh, 1996), as illustrated in Figure 8. However, though flow liquefaction does not occur in these tailings, significant deformations during and post-liquefaction still may occur for silt-sized material (Wijewickreme et al., 2005). Therefore it is recommended to employ a permissible strain criterion in order to construct a design chart such as Figure 6 for a particular tailings, rather than basing safe design solely on the contractive or dilative response of the tailings under monotonic loading.

It is clear that the dry-wet stress history induced by allowing desiccation does have the potential to increase the cyclic resistance of the tailings. However, much more work is needed to accurately characterise this contribution. For example, how much additional strength is gained when the suction exceeds the air-entry value? How will the gain in strength scale with drying to water contents greater than the shrinkage limit? In the field, desiccation is accompanied by cracking, how will this influence the cyclic strength?

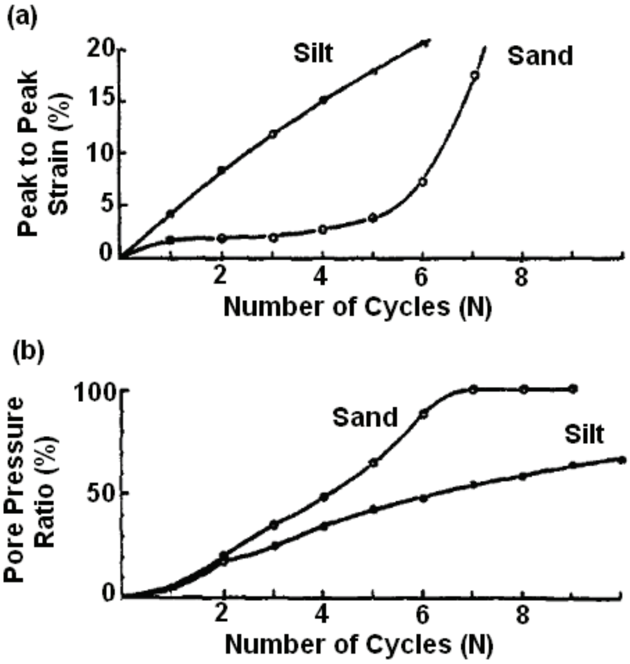

Figure 8 Comparision of cyclic response of sands and silts (Singh, 1996)

6 Conclusions

Significant strains can be induced in silt-sized tailings during earthquake loading, irrespective of whether the monotonic response is contractive or dilative. It is suggested that a strain criterion be used to determine a design chart for a particular tailings, relating cyclic resistance ratio to void ratio.

A preliminary examination of the influence of desiccation shows that drying to the shrinkage limit can potentially increase the cyclic resistance of the tailings, though much further work is required to accurately quantify this contribution.

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