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Liquefaction Potential of Surface Deposits of High-Density Thickened Tailings

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1 INTRODUCTION

One of the major perceived benefits of using high density thickened tailings for the surface disposal of mine wastes is the reduced risk of catastrophic failure. Utilisation of the procedure is, however, relatively new and there are few well-established operations from which field experiences can be gained. Concerns of potential liquefaction as a consequence of seismic activity are discussed in this paper and techniques for evaluating the potential for liquefaction derived from experience with natural soil deposits described. An inescapable conclusion is that although the likelihood of liquefaction failures in thickened tailings deposits are extremely low, care must be taken in utilising existing techniques that were derived from field data obtained from material that differs significantly in behaviour from that of thickened tailings.

2 BACKGROUND

There have been a number of high profile failures of conventional tailings storage facilities (TSFs) over the years. Example include Stava, Merriespruit, Baia Mare and Los Frailes and the reasons for some of these failures have recently been reviewed by Blight and Fourie (2005). These failures tend to attract the attention of the media, not to mention legislators and researchers. What tends to go unnoticed are the incidents and failures that do not result in fatalities, injuries or significant environmental damage and it is difficult to gauge how many of these events occur annually because they are so poorly reported.

A recent review by Bjelkevik (2005) of incidents at Swedish TSFs provides illumination of this issue. She shows that during the period 1990 to 1999 there were 18 reported events in Sweden, compared with 39 internationally (where this 39 does not include the Swedish events) reported by ICOLD (2001). In decades prior to this, Swedish failures and incidents accounted for about 10-15% of international events. The obvious question is what prompted this change and Bjelkevik (2005) argues that it is the changes in requirements for reporting of all events and releases from TSFs in Sweden that has increased the apparent contribution from this country. The reason this statistic is reviewed here is to highlight the fact that we may in fact be significantly underestimating the number of minor failures and near-misses that occur at TSFs operated according to traditional techniques throughout the world each year.

The adoption of thickened tailings as an alternative management strategy for mining waste is often touted as one way of addressing the above appalling statistic. However, we run the risk of promoting the technology as a panacea for all circumstances before understanding the potential risks associated with the stability of thickened TSFs, particularly when it comes to risks associated with dynamic loads such as earthquakes.

Given the potential importance of seismic loading, some available approaches for evaluating the stability of thickened TSFs in such circumstances is discussed in this paper.

3 CONCERNS REGARDING POTENTIAL FOR LIQUEFACTION OF THICKENED TAILINGS

Morales (2005) discussed the potential for the adoption of thickened tailings in the Chilean copper mining industry and described reasons for a reluctance to adopt the technology. One of the key concerns he described was the potential for liquefaction of the stored tailings and the potential consequences of such an occurrence. Such concerns are not surprising, given the experience of failures of TSFs in Chile under earthquake loadings. For example, failure of the El Cobre impoundments in 1965 resulted in 300 deaths and the flow of over 2 million m^3 of tailings was initiated by an earthquake of Richter magnitude 7.5. Changes to construction procedures for TSFs in Chile and other regions susceptible to earthquakes include the adoption of downstream construction and compaction of the outer embankment. It is not surprising that there is resistance to the adoption of a technique that differs so radically from this now tried and tested approach, ie the adoption of procedures such as centrally thickened discharge or even down-valley discharge of thickened tailings, resulting in a deposit that has no (or at best minor) retaining embankments.

The perception that liquefaction could cause the tailings within a TSF to have zero residual strength, effectively acting as a heavy liquid and coming to rest at a horizontal slope is one that is common, as mentioned by Barrera (2005). As a consequence, in Chile the legislation does not allow a TSF that has an elevation that is internally higher than the perimeter confining embankment. It therefore requires a facility that is essentially bowl-shaped, rather than the conical shape that inevitably results from the adoption of thickened tailings. There is a clash of two approaches and until it can be shown unequivocally that not only are thickened tailings inherently resistant to liquefaction, but that even were a failure to occur, the residual strength would be finite (and not zero) it is unlikely that the technology will find favour in seismically active parts of the world.

Aside from overcoming the concerns of legislators is the issue of public trust. Acceptance of thickened tailings as a viable alternative for the safe and environmentally sound management of mining waste has been slow and often begrudging. If a failure were to occur, due to an earthquake for example and injuries or fatalities were to result, or major environmental damage occurred, it would set back acceptance of the technology years, if not decades. Considering that thickened tailings are seen as a gimmick or a fashion by proponents of conventional approaches, we cannot countenance the failure of one of the new-generation facilities and the resulting negative publicity that would arise. Although much of the concern may be unfounded, if not hysterical, it is imperative that the potential for instability is recognised and accounted for in the design of all new facilities. The following section discusses the issue of seismic stability and some approaches that might be useful in analysing the problem.

4 SEISMIC STABILITY OF SANDS, SILTS AND CLAYS: INSIGHTS FROM CONVENTIONAL GEOTECHNICAL ENGINEERING

Seismically induced liquefaction of a soil (or tailings) is the sudden loss of stiffness and strength due to cyclic loading effects and is invariably accompanied by an increase in pore water pressure. In a dense material, loading will often cause dilative behaviour of the soil, resulting in a decrease in pore water pressure during undrained loading (e. g. an earthquake). This material will thus not liquefy, even if subjected to an extremely high magnitude earthquake. The intrinsic concern is therefore the in-situ density (or void ratio) of the tailings within a TSF. The same material can be extremely susceptible to liquefaction or immune, depending on its in-situ density and stress state.

Problems with seismically induced liquefaction of natural soil deposits have been most common in sands or silty sands. Reasons for this are many and varied and relate to the packing (or fabric) of the soil in-situ. If the soil were dry, seismic loading would simply densify the soil as the particles packed closer together. If the loading is applied rapidly to a saturated soil, such as during an earthquake, the water in the pores resists compaction and positive pore pressures develop, causing the effective stress to decrease and the soil to eventually become unstable. Liquefaction of clays is less common even though the generation of positive pore pressures during seismic loading is often inevitable. Reasons for this include the natural formation of a less collapsible structure and the component of strength in clay that is independent of normal stress.

Susceptibility to potential seismic liquefaction in granular deposits has been related to particle size distribution and some typical results are summarised in Figure 1. This shows the lower (finer) limit of the soils most susceptible to liquefaction (curve 1) and the lower limit of those considered to be potentially liquefiable (curve 2). This plot implies that natural soils having a median particle size (the d_{50}) finer than about 20 μm are highly unlikely to be susceptible to liquefaction. Included on this figure are the particle size distributions for tailings material considered to have a low resistance to liquefaction, according to Ishihara (1993). These lines are shown without markers. The reason that mine tailings appears to be more susceptible to liquefaction probably includes the gap-graded nature of some materials (e.g. the right-hand envelope of Ishihara's data) and the environment in which they were deposited. Many tailings are deposited under water and subsequently undergo limited consolidation, remaining essentially normally consolidated. Subaqeous deposition invariably results in a looser structure and has been linked to failures such as Merriespruit in 1994 (Wagener, 1997).

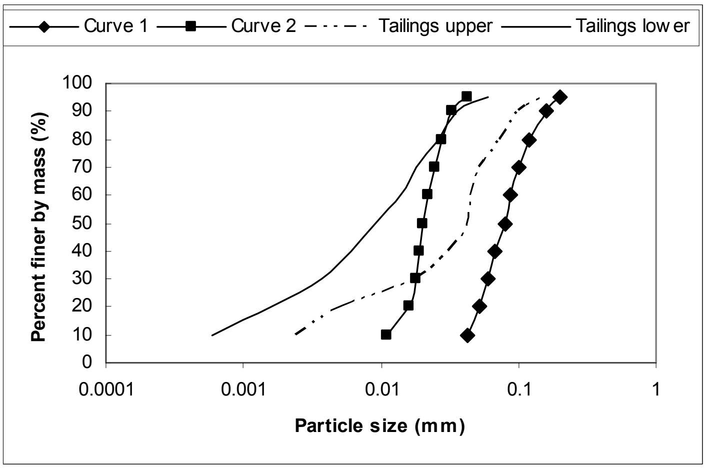

Figure 1 **Particle size distributions of natural soils and mine tailings and their liquefaction susceptibility**

Figure 2 shows the same plot, with particle size distributions of three thickened tailings that are from current operations added. The three sites are Bulyanhulu in Tanzania (Shuttleworth et al., 2005), Peak gold mine in Australia (Pirouz et al., 2005) and the CTP project in South Africa (Vietti, 2001). It is clear from this plot that the possibility exists that some thickened tailings may indeed be potentially susceptible to liquefaction. It is certainly true that some materials, such as the very fine muds, or slimes, that derive from the mining of mineral sands would plot very much to the left of the susceptibility envelope in Figures 1 and 2, but nevertheless the perception that all thickened tailings are too fine to be susceptible to liquefaction is given the lie by the plots shown in Figure 2.

Simply because a particular soil or tailings may be susceptible to liquefaction does not necessarily mean that a risk of liquefaction does indeed exist. The material would have to be in a meta-stable state, resulting from deposition at a low density. If sufficient time were allowed for consolidation and dessication drying (or freeze-thaw in cold climates) to increase the density of a newly placed layer of tailings to greater than a critical value, liquefaction susceptibility can be minimised or even eliminated completely. The question of whether or not a particular in-situ tailings is susceptible to liquefaction invariably requires the determination of density or some other surrogate property that reflects the effect of density (such as penetration resistance).

5 POTENTIAL CONSEQUENCES OF LIQUEFACTION

A dominant concern contributing to the reluctance to adopt the use of thickened tailings in seismically active regions is the concern about what will happen were the tailings to liquefy and behave as a viscous liquid, having zero shear strength. The scenario is that the material will flow and only come to rest when it encounters some form of physical barrier, eventually developing a horizontal profile. This may be hard to imagine, but appears to remain a concern in some quarters and it needs to be proven categorically that it is not possible.

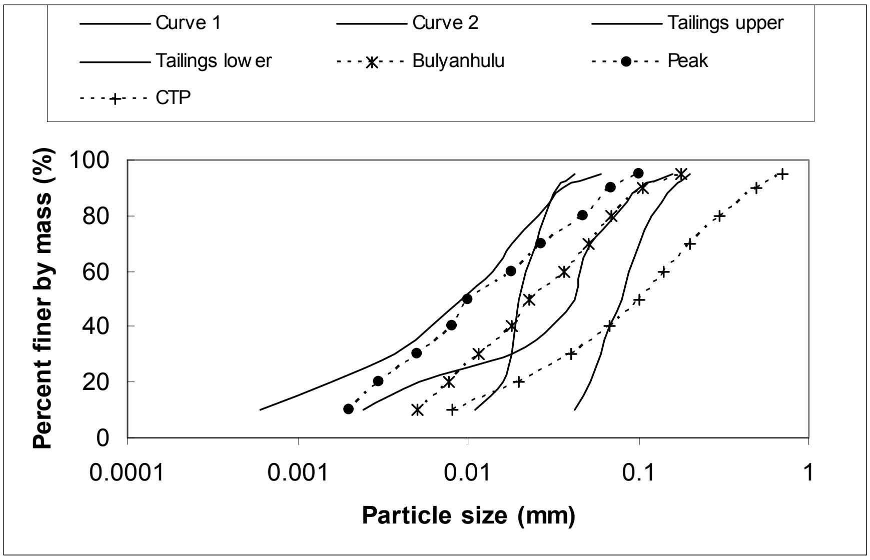

Figure 2 **Comparison of thickened tailings from three current operations with liquefaction-susceptible particle size distributions**

Much more likely is that the material, even when liquefied, will still retain a measurable viscosity and shear yield stress and thus come to rest at an inclination greater than zero. Previous failures of TSFs provide some guidance on this issue. Blight (1997) collected information from a number of failures of TSFs in South Africa and Zimbabwe. Table 1 summarises these results in terms of the inclination of the surface of the tailings post-failure and the inclination of the ground surface over which the tailings flowed.

With the possible exception of the Bulyanhulu gold tailings project in Tanzania, the reported slope angles of thickened tailings projects are less than about 5% or 2.8º. The deposition angle is thus similar to or less than the reported post-failure slope angles of tailings that have flowed for some distance after undergoing a liquefaction failure. Even if a thickened tailings were to experience liquefaction, it would be unlikely to flow because it would already be at a sufficiently flat angle. Thus once again, concerns about the likelihood of a catastrophic flow failure of thickened tailings resulting from liquefaction during an earthquake appear to be unfounded. Although the potential risk therefore seems to be minimal, it is important to develop techniques for determining potential liquefaction susceptibility so that a failure of this type never occurs.

6 DETECTING LIQUEFACTION SUSCEPTIBILITY IN-SITU

There are a range of laboratory tests that may be carried out to determine potential liquefaction susceptibility. A problem is obtaining sufficiently representative samples from the field for testing. The cohesionless nature of most tailings materials, particularly those deposited using conventional techniques means that traditional sampling techniques are ineffective. Samples tend to disintegrate or collapse on sampling, producing anything but undisturbed specimens. One technique that has been used with some success is in-situ ground freezing, but this is extremely expensive and subsequently thawing the specimens in a controlled fashion to prevent disturbance is difficult. Several field testing techniques have therefore been developed to avoid the problem of sample disturbance.

Table 1 Summary of observed post-failure surface slopes and inclination of ground surface over which flow occurred

Tailings	Post-failure surface slope	Ground slope
Gold	3°	1°
Gold	2.3°	-0.5°
Gold	3°	-0.5°
Platinum	4°	1.5°
Platinum	2°	1.3°
Gold	3°	1.5°
Gold	2°	0
Gold	2°	0

6.1 Empirical correlations of liquefaction susceptibility with in-situ tests

The most commonly used approach is that described by Seed et al (1985), which is based on the use of the Standard Penetration Test (SPT). A simplified form of the curve is presented in Figure 3 and shows results for soils with 3 different fines contents. The solid lines delineate zones of likely liquefaction (above line) from those where liquefaction is unlikely. The vertical axis represents the Cyclic Stress Ratio (CSR), where:

$$CSR = 0.65\left(a_{\max} / g \right)\left(\sigma_{vo} / \sigma'_{vo} \right) r_d \qquad (1)$$

a_{max} = peak horizontal acceleration at the ground surface generated by an earthquake, g = acceleration of gravity, σ_{vo} and σ'_{vo} are the total and effective vertical overburden stresses respectively and r_d = a stress reduction coefficient to account for the flexibility of the soil profile.

Figure 4 shows the variation of the CSR value with depth for an earthquake with a peak horizontal acceleration at the ground surface of 0.2g. The curve on the right is for the case where the water table is at the ground surface and the tailings is saturated throughout the profile. If Figure 3 is considered, a higher CSR value pushes a material into the liquefiable zone, illustrating the problem presented by having a saturated profile.

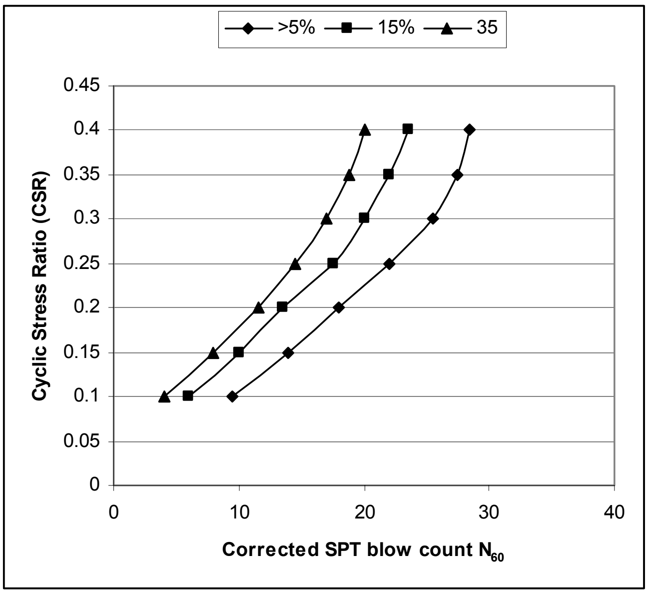

Figure 3 Relationship between cyclic stress ratio and corrected SPT blow count for magnitude 7.5 earthquakes for three different percentages of fines

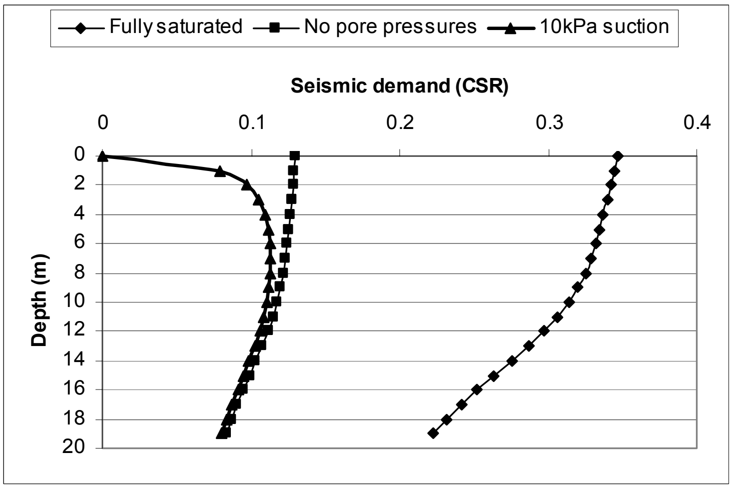

Figure 4 Effect of water pressure on cyclic stress ratio and thus liquefaction susceptibility

If drainage of the tailings were to occur, with the water level dropping to the base of the profile, with the tailings remaining saturated, the middle curve results. There is a significant decrease in the Cyclic Stress Ratio, with the material becoming significantly less susceptible to liquefaction. Another way of considering this effect is to consider the blow count necessary to ensure a material is not susceptible to liquefaction. For a lower CSR value, a lower blow count is necessary, whereas at a higher CSR, a higher blow count is required.

If sufficient drying of a new layer of tailings occurs, negative pore pressures (or suctions) will begin to develop. In fact, once the water table or phreatic surface drops below ground level, suction develops in proportion to the depth to which the water level drops. The curve designated, 'no pore pressures' ignored this effect for purposes of illustration. The third curve in Figure 4 is for a situation in which the water level has dropped to the base of the profile and a uniform suction of 10 kPa has developed throughout the profile. This is a relatively insignificant suction and much higher values can be sustained by most thickened tailings. Nevertheless, it illustrates that further reduction in liquefaction susceptibility occurs, particularly near the surface of the deposit.

The suction developed within a material is related to the degree of saturation, with zero suction corresponding to 100% saturation. Williams (2000) reported measurements of water content variation with depth at two operations where thickened tailings were in use. Figure 5 presents these results in terms of the variation of degree of saturation with depth and as can be seen, the profiles are unsaturated throughout, except one or two locations where 100% saturation occurs. This means that even the deeper material has not re-saturated during the placement of subsequent layers of tailings and finite suctions are retained throughout the profile, decreasing the susceptibility to liquefaction.

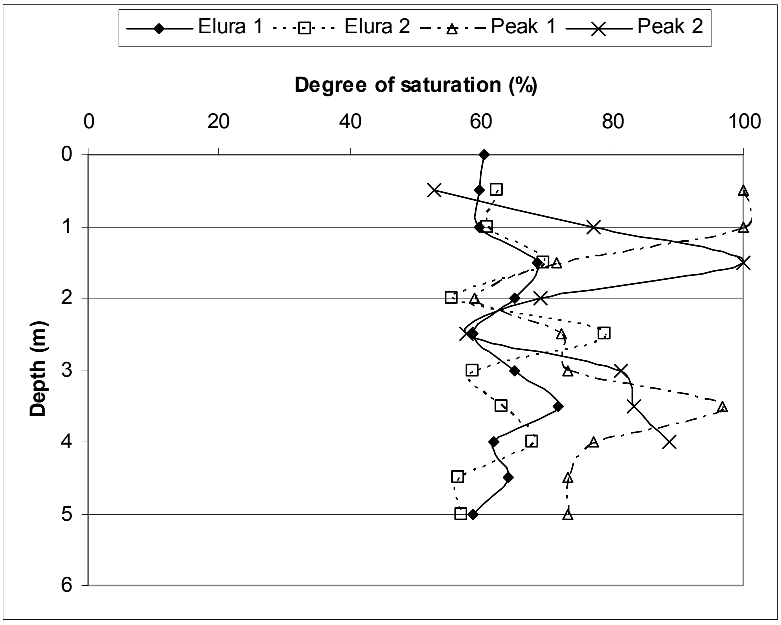

Figure 5 **Variation of degree of saturation with depth for two thickened tailings deposits in Australia (Peak and Elura), after Williams (2000)**

Other in-situ techniques are also sometimes used, such as the cone penetrometer test (CPT) and measurements of seismic shear velocity, which is related to in-situ density. As with the SPT procedure, these techniques rely on empirical correlations and the older techniques (the SPT procedure) have more extensive databases simply because they are older. The methods also require the use of a range of correction factors, which are themselves largely empirical. These corrections include those for hammer energy, borehole diameter and rod length, amongst others. Correlations such as those shown in Figure 3 are for one particular value of earthquake magnitude (in this case magnitude 7.5) and the likelihood of liquefaction failure due to larger (or smaller) earthquakes require another correction factor.

From the above discussion it is obvious that determination of the risk of an earthquake-induced failure of a tailings deposit leans heavily on empirical evidence and experience. With the relatively recent adoption of thickened tailings as an alternative waste management technique, this amount of empirical evidence has not yet been accumulated and we have to rely on extrapolations from other fields, such as natural sands and silts and tailings deposited using conventional techniques. Whilst there is nothing intrinsically different between these materials, the non-segregating nature of thickened tailings may render different behaviour during an earthquake than would be extrapolated from existing experience.

As mentioned earlier, most liquefaction failures have been associated with sands and silts. There is a perception that clayey materials are intrinsically safe from such problems. Seed and Idriss (1982) describe criteria for evaluating whether material with a relatively high clay content may be susceptible to liquefaction. These criteria, which are often referred to as the Chinese criteria (based on the origin of the empirical correlations) state that liquefaction will only occur if all three of the following criteria are met:

- The clay content (in this case defined as particles finer than 5µm) is <15% by mass.
- The Liquid Limit is <35%.
- The natural (in-situ) moisture content is >0.9 times the Liquid Limit.

This approach is straightforward to use and has the advantage that it takes implicit account of the saturation level (through the 3rd criterion), rather than relying on only particle size distribution (the 1st criterion). Applying the above criteria to thickened tailings also, however, illustrate the potential problems of extrapolating empirical results from one field into another. Considering that all three criteria have to be met before liquefaction becomes a concern, it means that if the percentage of fines is greater than 15%, liquefaction is not a concern. However, since many tailings consist of rock flour, the fines may be non-plastic. Empirical correlations are based on natural soils, where the very fine material contains true clay minerals. Empirical criteria based on these materials may thus be inapplicable to many mine tailings.

7 CONCLUDING REMARKS

The perception that thickened tailings deposits may pose a hazard during earthquake loading, because they are not confined behind retaining embankments, must be addressed. While valuable information is available from previous research on liquefaction of natural sands and silts and mine tailings, there is a need to extend this work to include the field of thickened tailings, which invariably will have aspects of response to dynamic loading that have not been covered in these existing studies.

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