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Assessing the flow liquefaction susceptibility of cyclone underflow material

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Abstract

It has been recognised worldwide that the liquefaction risk of unconstrained tailings stacks or cyclone underflow embankments requires careful consideration. The stability of a tailings deposit where the perimeter embankments are made up of hydraulic fill is often governed by post-liquefaction stability.

Apart from Australia, cyclones are frequently used in different parts of the world to classify tailings into a coarse underflow, for building a tailings impoundment wall, and a finer fraction that is disposed of into the basin. The shear strength of the tailings forming the outer embankment of a tailings storage facility and the location of the phreatic surface are the two most significant factors influencing the structural integrity of the facility. The coarse underflow is placed in such a way as to contain the overflow, which is finer, has low strength, and is often poorly consolidated.

Golder Associates Pty Ltd undertook a cyclone field trial at a gold mine site in Western Australia to assess the feasibility of using the cyclone deposition method to optimise and increase the capacity of an existing tailings cell. The aim of the cyclone trial was to collect information to demonstrate to the client and the regulators that cyclone deposition was a feasible option for raising TSF embankments. The cyclone trial provided an opportunity to assess the cyclone under field conditions and to assess the quantity and quality of the underflow fraction produced on site. A variety of methods were used to assess the flow liquefaction susceptibility of the tailings underflow sample produced during the cyclone field trial.

The field trial, laboratory testing and analysis will be discussed in this paper.

1 Introduction

The liquefaction risk of unconstrained tailings stacks or cyclone underflow embankments requires careful consideration. The stability of a tailings deposit where the perimeter embankments are made up of hydraulic fill is often governed by post-liquefaction stability.

Apart from Australia, cyclones are frequently used in different parts of the world to classify tailings into a coarse underflow, for building tailings storage facility (TSF) embankments, and a finer fraction that are disposed of into the basin of the TSF. The shear strength of the tailings forming the outer embankment of a tailings storage facility and the location of the phreatic surface are the two most significant factors influencing the structural integrity of the facility. The coarse underflow is typically placed in such a way as to contain the overflow, which is finer, has low strength, and is often poorly consolidated.

This paper covers test work carried out in a geotechnical laboratory and on site to assess the flow liquefaction susceptibility of a gold tailings underflow sample produced during a cyclone field trial.

2 Background

Golder developed a tailings deposition strategy for a Client to optimise and increase the capacity of an existing tailings storage cell by means of the upstream wall raising technique. The cyclone method of deposition was selected as the most feasible option to progress the tailings deposition strategy. The primary aim of the cyclone field trial was to collect information to demonstrate to the Client and the regulators that cyclone deposition is a feasible option for raising the embankments and hence extending the life of the existing tailings storage cell.

Observation of the performance and efficiency of a single 250CVX (350 mm diameter) cyclone provided an opportunity to enhance our understanding of the in situ geotechnical characteristics of the cyclone underflow and overflow tailings streams under field conditions. Continuous monitoring and relocation of the cyclone unit throughout the trial allowed the client's operational personnel to gain useful experience of cyclone deposition techniques and industry practices. The trial set-up is shown in Figure 1.

Figure 1 General trial set-up

The cyclone feed pipe extended from the main tailings feed line and approached the cyclone from the side as shown in Figure 2. The overflow pipe was positioned along the upstream face of the embankment towards the tailings beach. Sections of conveyor belt were placed underneath the outlet of the overflow pipe to minimise the effects of erosion on the engineered fill. The cyclone was placed on the crest of the tailings cell embankment with the cyclone outlet pointing downwards at an angle of approximately 45°.

Figure 2 Cyclone set-up

Five underflow fans or wedges were created during the trial period. As the operation progressed more thin layers were added to the underflow wedge as it settled at a slope of around 1:7 (V:H) as shown in Figure 3. Underflow deposition continued until the underflow reached an elevation of approximately 300 mm below the current embankment crest elevation. A gate valve was used to throttle the flow from the main tailings delivery pipeline to the cyclone. Two to three deposition points adjacent to the cyclone were also in operation in order to reduce the total feed and pressure to the cyclone. Pressures were observed to fluctuate between approximately 50 and 120 kPa, with optimum conditions being achieved at roughly 100 kPa.

Figure 3 Underflow fans created during trial

The average tailings flow rate from the plant to the tailings cell during the field trial was approximately 241 m^3/h at a slurry density of 1.4 t/m^3. In order to maintain the feed pressure to the cyclone at around 100 kpa, the flow rate to the cyclone was maintained at approximately 60 m^3/h by throttling the gate valve. Based on initial calculations and laboratory test results for underflow bulk density, the cyclone produced an underflow volume of approximately 460 m^3/day during the field trial at a solids concentration of 68%. This relates to a mass split to underflow of approximately 40%. The daily overflow volume was estimated at 988 m^3/day.

3 Design aspects relating to cyclone TSFs

Cyclones are devices that function on a centrifugal separation principle with no moving parts. Whole tailings slurry enters the cylindrical feed chamber under pressure. Coarser particles in the slurry spiral downward through a conical apex at the bottom of the cyclone and are released as the 'underflow' (or sand fraction). The finer fraction and the majority of the slurry water rise to the outlet and are discharged as 'overflow' (sometimes called 'slimes').

The performance of cyclones is a function of the size and design of the device, and is influenced by operating parameters such as pressure solids concentration, the feed particle-size distribution and the density of the tailings feed slurry.

Cyclones deposit underflow at specific points in conical stacks. Consequently, cyclone walls are developed as a combination of overlapping cones that longitudinally form a triangular or trapezoidal cross-section with the tailings being deposited onto the outer slopes of the section. The crucial design aspect of the design of a cyclone facility is the balance (or split) between the underflow and the overflow. The former is intended to form an embankment at a higher elevation compared to the overflow basin level, in order to provide sufficient freeboard. The underflow embankment must be sufficiently wide to manage the phreatic surface for stability purposes.

The use of cyclone tailings in an upstream embankment may be an attractive option, as a significant cost advantage can arise by substituting cyclone sand for natural soils or mine waste. This arises from the underflow sands being produced on the embankment, which substantially reduces or eliminates the need for fill hauling and placement. By removing the sand fraction from the total tailings stream for use in the downstream embankment, the remaining volume of tailings discharged to the basin is reduced. With reduced impoundment storage requirements, the height of the embankment, its volume, and its cost are lower.

4 Tailings characteristics

The typical grading or particle-size distribution (PSD) of the tailings feed has approximately 58% passing 75 microns. The PSDs are indicated in Figure 4. The feed density was kept constant below 1.35 t/m^3. However, occasionally the feed density increased to 1.40 t/m^3, which resulted in cyclone roping conditions and lead to the loss of coarse material to the overflow. Similar results were obtained by Wates et al. (2014).

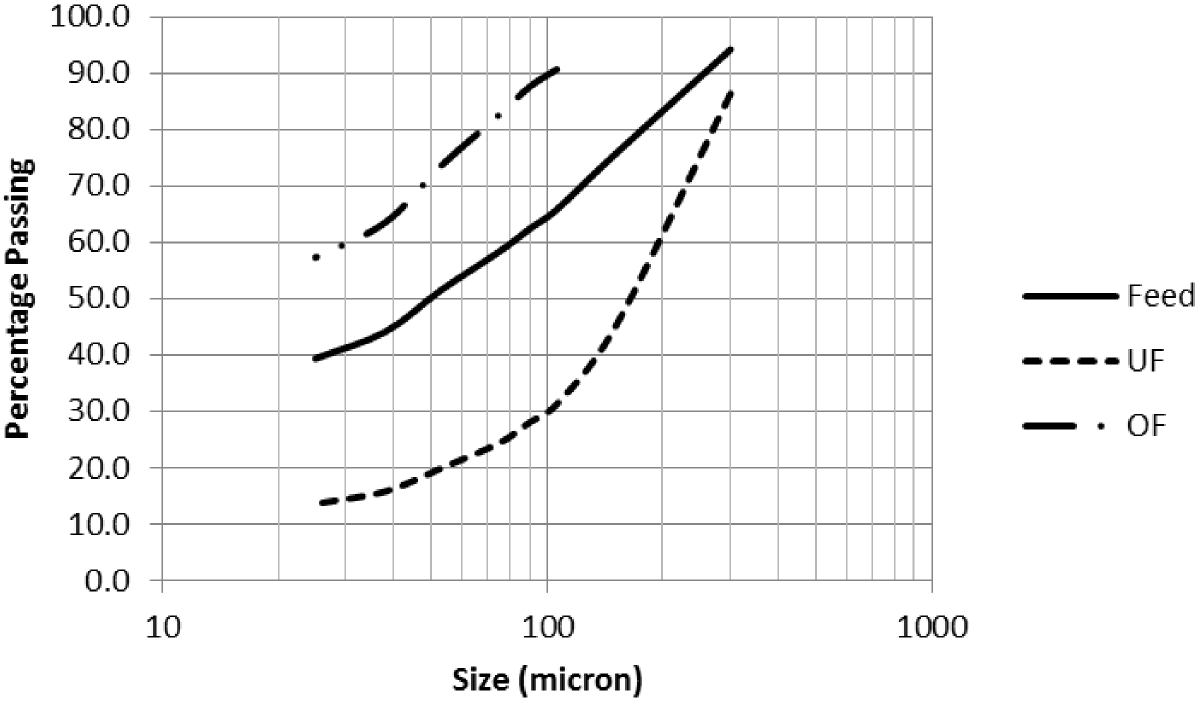

Figure 4 Tailings PSD

5 Laboratory testing

5.1 General

As outlined above, it was proposed to develop exterior embankments through the deposition of cyclone underflow material. Given the relatively low fines content of the material, it was expected to be free draining, and thus predominately in an unsaturated state. This would obviate the potential for liquefaction or contractive undrained shear. However, given the relatively novel nature of cyclone-constructed embankments in Western Australia, it was deemed prudent to obtain additional evidence regarding the likely state of the material to be produced.

To provide an assessment of the expected in situ state of the underflow material, an estimate of the critical state line (CSL) was obtained and compared to the expected normal consolidation line (NCL) of the underflow. This technique is similar to that utilised by McPhail et al. (2004).

Owing to visual observations of segregation in the sample during pouring and initial settling, and additional monotonic direct simple shear (DSS) test was also undertaken on material prepared from a slurry state. This was undertaken to assess the possible effects of layers of looser, fine grained material within the deposited underflow.

5.2 Methods

5.2.1 *Triaxial testing*

The CSL was estimated through a series of four triaxial tests, on moist tamped samples prepared as loose as practical. Two tests were drained, while two were undrained. One of the undrained tests was consolidated via K_0 consolidation, to assess the effects of initial stress state on the CSL obtained. K_0 consolidation was undertaken by ramping cell pressure, while computer control adjusted the loading ram such that all volume change was a result of axial strains, i.e. radial strains were zero. The calculations for the computer control system were based on average sample dimensions and back volume measurements. All tests used oversized lubricated end-platens to promote uniform stresses and strains throughout the sample at high strain, which are often required to achieve critical-state conditions. Void ratios were obtained through freezing of the sample at the end of test, and then obtaining gravimetric moisture content on the resulting frozen sample. Further detail on the measured CSL from laboratory testing is provided by Jefferies & Been (2006).

5.2.2 *Consolidation*

To estimate the expected NCL of the underflow following deposition, a slurry consolidometer (Sheeran & Krizek 1971) test was undertaken on underflow material. The underflow was poured into the slurry consolidometer cell, allowed to settle, and then one dimension load increments were applied to the sample.

5.2.3 *Direct simple shear*

A monotonic DSS test was undertaken to assess the response of the material to undrained shear, where such segregation-induced layering would be present. Sample was prepared by pouring material directly into the DSS by means of a mould, where the membrane was held against the mould with a vacuum. After pouring the material in, a one dimensional load of 25 kPa was applied to the sample. Following consolidation, the mould was removed, and the sample wrapped in Teflon rings and assembled for testing. The material was sheared under constant volume conditions at a shear rate of approximately 20% per hour.

5.2.4 *Compaction and density*

The cyclone underflow material is classified as a non-plastic silty sand with a solid specific gravity of 2.83. The particle-size distribution indicates that the underflow material has a P_{80} of 290 µm with approximately 24% of particles finer than 75 µm. The cyclone produced a mass split to underflow of 40% at a solids concentration of approximately 68%. At this solids concentration, the underflow material is deposited at approximately 72% of standard maximum dry density (SMDD). Undisturbed samples retrieved from the trial underflow wedge after five days indicated in situ dry density values of approximately 92% of SMDD. This is an indication that consolidation occurs rapidly which has the potential benefits of quick access time and increased water recovery via the decant system.

5.3 Results and implications

The CSL obtained for the underflow material is presented in Figures 5 and 6. Figure 6 includes the NCL obtained from the slurry consolidometer test. The vertical stresses from the slurry consolidometer were converted to mean effective stresses based on an assumed K_0 of 0.5.

Also included in Figure 6 are tube densities obtained during the trial. These indicate that denser initial states appear to be achieved on the underflow beach, possibly as a result of some air drying, double drainage effects (when compared to the slurry consolidometer), and the potential for 'shear' during deposition to increase density. This provides further indication that the in situ state of the cyclic underflow material will be dilative.

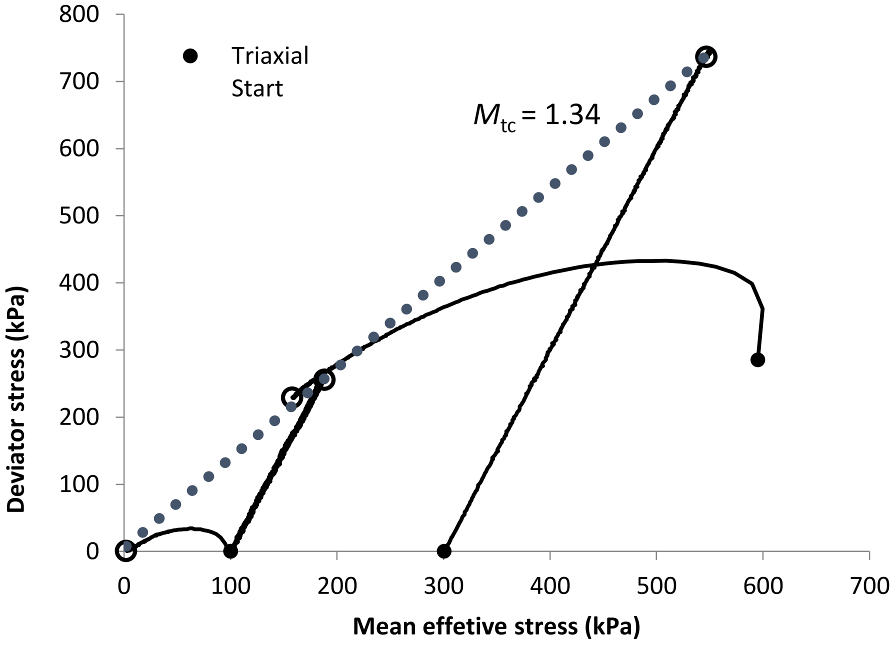

Figure 5 Inferred critical state in p - q space

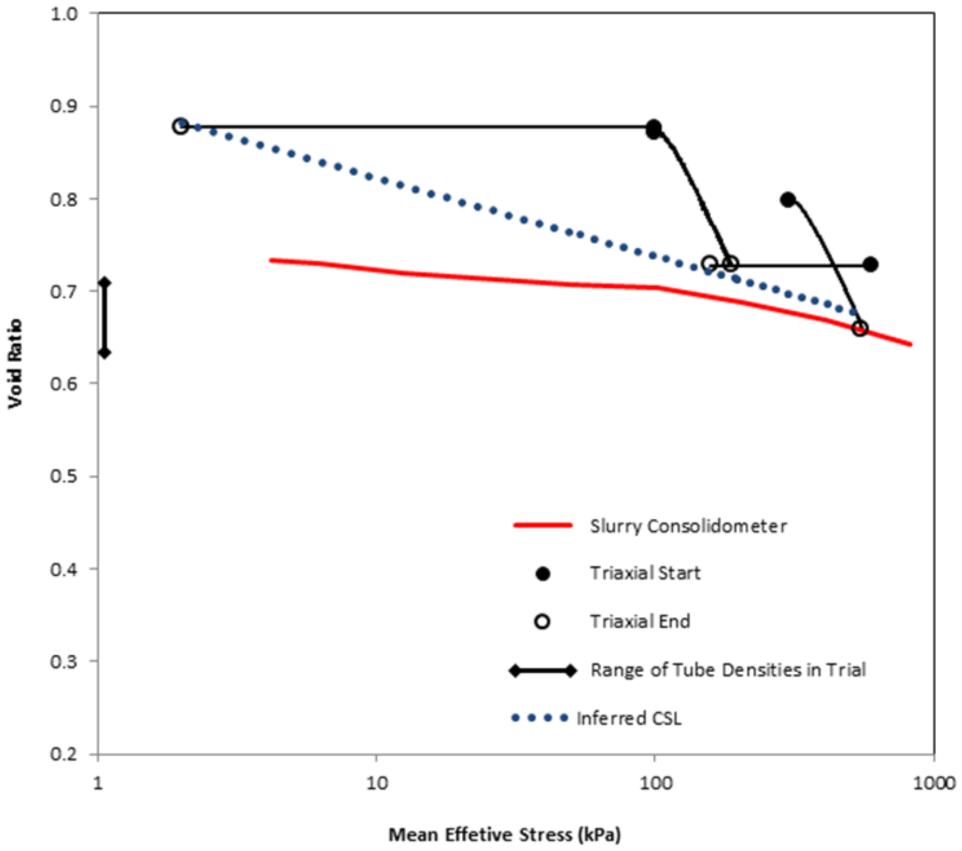

Figure 6 Inferred critical state in e - log p space

It can be seen from the comparison made that it is likely that underflow material will be in a dilative state, up to at least 100 kPa mean effective stress (~150 kPa vertical effective stress). This suggests that even were significant portions of the underflow material to become saturated, they would likely be dilative under shear and hence resistant to flow liquefaction. While at higher stress the NCL and CSL converge, such a situation would not develop until cyclone deposition had been occurring for a long period. Therefore, an assessment of the underflow embankment conditions *in situ* could be made prior to such depths of material being deposited.

The CSL obtained is consistent between drained and undrained tests, and tests commencing shear from both isotropic and K_0 consolidation. The latter result is consistent with previous studies of the impacts of K_0 consolidation in this context (Fourie & Tshabalala 2005), although in the cited study, greater scatter was evident. It is suggested that this may been a result of the use of the cell-calibration technique to measure sample void ratio. For the tests outlined herein, end-of-test soil freezing is likely to provide a more accurate measure of void ratio. The inferred CSL parameters of $\lambda = 0.037$, $\Gamma = 0.91$, and $M_{tc} = 1.34$ are consistent with published results for low fines-content hard rock gold tailings, e.g. Fourie & Papageorgiou (2001) and Bedin et al. (2012).

The results of monotonic DSS test are presented in Figure 7. The material behaviour under constant volume shear was observed to be dilative, with the undrained strength exceeding the estimated drained strength based on $M_{tc} = 1.34$. However, it is noted that the estimated drained strength is approximate, owing to uncertainties regarding stress conditions within a simple shear specimen, e.g. Atkinson & Lau (1991).

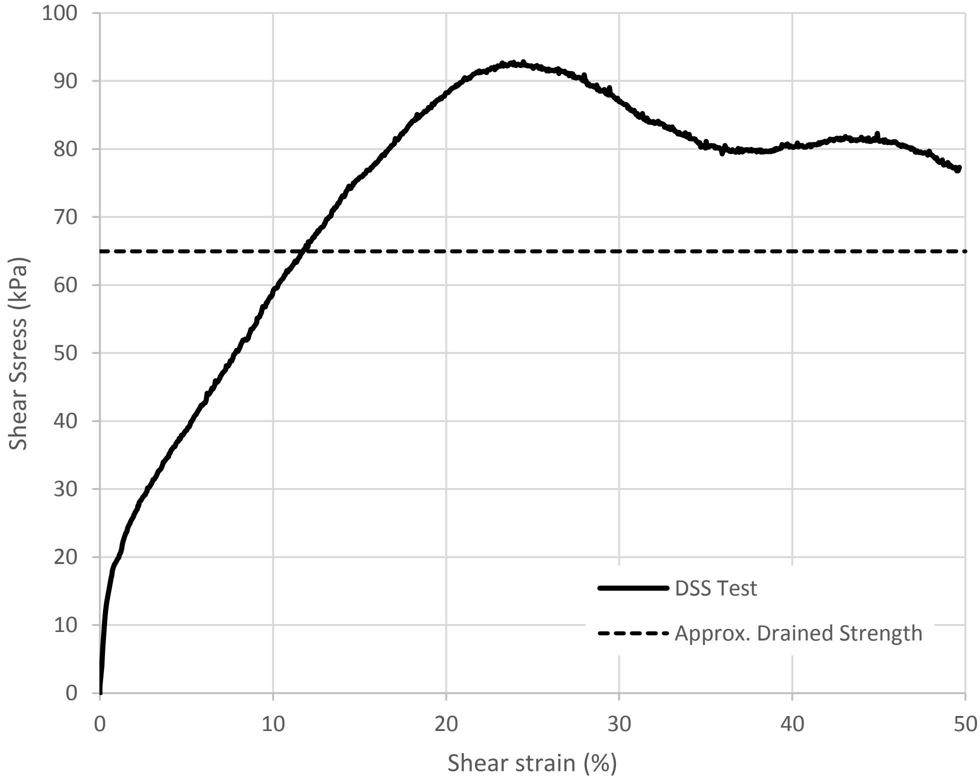

Figure 7 Monotonic DSS results

6 Conclusions

The cyclone unit is used to modify the tailings into two fractions, a coarser and a finer fraction, which have different characteristics to each other, and to the original feed. Cyclones deposit underflow at specific points in conical stacks and typically discharge overflow on to the tailings beach.

The purpose of using a cyclone is to create an underflow material that has superior geotechnical characteristics and can therefore form an impoundment wall to contain the overflow. The crucial aspect of the design of a cyclone tailings storage facility is the balance between the underflow and overflow. With the on-wall generation of underflow, the wall can be developed faster at a greater rate of rise independent of the need for sun-drying desiccation of the tailings to achieve adequate shear strength with obvious economic benefits.

The cyclone trial provided an opportunity to assess the cyclone under field conditions and to assess the quantity and quality of especially the underflow fraction produced on site. The cyclone performed extremely well on site and produced a split of at least 40% by mass compared to the norm of between 20% and 30%. The underflow was also relatively clean and free draining with a very small percentage of fines contained within the underflow. The cyclone field trial was a success and the cyclone deposition method proved to be a feasible option for extending the life of the tailings storage cell.

The expected in situ state of the underflow material was assessed; an estimate of the critical state line (CSL) was obtained and compared to the expected normal consolidation line (NCL) of the underflow. It is evident from the test work that it is likely that underflow material will be in a dilative state, up to at least 100 kPa mean effective stress. This suggests that even were significant portions of the underflow material to become saturated, they would likely be dilative under shear and hence resistant to flow liquefaction. While at higher stress the NCL and CSL converge, such a situation would not develop until cyclone deposition had been occurring for a long period. Therefore, an assessment of the underflow embankment conditions in situ could be made prior to such depths of material being deposited.

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