Field and laboratory research into the undrained behaviour of tailings at the University of Pretoria

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Synopsis

Several high-impact tailings dam failures around the world in recent years have placed a renewed focus on the stability of tailings dams and pointed to potential shortcomings in traditional drained design and safety evaluation procedures. A need to consider undrained shear strength in the design of tailings facilities has become apparent. However, there are specific requirements that need to be met before undrained shearing occurs. In South Africa, the last major failure was likely the Merriespruit disaster in 1994, which leads to the question of whether the conditions required for undrained shearing are readily applicable to South African tailings dams. This paper describes research at the University of Pretoria that has recently commenced to further investigate the conditions required for undrained failure to occur. The research includes laboratory and field testing to replicate these conditions in the laboratory and relate them to those found in an active tailings dam.

Keywords

tailings, liquefaction, centrifuge modelling.

Introduction

Several high-impact tailings dam failures around the world in recent years have placed a renewed focus on the stability of tailings dams and pointed to potential shortcomings in traditional drained design and safely evaluation procedures. The phenomenon of static liquefaction has been cited as a contributor to several of the recent failures. A need to consider undrained shear strength in the design of tailings facilities has become apparent (Morgenstern, 2018). This is thought to be especially applicable to upstream tailings dams where the walls containing the tailings are themselves constructed from initially saturated silty/sandy slurries and the material is deemed to be in a state susceptible to undrained shearing. Over the years, this has led to the construction and operation of tailings dams using the upstream deposition method being banned in Brazil and Chile (Ministerio de Minería de Chile, 1970; Agência Nacional de Mineração, 2019).

Several experts suggest that for tailings dams where the tailings material is found to be in a state where it is susceptible to undrained shearing, and where the consequences of failure are severe, it must be assumed that undrained conditions can occur. However, under the same effective stress, peak undrained shear strengths are typically only half of the peak drained strengths (*e.g.* Olson and Stark, 2003). Therefore, when undrained shear strengths are applied, stability analyses of many existing South African tailings dams indicate unsatisfactory factors of safety. To provide adequate factors of safety, expensive remedial works, generally the construction of stability buttresses, are required. For many mine owners, the associated costs can be unaffordable.

In the field, in addition to potentially unstable geometry, three conditions are necessary for undrained failure to occur, namely:

1. The material must be loose and of a contractive nature
2. The material must be saturated
3. A trigger initiating undrained shearing must occur.

When evaluating whether these conditions occur in South African tailings dams, the authors must, without doubt, answer in the affirmative in the case of the first two requirements. However, large-scale flow failure of tailings dams is rare in South Africa, with the last major event probably being Merriespruit in 1994, despite the presence of hundreds of upstream tailings dams in the country, some of which are older than 100 years. It therefore appears that flow failures are rare because the triggers do not commonly occur.

What would constitute a trigger event resulting in a tailings flow failure? The first that comes to mind is a seismic event. Despite being in an area of low seismic hazard, mining-related seismicity is common in South Africa, with the most severe event being of magnitude 5.5 on the Richter scale in Orkney in 2014 (Midzi *et al*., 2015). However, the authors are not aware of any seismic event that resulted in damage to a tailings dam in the country. In neighbouring Botswana, a magnitude 6.5 earthquake took place in 2017 (Midzi *et al*., 2018). No damage was reported at the three nearest tailings dams at Ghaghoo mine (25 km), Orapa mine (160 km), and Jwaneng mine (210 km) (Anglo American, 2017; Gem Diamonds, 2017), all three of which were constructed using the upstream method. More intense seismic events may possibly provide a sufficient trigger and their likelihood of occurrence can be probabilistically expressed.

This paper describes research under way at the University of Pretoria to further investigate the three conditions for undrained failure. The potential contractive nature of a soil depends on its void ratio and stress history, including the current stress state. These elements will be investigated using high-quality sampling, advanced laboratory testing, and *in-situ* measurement of the stress state. In addition, the effect of trigger events such as a gradually rising water table is being studied using physical modelling in the geotechnical centrifuge. The paper presents work planned in terms of the determination of *in-situ* void ratio and the associated behaviour of tailings under shear using laboratory testing. The measurement of negative pore water pressures in an active tailings dam, providing insight into the stress history that the tailings is subjected to, is presented. This is followed by a description of a centrifuge model investigating a rising water table as a trigger mechanism for a flow failure.

Research undertaken

The University of Pretoria has been conducting research into tailings dams safety for several decades and this is planned to continue. The current research is focused on understanding undrained shearing in the context of South African tailings dams and is presented in three aspects.

- The first aspect entails high-quality sampling of tailings material *in situ*. This is important as the first two requirements for undrained shearing relate to the state of the material. The intent is to design and construct a sampling device and to develop a repeatable sampling procedure with the aim of reducing sample disturbance associated with sampling, transportation, and storage.
- The second aspect concerns field monitoring of active tailings dams. Although sampling provides an indication of the current state of the material, the development of the material state is also of importance. As it is difficult and costly to obtain undisturbed samples, in many instances reliance is placed on laboratory testing of disturbed samples to obtain relevant geotechnical soil parameters. Understanding the stress paths imposed on active tailings dams may assist in the development of improved methods of preparing samples in the laboratory for testing. Current field monitoring systems are discussed as well as plans for future systems.
- The third aspect is laboratory testing. The third requirement for undrained shearing to occur is that a trigger must initiate undrained shearing. The University is in the unique position of having a geotechnical centrifuge. This enables physical modelling of geotechnical structures at a small scale while maintaining appropriate prototype (full-scale) stress conditions (Jacobsz *et al*., 2014). The current research involves the investigation of likely trigger mechanisms in a South African context and observation and analysis of the subsequent instability. Results from recent testing are discussed.

Research aspect 1: High-quality sampling

On upstream tailings dams, tailings are typically pumped as a slurry from the beneficiation plant to the tailings dam, where the material is deposited. When using paddock deposition, a layer of slurry, typically 100 mm thick, is deposited. The coarse material in the slurry will settle out first, forming a coarser more permeable layer at the base of the newly depositedmaterial, while the upper part will be more fine-grained and impervious. This separation into coarse and fine fractions results in an intensely layered profile as demonstrated by the sample shown in Figure 1. CPTu soil identification charts from tailings profiles typically also demonstrate extreme heterogeneity, with material over short depth intervals ranging across much of the soil type spectrum, from very soft clays to dense sands.

In upstream tailings dams where deposition occurs by means of spigoting and cycloning, an effort is made to separate the coarse and fine fractions. The coarse fraction is then used for the construction of the outer walls, while the fine fraction is discharged on the beach, with excess water flowing towards the pond. These methods of deposition are likely to result in a less heterogeneous soil profile.

The question arises how significant the differences in the behaviour of the various layers comprising the tailings profile will be upon shearing and how this would affect the behaviour of the profile as a whole. In order to begin to assess this, it is of interest to know the variation in the *in-situ* void ratio and also the variation in the critical state line applicable to the various soil layers. Vermeulen (2001) presented data illustrating how tailings samples from different strata can have significantly different critical state lines.

A major challenge with the assessment of the behaviour of tailings samples is that of sample disturbance. The relatively high permeability of tailings means that negative pore pressures generated during the extraction of samples rapidly dissipate, so that the effective stress is not preserved to the same degree as in the case of clays. Recovering high-quality samples from a tailings dam is therefore challenging, especially below the water

Figure 1—Tailings sample demonstrating layering

table. As a consequence, engineers often resort to the testing of reconstituted samples. However, reconstituting destroys the *in-situ* sample fabric and results in behaviour during shearing that can differ very significantly from the response of tailings in the undisturbed state (Chang *et al*., 2011). The response of reconstituted samples is highly dependent on the method of sample preparation (Zlatovic and Ishihara, 1997). Moist tamping, the easiest and most popular means of sample preparation, results in samples showing a tendency to contract and potentially liquefy, while samples prepared from a slurry tend to initially contract somewhat and then dilate strongly. It is not clear how samples should be prepared to replicate *in-situ* material behaviour in the field (Reid and Fanni, 2020). In addition, uncertainties exist about the behaviour of samples in the field due to the difficulties associated with recovering high-quality undisturbed samples.

The questions raised above are not easily answered. However, a sampling study is planned to recover high-quality undisturbed samples from above the water table in tailings dams. It is proposed to use hand augering to drill to the required depth to minimize vibration-related disturbance during sampling. Large-diameter (100 mm) Shelby tube samples will be taken. The angle of the cutting edge of the samplers will be 5°. A vacuum will be applied to the sample as it is being extracted. It is well established that, aside from disturbance during sampling, sample disturbance also occurs during transportation and storage before testing is conducted (Amundsen *et al*., 2016). To address this, a unique feature of the sampling programme is that arrangements are being made to extrude the sample while still on the tailings dam, immediately upon recovery. The sample will be placed in a triaxial cell and pressurized before being transported off the dam for testing. It is hoped that in this way sample disturbance during sampling, transportation, and storage can be minimized.

Research aspect 2: Field monitoring

Stress history and state in an active tailings dam

It is often useful to perform tests in the laboratory to observe soil behaviour in a controlled environment. However, these controlled conditions rarely present themselves in the field. An example of this is the stress conditions during the consolidation phase of a triaxial test, where it is common to consolidate the soil specimen isotropically (*i.e.* under zero shear stress). However, this will be representative of field conditions only if the horizontal and vertical stresses are the same, which is unlikely to be the case. The result is that in q-p’ space, the stress state does not find itself on the p’ axis ($q = 0$) after completion of consolidation, but at a shear stress offset above the p’ axis, which is dependent on the coefficient of lateral earth pressure, K_o. This potentially locates the stress state much closer to the critical state line compared to isotropic conditions.

After deposition, the solids in a tailings slurry settle out and excess water is decanted. During deposition, a small amount of excess pore pressure is generated which, in silty tailings such as gold tailings commonly found in South Africa, dissipates very soon after deposition (Lebitsa *et al*., 2020). Consolidation is associated with the dissipation of excess pore pressure, matched by an equal increase in effective stress, and is therefore associated with a small gain in strength. This, however, is not the only mechanism of strength gain active in tailings after deposition.

As excess water is decanted and the tailings begin to dry out, negative pore water pressures rapidly develop due to menisci receding into the drying tailings as evaporation takes place. The magnitude of the negative pore pressures (or suctions) depends on the soil water retention curve (pore water suction *vs* water content). In a saturated state the suction generated will be matched by an equal increase in effective stress. As the degree of saturation reduces during drying, reduced continuity develops in the pore water, accompanied by an increase in suction. The suction component contributing to the effective stress, and hence shear strength, can be expressed using the suction stress characteristic curve (Lu *et al*., 2010). The increase in effective stress may result in a volume reduction if the settled tailings is compressible, resulting in cracking and desiccation.

When a new layer of tailings is placed, the pore water suctions will dissipate, reducing the effective stress. However, due to the effects of over-consolidation contributing to phenomena such as interlock and fabric, dissipation of suction during a new deposition event only results in a relatively small reduction in the shear strength gained during desiccation (Daliri *et al*., 2014). As new layers are deposited, consolidated, allowed to dry out, and become desiccated, complex effective stress cycles are imposed on the drying tailings, resulting in a complex stress history and an uncertain current stress state. Critical state theory demonstrates how the stress history and current state, in combination with void ratio, influence undrained soil behaviour. The stress history and state in actual tailings dams are topics that have not been researched in depth.

As knowledge about the actual stress path associated with normal deposition cycles becomes available, stress path testing can be carried out to assess material behaviour in terms of stress path dependence. Given the changes that tailings deposited on a tailings dam are subjected to, it will be necessary to model unsaturated behaviour. Testing equipment with unsaturated capability is therefore required.

High-capacity tensiometers

Harrison and Blight (2000) mentioned that simple and reliable measurement of *in-situ* pore water suction is challenging. Various indirect means of suction measurement are available. However, these methods typically suffer from lagged response times. High-capacity tensiometers provide a direct measurement of pore water suction with minimal response time lag. However, these instruments are difficult and costly to source.

A low-cost high-capacity tensiometer was developed at the University of Pretoria (Jacobsz, 2018). The tensiometer has been demonstrated measuring suctions as high as 1 700 kPa (Jacobsz, 2019). The tensiometer comprises a commercial pressure sensor to which a high-air-entry ceramic filter is glued. The first tensiometers were encapsulated in a structural epoxy adhesive, but current versions are potted in a stainless steel housing using a structural epoxy adhesive. These tensiometers have been installed in trials in active tailings dams, with the first installed now operating for a period of 2.5 years.

Pore water suction monitoring

Figure 2 shows a cross-section of a gold tailings dam where pore water suctions have been monitored since April 2019. The tensiometers were installed in the daywall at the locations shown shortly after stepping in of the wall. The new daywall was at a height of 5 m in July 2021, implying a rate of rise of approximately 2.5 m per year.

The tensiometers were installed at depths of 150 mm and 300 mm below the tailings surface in shallow holes which were backfilled with loose tailings. The sensors were saturated in the

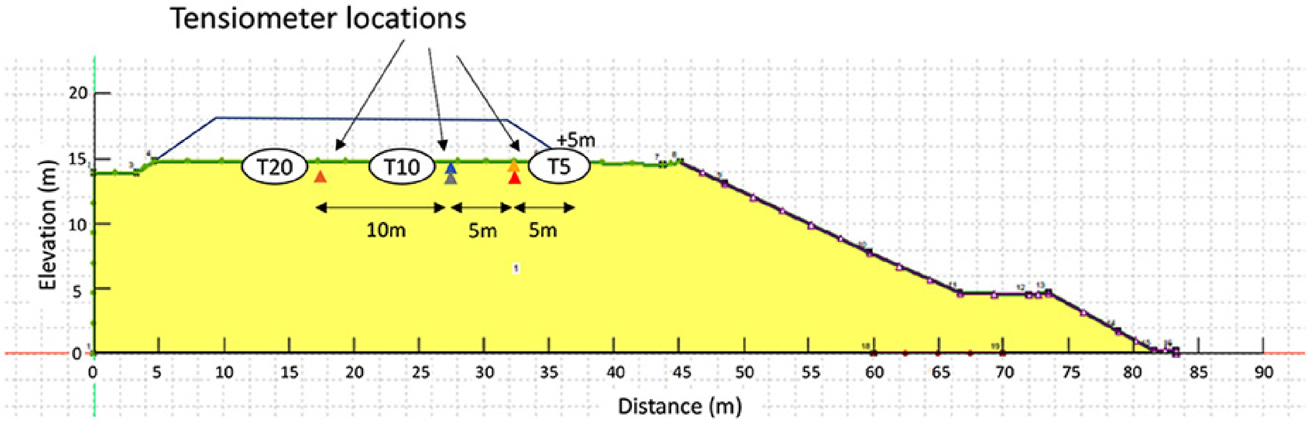

Figure 2—Tensiometer locations

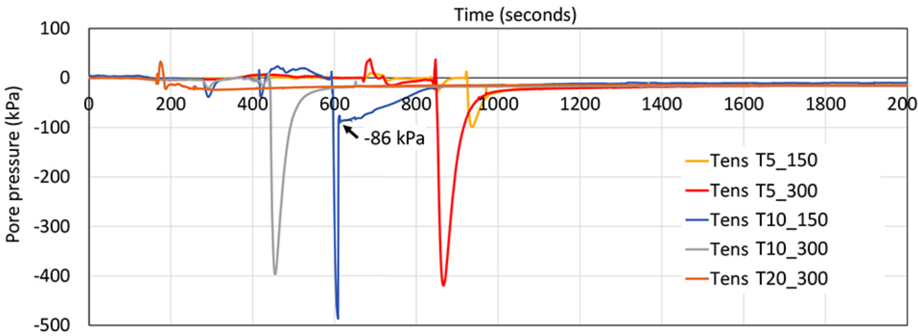

Figure 3—Pore pressure measurements during tensiometer installation

laboratory and transported to site in de-aired water. Readings were zeroed shortly before installation. The sensors were logged during installation, with the data displayed in Figure 3. The colours correspond with the sensor locations in Figure 2. The tensiometers were installed by excavating shallow holes, adding water to cover the base of the hole, and initially gently pushing the tensiometer into the underlying tailings. Figure 3 shows that pushing of the tensiometers resulted in large negative pore pressures caused by dilation, which could cause the tensiometers to cavitate. Cavitation was in fact observed on tensiometer Tens T10_150, with pore pressure rapidly increasing to –86 kPa (absolute zero for the site elevation). Cavitation is an essentially irreversible process under field conditions and renders the tensiometer useless. This behaviour is distinctly different to the other tensiometers which were pushed in. These tensiometers show a smooth return to the ambient pore pressure, indicating normal operation. An improved installation procedure is to simply bury the tensiometers in saturated tailings, adding additional water to ensure thorough saturation of the surrounding material when the sensors are covered. It can be seen that the pore pressure rapidly equilibrated after installation to an ambient pressure of approximately 15 kPa.

Figure 4 presents pore water pressures recorded over a period of four months. It also shows temperatures recorded using thermistors installed with the tensiometers at 5 m and 10 m from the edge of the stepped-in daywall. Deposition events and the daily rainfall record are indicated. Daily tailings temperatures generally fluctuated between 12°C and 20°C, with temperatures falling during the winter months and beginning to rise in August. The daily temperature fluctuation is evident, reducing with time as the tailings thickness increased above the instrumentation as deposition took place.

The gravimetric Soil Water Retention Curve (SWRC) for the gold tailings, as measured with the tensiometer method (le Roux and Jacobsz, 2021) is presented in Figure 5. This curve shows how moisture content influences the soil suction. The air entry value is shown on this SWRC at about 14 kPa. Due to the flat slope of the SWRC beyond air entry, the application of suction above the air entry value will result in rapidly desaturation.

The tensiometers were installed approximately one week after the last deposition event. The surface was relatively dry. Shortly after installation the suctions equilibrated to between 15 kPa and 20 kPa, with the suction at 20 m from the daywall edge being slightly higher than at the other locatins. During installation, the material here appeared more fine-grained. The suction values gradually increased over the first 10 days, reaching a maximum of 30 kPa and showing daily temperature-related fluctuations and fluctuations due to rainfall. Unfortunately not all the tensiometers provided reliable suction measurements over the study period. For example, tensiometer T20_300 ceased to provide suction measurements around 22 April. However, based on the available suction record, it appears that the suction state in the tailings was on the flat plateau on the SWRC for the entire study period, as presented in Figure 4.

Suction trends matched each other closely for the three of the instruments, with suctions at 150 mm depth slightly exceeding those at 300 mm depth initially, as indicated by the measurement taken at 5 m offset from the daywall edge. The influence of deposition events is clearly evident, with the first event resulting in the complete dissipation of suctions. With subsequent events,

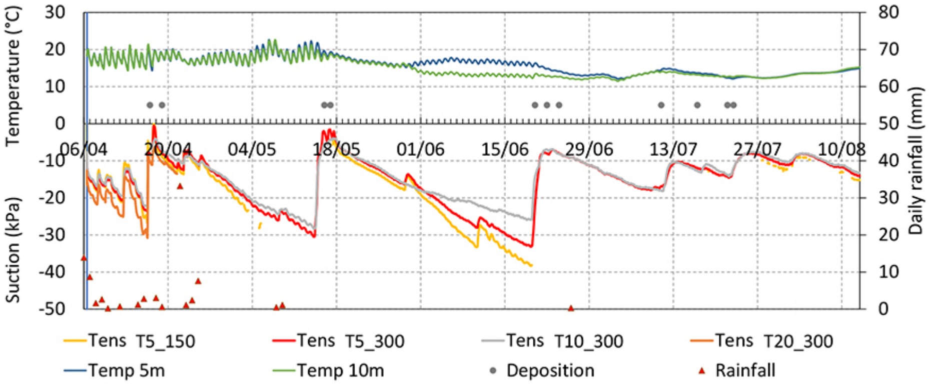

Figure 4—Pore pressure, temperature, rainfall, and deposition events over a four-month period after installation

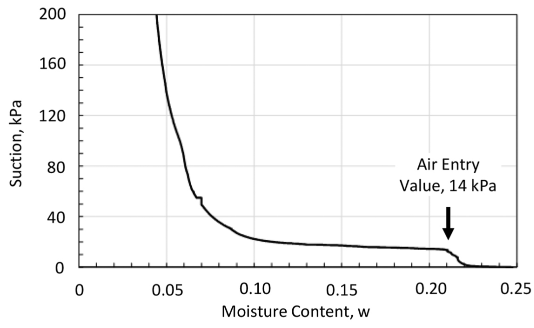

Figure 5—Gravimetric soil water retention curve for gold tailings

suction dissipation became progressively less as the thickness of tailings increased. After the June deposition events, the suction state remained quite constant during the winter months, varying between 8 kPa and 18 kPa.

The suction record shows that an average maximum suction value of approximately 30 kPa developed gradually following deposition-associated dissipation. These cycles would have resulted in some overconsolidation and strength gain of the tailings. The thickness of tailings reached approximately 1 m at the end of the record shown in Figure 4, which would have resulted in about 15 kPa of overburden pressure. The data illustrates how suction measurements can provide insight into the effective stress history imposed on tailings deposited on an active tailings dam as it repeatedly desaturates and becomes resaturated again. To assess whether this process has a temporary or permanent influence, these measurements needs to be coupled with void ratio and saturation measurements.

Future field instrumentation

To gain insight into the stress history of the material in the wall of a paddock-type upstream tailings dam, a new instrumentation programme is planned. Most instrumentation systems installed on tailings dams are only able to measure aspects of the soil state (*e.g.* pore pressure) and assumptions need to be made to fully define the soil state. To improve on this, the University intends to design and install an instrumentation system capable of measuring the complete soil state in an active tailings dam. The system will comprise total stress cells, high-capacity tensiometers, and volumetric water content sensors. The instruments will be placed in clusters at selected locations in the walls of active tailings dams, allowing them to be 'slimed in' during normal deposition to minimize installation conformance errors. Preparatory trials will be carried out in the laboratory, where better control over conditions during experiments is possible, prior to field installations. With both total stresses and pore pressures (measured by the tensiometers) known, the development of the effective stress path in an active dam can be tracked. An important aspect to be gained is an indication of the *in-situ* horizontal effective stress.

Research aspect 3: Laboratory testing

In order for undrained failure of a slope to occur, the material must be contractive (a sufficiently high void ratio), it must be saturated, and subjected to a trigger mechanism to initiate undrained loading (Take and Beddoe, 2014). Perhaps the most obvious trigger mechanism that comes to mind is a seismic event. However, as discussed earlier, South Africa is generally an area of low seismic hazard, and to the authors' knowledge seismic events have not to date resulted in damage to a tailings dam in South Africa. There are, however, other potential triggers. These could include events such as loss of confinement, overtopping, and significantly, static liquefaction. Static liquefaction occurs as a result of a loss of strength of loose contractive soils under undrained conditions (Olson *et al.*, 2000). Also potentially significant is a gradual increase in the water table, which then reaches a 'trigger' pressure, causing failure.

It is difficult to study the impact of trigger events and static liquefaction analytically or numerically, and although case studies are available of major tailings dam failures they provide limited scope to carry out sensitivity studies. Many examples of physical models studying landslides can be found in the literature (*e.g.* Eckersley, 1990) and these may be informative regarding the possible behaviour of tailings slopes. However, we are not aware of centrifuge model studies investigating the liquefaction behaviour of tailings dams. Based on the success of many studies of landslides in the centrifuge, it is likely that physical models may also provide valuable insight into the conditions under which liquefaction-type failure of tailings dams may occur. A physical model study has recently commenced at the University of Pretoria to model tailings slope failures in the geotechnical centrifuge in order to investigate the conditions under which such a failure can occur.

Centrifuge model

Figure 6 shows a model tailings slope constructed from gold tailings at an angle of repose of 34°, compacted using moist tamping in an attempt to create a contractile fabric (Reid and Fanni, 2020). The material was compacted to a void ratio of

0.95 at a gravimetric water content of 6.5%. The model scale was 1:60, implying a test acceleration of 60g. The 300 mm high slope therefore scaled to 18 m.

The intention was to trigger static liquefaction failure of the model slope. A trigger to impose during testing had to be selected. Chu *et al*. (2012) noted that drained failure resulting in monotonic shearing can act as a trigger for undrained instability and that the loss of shear strength during undrained instability may be of short duration. Monotonic loading in the form of a slowly rising fluid level was therefore imposed. A high water table, resulting in seepage at the toe, and toe instability are often causes of stability problems on tailings dams.

A pore fluid comprising a mixture of glycerine and water was used to provide a kinematic viscosity 60 times that of pure water. This is necessary in order to satisfy scaling laws for the latter of the two processes associated with a liquefaction event, namely contractive collapse of loosely packed particles into void spaces and the subsequent dissipation of excess pore pressure (Askarinejad *et al*., 2014). The slope was monitored with six pore pressure transducers, with two displacement transducers monitoring crest settlement. Photogrammetry was used to monitor the model in section.

The upstream side of the model slope was constructed against a well in which a constant fluid level could be maintained throughout the test. The well was separated from the slope using a needle-punched non-woven geotextile. After accelerating the model to 60g, the fluid level in the well was raised to just below the crest of the embankment. The pore fluid was allowed to seep into the model for the pore pressure regime to establish. The development of the pore pressure regime was monitored visually using cameras and pore pressure transducers.

Figure 7 presents pore pressure changes during the course of the centrifuge test. Pore water pressures generally decreased as the model dried out during testing, but then rose as they were influenced by the advancing wetting front. It took approximately 24 hours for the pore pressure regime to fully develop. As the fluid began to emerge at the toe of the slope, sloughing of the toe began to occur, slowly advancing backwards along the slope, with cracks gradually appearing parallel to the strike of the slope. At a certain point in time, the cracks propagated rapidly upwards against the slope and the slope failed suddenly, also illustrated by the spiking pore pressures in Figure 7.

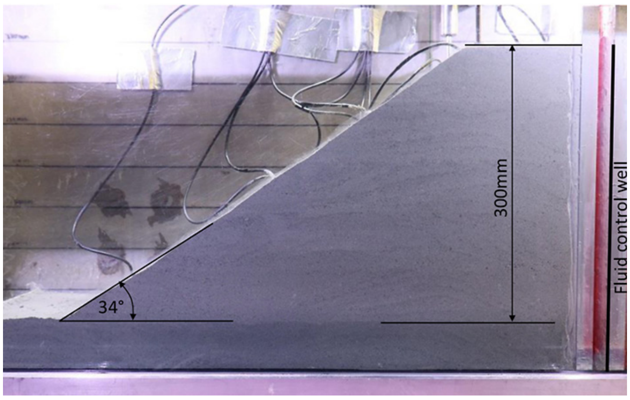

Figure 6—Model tailings slope

The failure surface was located slightly below the fluid level (shown as a dotted yellow line in Figure 8). Examination of the pore pressure response revealed a small increase in pore pressure at the base of the slope at the moment of failure, demonstrating contractive behaviour. Another aspect to note is that sloughing at the toe resulted in a local loss of confinement, often seen to be a factor in major tailings dam failures. The model slope failure demonstrated how drained instability can trigger undrained, or at least partially undrained, failure. The purpose of this discussion is to demonstrate the potential of centrifuge modelling as a means of studying tailings dam slope failures and a detailed analysis of the event falls outside the scope of the present paper. Further modelling is ongoing.

Conclusions

A number of high-impact tailings dam failures around the world in recent years have placed a renewed focus on the stability of tailings dams and pointed to potential shortcomings in traditional drained design and safely evaluation procedures. A need to consider undrained shear strength in the design of tailings facilities has become apparent. In the field, in addition to potentially unstable geometry, a number of conditions are necessary for undrained failure to occur, namely:

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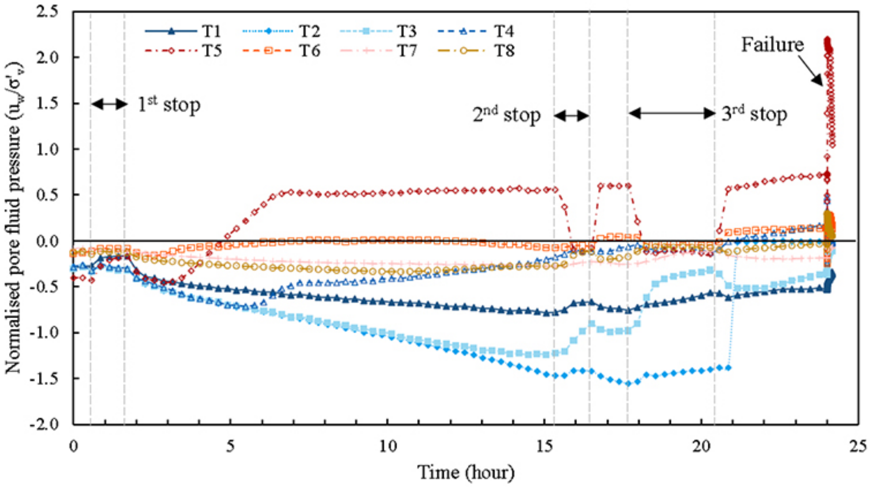

Figure 7—Pore pressure response during saturation and failure of the model slope (Crous, 2022)

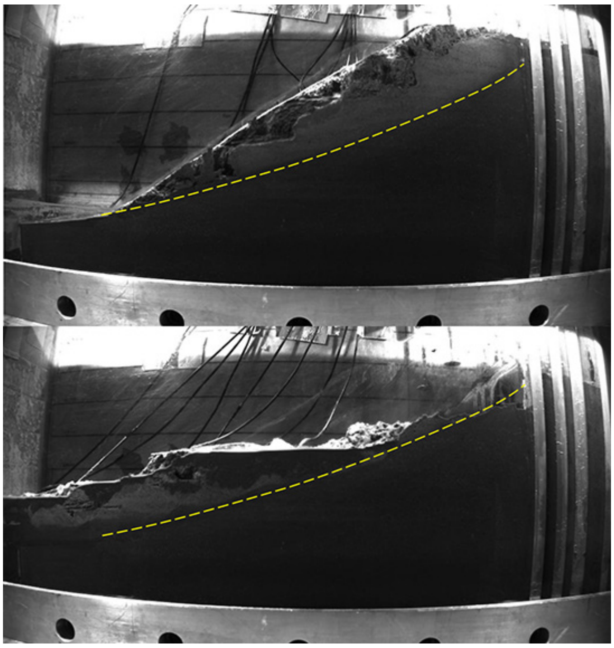

Figure 8—Before and after images illustrating slope failur

Large-scale flow failure of tailings dams is rare in South Africa, with the last major event probably being Merriespruit in 1994, despite hundreds of upstream tailings dams in the country, some of which are older than 100 years. It therefore appears that flow failures are rare because the triggers do not commonly occur.

Three aspects of research being undertaken at the University of Pretoria to investigate the requirements for undrained shearing were presented. These include high-quality sampling of tailings materials so that the *in-situ* state of the tailings can be determined, field monitoring to understand the stress imposed on the tailings during operation, and advanced laboratory testing to simulate undrained trigger mechanisms and observe the subsequent instability. Preliminary results from some of these studies were presented. The intent of this research is to improve the understanding of tailings behaviour, specifically in relation to undrained shearing in South African conditions. It is hoped that this will lead to the continued safe construction and operation of tailings dams in the country and around the world. This research is ongoing and additional results and analysis will be published as they become available.

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