Geotechnical centrifuge modelling undrained triggers of tailings dam instability

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As Traditionally tailings dams have been designed assuming drained conditions. However, the possibility of undrained failures needs to be considered. However, the mobilisation of undrained failures requires a trigger. Drained triggers may lead to undrained failures, owing to the rapid shearing within the slope during such failures. However, with modern standards, undrained triggers must be considered during the design and construction of tailings dams. In spite of modern standards, the triggers and associated failure mechanisms are often hypothesised and not well understood. To investigate potential undrained triggers and failure mechanisms of tailings dams, centrifuge tests were conducted at the University of Pretoria on model tailings dams. The potential triggers considered were borehole drilling using water, a sudden loss of confinement, the rapid construction of a buttress and downward migrating waterfront meeting the ambient water table.

INTRODUCTION

Mining activities have increased significantly due to the increasing need for mineral commodities. Owing to this, the amount of solid and liquid waste produced by the mining industry (referred to as tailings) has also increased. Large tailings dams are constructed to dispose of the tailings. These dams are often constructed by placing the tailings as a slurry, which may result in the tailings being in a loose, saturated state, especially for dams constructed using the upstream method. This can cause the tailings to exhibit contractive tendencies during shearing, which would result in a brittle response during undrained shearing (Chang *et al*., 2011; Fourie *et al*., 2001; Reid and Fanni, 2022; Riveros and Sadrekarimi, 2021).

Due to the brittle nature that tailings can exhibit during undrained shearing, along with the long runout distance associated with such a failure, static liquefaction is often deemed a probable failure mechanism associated with these failures (Fourie *et al*., 2001). The failure of the Brazilian Feijão tailings dam in 2019 illustrated the environmental and economic impact that can result from a containment failure, and the subsequent run-out distances that can occur during such a failure (Robertson *et al*., 2019). In addition, this failure led to the death of 270 people. Despite the known repercussions of such failures, tailings dams continue to fail at an unacceptable rate, with Azam and Li (2010) reporting a failure rate of 1.2% over the past century. However, the mobilisation of such undrained failures requires a trigger.

It is well known that drained instability can be a cause of tailings dam failure. It has been shown experimentally that drained instability may lead to failures of tailings dams, owing to the rapid shearing that occurs within the slope once drained instability has been triggered (*et al.*, 2022; Ng *et al.*, 2023). However, with the increasing adoption of modern standards, such as the Global Industry Standard on Tailings Management, triggers that directly induce undrained conditions have to be identified and considered in the design of tailings dams. These triggers and the associated failure mechanisms are often hypothesised and not well understood.

This paper presents centrifuge tests that are being conducted at the University of Pretoria to investigate potential undrained triggers and the associated failure mechanisms of tailings dams. Four centrifuge tests are described, each investigating a different undrained trigger. The first trigger investigated was that of a borehole drilling using water discussed by CIMNE (2021). CIMNE suggested that the drilling process, which used water pressure to dispose of tailings, caused the pore pressure to rapidly increase in a sand layer, triggering the failure of the dam.

Wagener (1997), supported by Fourie *et al.*, (2001), concluded that an overtopping event caused the Free State town of Merriespruit's failure. The water overtopping the tailings dam eroded material at the toe of the slope, causing a rapid loss of confinement. This caused rapid monotonic shearing at the toe, which eventually caused the collapse of the slope. This rapid loss of confinement is the second trigger to be investigated.

The third undrained trigger to be investigated is the rapid construction of a buttress. Although buttressing is a method used to increase the stability of tailings dams, the rapid construction of a buttress can cause a rapid and significant increase in pore pressure at the toe of a slope, which will cause a reduction in effective stress and shear strength, thus triggering the failure of the slope.

The final trigger to be investigated is a downward migrating wetting front meeting the ambient phreatic surface. The hypothesis is that when the two fronts meet, a sudden increase in pore pressure would result throughout the entire slope, potentially triggering the failure of the slope.

GENERAL CENTRIFUGE MODEL LAYOUT

A series of four centrifuge tests, each investigating a different undrained trigger, are being conducted at the time of drafting this paper. All centrifuge testing is done at the Geotechnical Centrifuge Facility at the University of Pretoria (Jacobsz *et al.*, 2014). All model tailings dam embankments were constructed using gold tailings obtained from a mine situated east of Johannesburg. The tailings used, classified as a silty sand, were collected from the daywall of the slope. The tailings have a fines content ($D < 63$ µm) of 26.5%, an average grain size (D_{50}) of 120 µm and a maximum particle size of 500 µm. The saturated permeability of the tailings is 3×10^{-7} m/s. The tailings are predominantly quartzite. More details about the tailings used are presented by Ng *et al.*, (2023). During all tests, the model slopes were initially subjected to a rising groundwater table to establish an existing water table before being subjected to the undrained triggers. For all tests presented, the model scale used was 1:60. Thus, the acceleration level in the centrifuge for all tests was 60 g. This acceleration was chosen, as it provides the prototype geometry for a mid-sized tailings dam (i.e. approximately 20 m high).

Model Preparation

All models were, or will be, constructed in a model container with internal dimensions of 800 × 160 × 360 mm. The container was constructed from 50 mm thick aluminium panels, with a glass viewing panel. All model slopes were constructed using the moist tamping method. This method allows for the preparation of loose specimens due to the capillary effect between soil particles (Cai, 2001; Castro, 1969; Kramer & Seed, 1988). The loose soil structure exhibits a more brittle response than other sample preparation methods (Chang *et al.*, 2011), which increases the chances of triggering a liquefaction failure. The general design and construction of the model slopes consisted of moist tamping the gold tailings in six 50 mm thick layers at a moisture content of 6.5%. The target density was controlled by placing a predetermined amount of tailings and compacting it by hand until the layer was compacted to a 50 mm thickness. All model slopes had a design initial void ratio of 1.0. Once all the layers were compacted, the slope was cut by hand to the general geometry shown in Figure 1. The design geometry was chosen to create a slope that is marginally stable under drained conditions at 60g acceleration, depending on the water table.

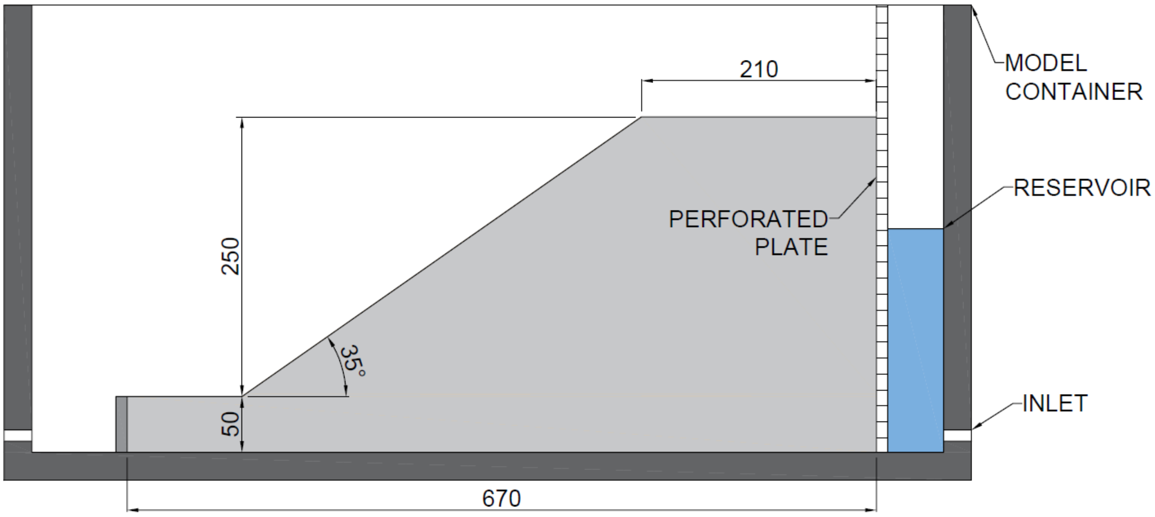

Figure 1. General geometry for model constructed for centrifuge tests.

Groundwater Control System

The groundwater control system adopted for all the centrifuge tests is like that used by Ng *et al.*, (2023). The system consists of a dedicated water supply system in the geotechnical centrifuge, a solenoid valve, a pressure transducer, a perforated steel plate covered by geotextile and an outlet (see Figure 1). The perforated plate created a reservoir at the upstream section of the model slope, allowing for control of the entrance height of the phreatic surface. The solenoid valve was used to control the water level in the reservoir and the pressure transducer was used to monitor the water level. As the water seeped through the slope, establishing a water table, excess seepage water drained through the outlet, preventing submergence of the toe and the lower slope face.

Instrumentation

A 10 mm diameter miniature piezocone penetrometer (CPTu) was driven into the crest of the model slope to characterise the material in flight. The location was chosen to give a broad overview of the state of the material beneath the crest. The miniature CPTu measures the cone tip and friction sleeve resistance, along with the pore pressure response. This allows for assessing the material properties in flight, as well as verification of the subsurface stratigraphy, density and material strength of each model.

The pore pressure response in the slopes was measured during the entire test in order to observe the undrained shearing of soil during failure. Tensiometers designed and constructed at the University of Pretoria (Jacobsz, 2018) were used throughout all tests at selected positions throughout the slopes to give a comprehensive overview of the pore pressure responses during each centrifuge test.

The deformation of the slope was measured using linear variable differential transformers installed at the toe, crest and on the face of the slope. To differentiate drained from undrained behaviour, slope deformation and pore pressure responsse were compared. For an undrained trigger, a change in pore pressure was expected to be visible before any deformation was observed, and vice versa for a drained trigger. To ensure that the type of trigger could be identified, the sampling rate in all tests was set at 100 Hz with data recorded using the centrifuge data acquisition system.

To capture rapid slope failures three cameras installed in the centrifuge were used. One DSLR camera was used to obtain high quality photographs of the side profile of the slopes throughout the tests. These photographs were used to conduct particle image velocimetry on the tests, which allows for the deformation of patches of pixels to be tracked. A video camera also aimed at the side profile of the model slopes was used to capture a continuous video of the model slopes from the start of the tests up until the point of failure. Lastly, a high-speed camera was used to capture the failure process during each test.

CENTRIFUGE MODELLING OF UNDRAINED TRIGGERS

Trigger 1: Borehole Drilling Using Water

On 25 January 2019, arguably the worst tailings dam failure in recent years occurred, when the Brumadinho tailings dam, situated in Minas Gerais, Brazil, failed without warning. The majority of the face of the slope failed and the slope collapse occurred in under 10 seconds (Robertson *et al.*, 2019). The failure resulted in 9.7 million m^3 of fluidised tailings being released from the dam within five minutes. An approximately 10 m high wave of fluidised tailings spread 10 km downstream of the dam, killing 270 people.

CIMNE (2021) published a report on the Brumadinho failure. One of the triggers considered in their numerical analyses was the water overpressure associated with the drilling of a borehole on the dam at the time of failure. Under stress and hydraulic conditions resembling those during drilling at the bottom of the borehole under consideration, numerical analyses indicated that local liquefaction which propagated outwards due to water overpressure may have occurred.

Failure of the dam section occurred in the 2D simulation when liquefaction was imposed in a limited zone around the bottom of the borehole. The geometrical feature of the failure and the pattern of displacements that resulted from the failure were consistent with visual observations of the actual failure, supporting the conclusion that the drilling of a borehole using water is a potential trigger of liquefaction that caused the collapse of the dam.

To investigate this potential undrained trigger in the centrifuge, a centrifuge model similar to that shown in Figure 1 was designed. However, to simulate conditions similar to that proposed by CIMNE (2021), a sand layer was incorporated within the model slope near the bottom of the model, shown schematically in Figure 2. Additionally, a standpipe was installed within the slope, with an opening within the sand layer. In this test, after accelerating the model to 60 g, a water table was first established using the groundwater control system discussed earlier. Once the slope started to show signs of distress (i.e. the slope being marginally stable), a valve connected to the standpipe was opened. This rapidly filled the standpipe with water, which rapidly raised the water pressure in the sand layer. If the material is saturated, minimal flow, if any, is necessary to raise the pore pressure. This reduced the effective stress and thus the available shear strength, triggering the failure of the slope.

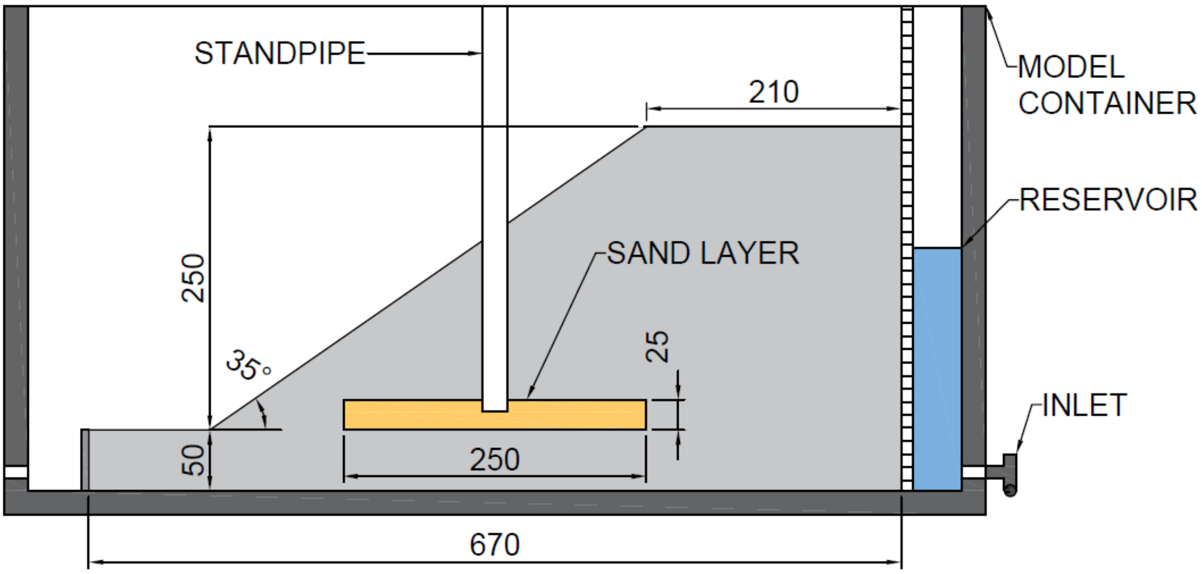

Figure 2. Centrifuge model for borehole drilling using water trigger.

Trigger 2: Loss of Confinement
On 22 February 1994, a 31 m high tailings dam, situated near the Free State town of Merriespruit failed. On the evening of the failure, 55 mm of rain fell in approximately 30 minutes during a storm event. After the rainfall event, the daywall breached by water flowing over the crest, releasing 600 000 m^3 of fluidised tailings. A significant portion of the tailings flowed into the town located downstream of the dam, killing 17 people, and causing severe property and environmental damage.

On the night of the dam breach, the high intensity rainfall caused the water level on top of the dam to increase. As the dam had limited available freeboard, the daywall soon overtopped. The stream of water flowing over the dike started to erode the tailings at the toe of the slope. It is hypothesised that this mobilised a sudden increase in shear stress in the toe region, resulting in the shearing of the tailings under undrained conditions. This was accompanied by the generation of excess pore pressures, resulting in the loss of shear strength and the triggering of liquefaction (Fourie *et al.*, 2001).

To study the loss of confinement as a potential undrained trigger, a centrifuge test will be conducted. The general layout of the centrifuge model is like that shown in Figure 1. However, material at the toe will be further excavated to create a vertical face (see Figure 3). To provide confinement of the material upstream of the toe, a steel plate, attached to a pneumatic piston, will be installed at the toe. The plate will prevent the slope from collapsing. The model will be accelerated to 60 g and the phreatic surface will be established using the built-in groundwater control system. Once the phreatic surface has reached the toe, the pneumatic piston will be used to rapidly remove the steel plate. This will suddenly remove confinement from the material upstream of the toe, potentially triggering the failure of the slope.

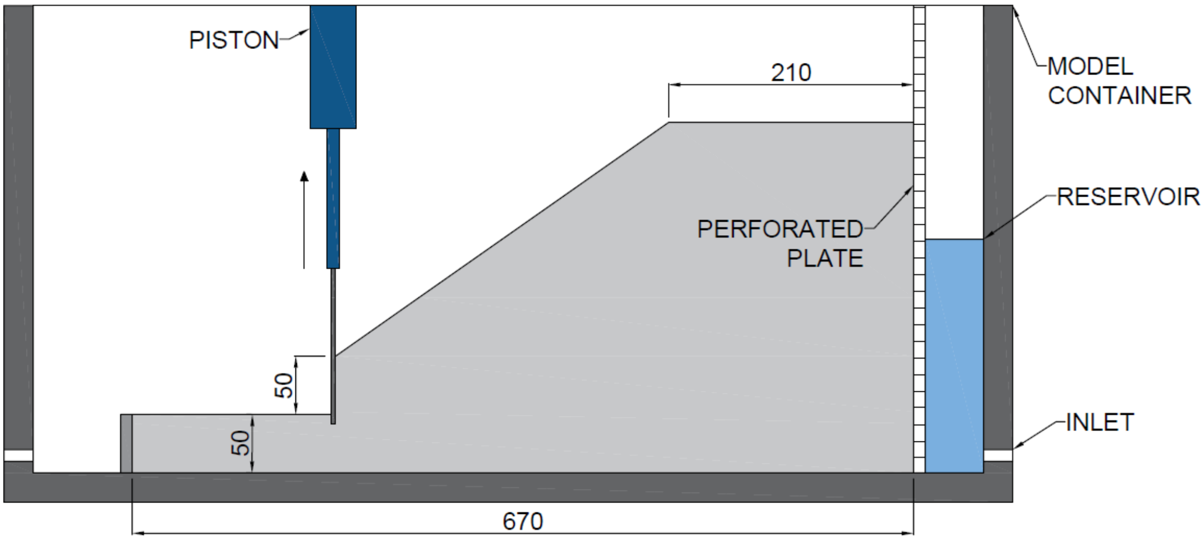

Figure 3. Centrifuge model modelling the loss of confinement undrained trigger.

Trigger 3: Rapid Construction of a Buttress
One of the most common stabilisation methods for tailings dams is buttressing the toe of the slope (Golder Associates, 2015). Buttressing involves one basic principle: to provide sufficient dead weight near the toe of a slope to prevent movement. A buttress is a passive stabilisation method, which increases the effective stress at the toe of the slope and increases the length of potential failure surfaces that pass through the foundation soils. This increase in effective strength increases the shear strength, and subsequently increases the stability of the slope.

Although the stability before and after the construction of the buttress is critical, the stability during construction should also be considered. Owing to the lower permeability of tailings, positive excess pore pressures may develop in the saturated zone of the slope due to the added weight of the newly placed rock. If a buttress is constructed too rapidly, the excess pore pressures generated may be sufficient to trigger undrained or partially drained instability, and hence failure of the slope.

To investigate this potential trigger, a centrifuge test based on the geometry in Figure 1 was designed and will be conducted at the University of Pretoria. However, to simulate the rapid construction of a buttress, a sand hopper was designed and installed on the centrifuge model container. The sand hopper was constructed from stainless steel. An outlet will be located 30 mm above the face of the slope, approximately one third along the face. Coarse sand will be placed within the sand hopper and kept within the hopper using a sliding plate. The plate will be attached to a pneumatic piston, which will be used to rapidly remove the plate, creating an opening for the sand to flow out, depositing at the toe of the slope, modelling rapid construction of a buttress along the lower slope face.

The general testing procedure will remain the same as the other tests. The model will first be accelerated to 60 g, upon which the water table will first be established. However, once the water table nears the toe of the slope, the pneumatic piston will be activated, discharging the sand from the sand hopper and depositing it along the lower face of the slope at the angle of repose. Due to the low permeability of the tailings, this may cause the pore pressure at the toe of the slope to increase rapidly, causing a sudden loss of shear strength, triggering slope failure under the weight of the buttress.

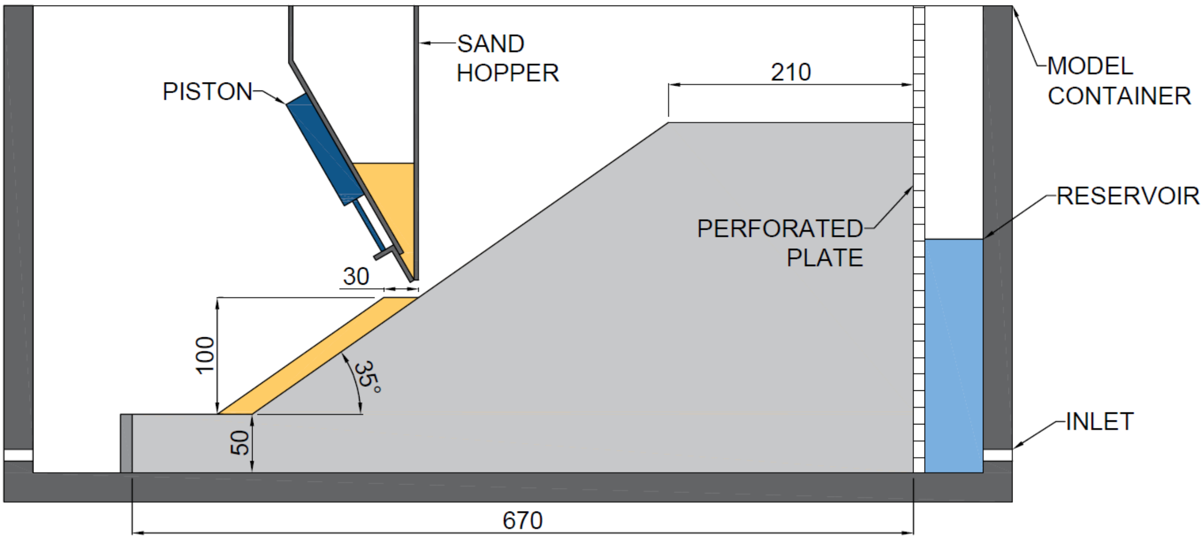

Figure 4. Centrifuge model modelling rapid construction of buttress.

Trigger 4: Meeting of Two Wetting Fronts
As previously discussed, a sudden and significant increase in pore pressure may result in a large enough reduction in effective stress in a slope to trigger the failure of the slope. It is hypothesised that a marginally stable tailings slope may fail if a downward migrating water front reaches the ambient water table, which might happen, for example, in the case of a heavy rainfall event or a significant increase in the rate of rise. The hypothesis is that when the wetting front reaches the ambient phreatic surface, it will cause the pore pressures to instantly increase throughout the slope, resulting in an instantaneous reduction of shear strength and possible failure.

To investigate the hypothesised undrained trigger, a centrifuge test based on the geometry shown in Figure 5 was designed and will be conducted at the University of Pretoria. The geometry differs from the general geometry shown in Figure 1, as the slope contains a bench approximately two thirds along the slope face. The bench will act as a deposition space, where water could be allowed to pond. A water outlet system, connected to the centrifuge water supply system via a solenoid valve, will be placed on top of the bench to allow for control over water ponding on the bench.

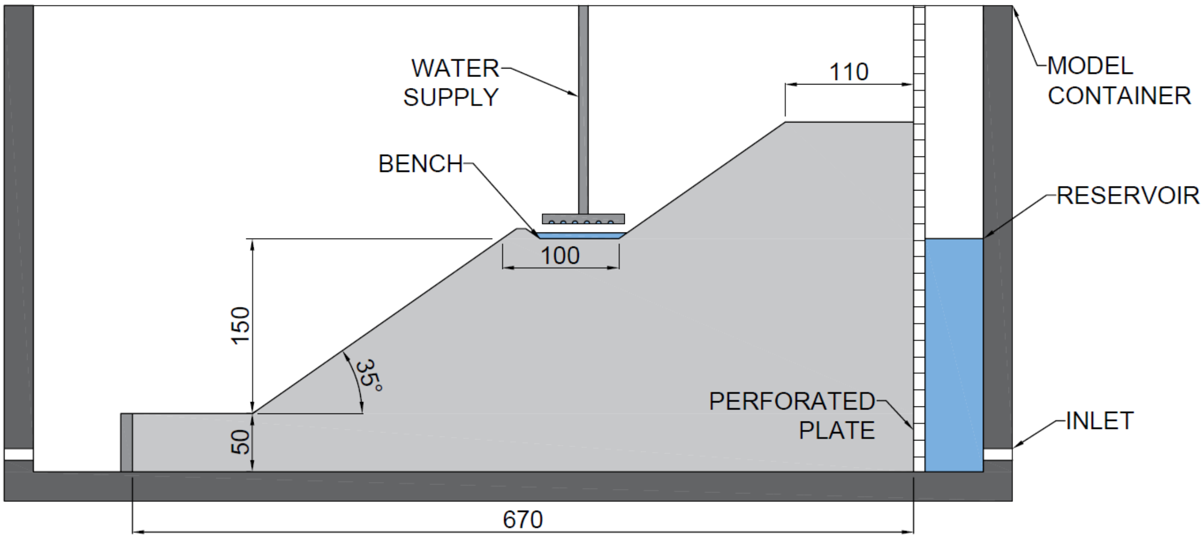

Figure 5. Centrifuge model modelling the meeting of two wetting fronts.

The general testing procedure will be similar to the other centrifuge tests described. Firstly, the centrifuge will be accelerated to 60 g. Once the model is at the design acceleration, the reservoir will be filled with water and the water table will be allowed to rise within the slope. As the water table nears the toe of the slope, the solenoid valve controlling discharge on the bench will be opened, allowing for water to pond on the bench. This will allow the water to seep downwards through the tailings slope. Once the downward migrating waterfront reached the existing water table, it caused an instantaneous increase in pore pressure throughout the entire slope, triggering the failure of the slope.

SUMMARY AND CONCLUSIONS

Traditionally, tailings dams have been designed and monitored assuming drained conditions using drained stability analyses. However, with the introduction of new global standards for tailings dam design and construction, the possibility of undrained triggers needs to be considered. For undrained failures to occur, a trigger is required to initiate undrained behaviour and hence failure. Four potential triggers that could induce liquefaction were introduced. Centrifuge tests designed to investigate the potential undrained triggers were presented and described.

The first undrained trigger and centrifuge test under consideration was the drilling of a borehole with overpressure caused from injecting water into the slope. The overpressure caused by the borehole drilling caused a localised increase in pore pressure, causing the effective stress and subsequently the shear strength to reduce. This localised liquefaction caused the soil at the bottom of the borehole to lose shear strength, triggering the failure of the slope.

The second undrained trigger and associated centrifuge test described was the loss of confinement at the toe of the slope. An overtopping event, like the event that triggered the Merriespruit tailings dam failure, can cause the erosion of material at the toe of the slope. This removal of material will result in a loss of confinement, triggering the failure of the slope. This loss of confinement will be simulated in a centrifuge test by providing confinement using a steel plate that will be rapidly removed using a pneumatic piston.

The third undrained trigger and centrifuge test discussed was the rapid construction of a buttress. Although buttresses are used to increase the stability of tailings dams, rapid construction may cause an increase in pore pressure. If construction takes place too quickly, the pore pressures generated can be large enough to trigger the failure of the slope. The design of a centrifuge test was described where a sand hopper was designed to rapidly deposit sand on the face of the slope, simulating the rapid construction of a buttress. The excess pore pressures caused by the deposition of the sand may be sufficient to trigger the collapse of the slope.

The final undrained trigger and centrifuge test discussed involves a downward migrating wetting front reaching the ambient water table. When this occurs, this might cause an instantaneous increase in pore pressure throughout the slope, which could trigger the failure of the slope. In the designed centrifuge test the water supply system of the centrifuge will be used to cause water to pond on a bench on the model slope. This will allow the water to seep downward towards the ambient water table. Once the waterfront reaches the existing water table, it might trigger the collapse of the slope.

It is believed that the centrifuge tests described will shed light on conditions under which catastrophic undrained loading of tailings slopes can occur in practice, thereby allowing such instability to be better understood.

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