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Lessons learnt modelling tailings dam flow-type failures in the centrifuge

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ABSTRACT: Internationally, the stability of tailings dams is under scrutiny due to the relatively high failure rates and the disastrous consequences of these events. Tailings dams have traditionally been designed assuming drained analyses, but it has become apparent that the possibility of undrained failure needs to be considered. A possible mode of failure of tailings dams is a flow type failure, possibly resulting from localised static liquefaction. These failure events are often costly, destructive, and deadly. The mobilization of undrained failure requires a trigger event. To study potential triggers and failure mechanisms of flow type failures of tailings dams, multiple centrifuge tests were conducted on model tailings dam slopes using gold tailings and a viscous pore fluid. Modelling tailings dam slope failures in the centrifuge has been found to be challenging and several practical challenges had to be overcome before a failure event was successfully modelled. These problems include the selection of an appropriate pore fluid, preventing the development of preferential flow paths leading to undesired piping erosion, oxidation of the tailings, and simply getting the viscous fluid to flow from a storage tank to the model. The paper discusses the lessons learnt during the development of a centrifuge model to study tailings dam failure events as well as the solutions to the problems encountered.

Keywords: physical modelling, modelling techniques, sample preparation and characterization, dam and embankments.

1 INTRODUCTION

The global mining industry is considered to be one of the largest producers of waste. Due to the expanding market for mineral commodities, mining activities has resulted in a proportional increase in mining waste (tailings). Due to the sheer amount of volume of tailings produced, tailings dams are constructed to dispose of the tailings. Due to the construction methods used to build tailings dams, these geotechnical structures are often susceptible to flow type failures, too often resulting in catastrophic environmental and economic damage and major loss of life.

Despite the frequency of these failures, the failure mechanisms and associated trigger events are often hypothesised based on post-failure investigations and eye-witness reports, with few of these events being captured on record. To better understand the failure mechanisms and potential triggers, multiple centrifuge tests were conducted on model tailings dams using gold tailings and a viscous fluid. Successfully modelling a failure event was found to be challenging. The objective of this paper is to describe the difficulties encountered during the centrifuge modelling of tailings dam failures and the solutions to solve these problems.

2 GENERAL CENTRIFUGE PACAKGE

The centrifuge tests were conducted at the University of Pretoria (Jacobsz et al., 2014). The model tailings dams were constructed in a model container using gold tailings obtained from a gold mine near Johannesburg, South Africa. The model slopes were constructed using moist tamping, creating a contractive fabric to maximise liquefaction potential. Fig. 1 shows a side view of the centrifuge package used in the tests, along with the dimensions of the model slopes. The slopes were constructed at a 35° angle, near the friction angle of the tailings, to create marginally stable slopes, which increases chances of inducing instability. A perforated plate covered by geotextile was installed immediately upstream of the model slope, creating a reservoir in which the pore fluid level upstream of the model slope could be maintained. Once the model slope was prepared, the model was accelerated to 60g. Once at the design acceleration, a viscous fluid was used to fill the reservoir, providing the required hydraulic head upstream of the slope. The viscous fluid then seeped into the model slope, resulting in the development of the phreatic surface.

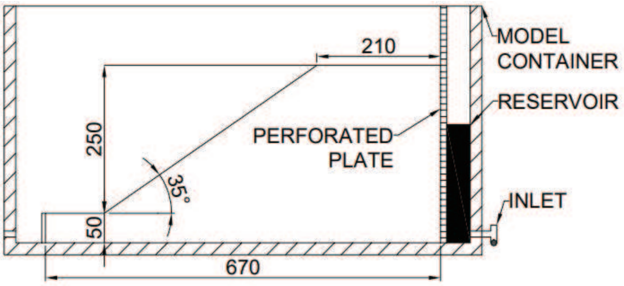

Fig. 1: General centrifuge package.

3 SELECTION OF AN APPROPRIATE VISCOUS FLUID

Centrifuge modelling requires various scaling laws to be satisfied. To study post liquefaction behaviour, a fluid *N* times more viscous than water is also required (Zhang and Askarinejad, 2021). However, to study the onset of static liquefaction, a fluid $\sqrt{N}$ times more viscous than water should be used. Irrespective of which viscosity is chosen when designing a centrifuge test, a viscous fluid is necessary when studying flow type failures.

Initially carboxymethylcellulose (CMC) was chosen to increase the viscosity of water (1 mPa.s), as it has been widely adopted in centrifuge modelling (Dewoolkar et al., 1999; Stewart et al., 1998; Zhang, 2006; Zhang and Askarinejad, 2021). To determine the concentration of MC required to prepare a fluid with the design viscosity, different concentrations of CMC were added to water. The viscosity of each mixture was measured at 25°C using a rheometer. In addition, the viscosities were measured at different shear rates (s^{-1}). Fig. 2 shows the viscosities of the CMC-water mixtures at different concentrations and shear rates. At a specific concentration, the viscosity of the mixtures become with shear rate dependent, meaning that the CMC-water mixtures are non-Newtonian fluids (i.e. viscosity changes with applied stress rate). This is not desirable in tests where significant shear rates are expected, e.g. in this case flow-type failures of model slopes.

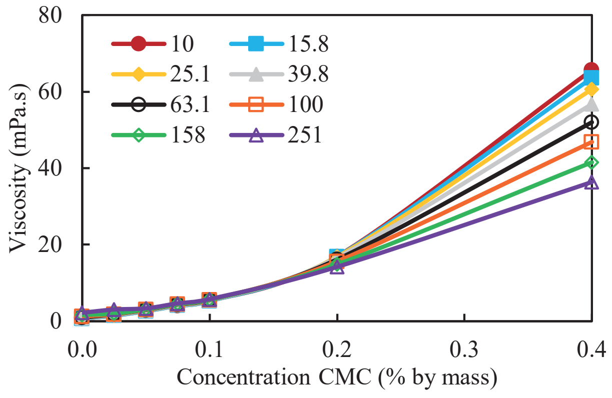

Fig. 2: Viscosity of CMC-water mixtures at different concentrations at various shear rates.

In addition, further challenges were encountered using CMC-water mixtures. An initial centrifuge model test was conducted using an CMC-water mixture with a viscosity of 60 mPa.s measured at a shear rate of 10 s^{-1}. Initially when the water level was raised in the reservoir, the viscous fluid seeped into the model slope without any indication of problems. However, after a few hours the inflow stagnated with no further changes in the fluid levels in the slope and the upstream reservoir. Upon excavation of the model, the tailings at the water table was found to have a rubber-like textures, clogging the tailings body from further inflow. It is hypothesised that as the CMC-water mixture seeped into the slope, the concentration of CMC at the wetting front increased due to osmosis effects. This caused the viscosity of the fluid to increase, ultimately creating a rubber like membrane in the slope, preventing the fluid to seep further into the slope.

Following these challenges the pore fluid was substituted with glycerine-water mixtures. Like the CMC-water mixtures, glycerine was mixed with water at different concentrations and the viscosities of the mixtures were measured at various shear rates using a rheometer. Fig. 3 shows the viscosities of the glycerine-water mixtures at different shear rates. In contrast to the CMC-water mixtures, the glycerine-water mixtures are Newtonian fluids (i.e. viscosity is independent of the stress or shear rate). Glycerine-water mixtures were therefore adopted for subsequent centrifuge tests.

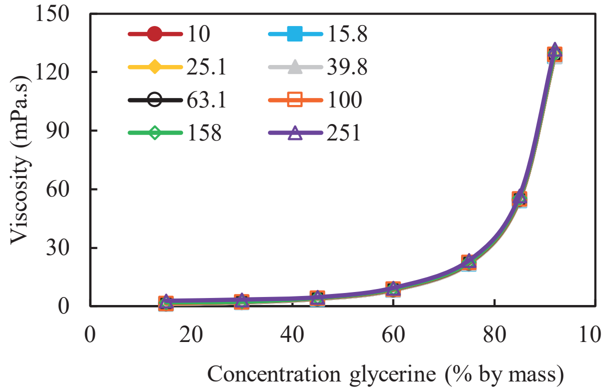

Fig. 3: Viscosity of glycerine-water mixtures at different concentrations at various shear rates.

4 PREFERENTIAL FLOW PATHS

During initial tests, preferential flow paths formed at the boundaries between the model container and the model slopes. This was due to the granular particles of the tailings not being able to embed into the aluminium or acrylic walls of the container. As a result, the preferential flow paths caused internal erosion (piping) due to the significant hydraulic gradients (see Fig. 4).

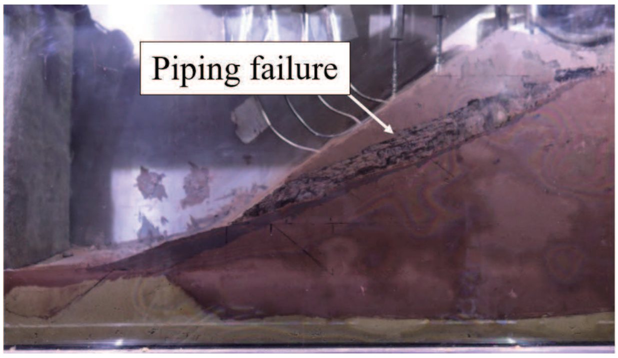

Fig. 4: Piping failure of model tailings dam due to preferential flow path.

As a piping failure is undesirable when studying triggering mechanisms of flow type failures, a system was developed to prevent preferential flow paths from forming along the boundaries between the model slope material and the model container. The bottom surface of the model container was coated with a thin layer of silicon sealant, allowing the tailings particles to embed into the bottom surface of the container. This prevented preferential flow paths from forming along the bottom boundary.

To prevent preferential flow along the vertical boundaries of the model container, two measures were devised. Firstly, aluminium baffles were installed upstream of the model slope (see Fig. 5) to increase the flow path length and to force the fluid to flow away from the vertical boundaries towards the interior of the slope. Secondly, a graded sand filter was placed immediately upstream of the slope, with a coarse sand zone against the reservoir and a fine sand zone separating the coarse sand and the tailings slope. The purpose of the sand filter was to allow for the fluid to first seep evenly through the sand before reaching the model tailings dam slope, minimising the potential for internal erosion in the model slope as concentrated ingress is likely to result in internal erosion (Zhang, 2006; Ng et al., 2022).

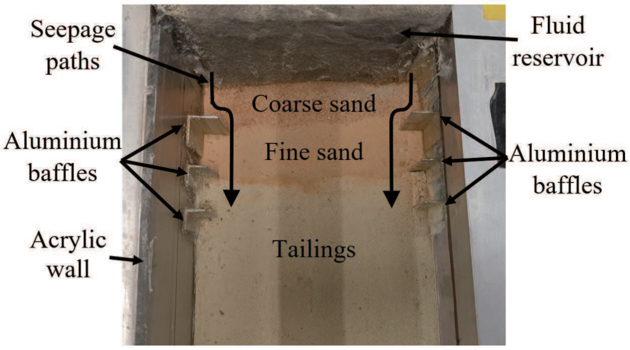

Fig. 5: Upstream view of model slope with aluminium baffles, sand filters and acrylic wall.

5 OXIDATION OF TAILINGS

During initial centrifuge tests it was observed that cracks formed between the model slopes along the aluminium walls of the model container. Upon inspection it was observed that the tailings oxidised against the aluminium (see Fig. 6), forming a thin, hard layer against the aluminium. Tailings is treated with chemicals during the mineral extraction process and it is hypothesised that some of the caused the aluminium to oxidise.

As the models were accelerated, the slopes settled due to the increased acceleration However, the rough oxidised interface did not settle, creating differential settlement, which created cracks along the length of the slopes.

Fig. 6: Oxidised aluminium container

To prevent the tailings from reacting with the aluminium, a 5 mm thick acrylic panel was placed along the aluminium wall of the model container. To prevent preferential flow paths from forming between the acrylic panel and the model container, the panel was attached to the container with silicon sealant and all the gaps were sealed with sealant.

6 SUPPLY OF FLUID TO MODEL

A fluid storage tank was placed at an elevated location in the instrumentation cabinet on top of the centrifuge. The cabinet rotates with the centrifuge. Due to space considerations, the tank had to be placed slightly off-centre from the axis of rotation. The viscous fluid was fed to the model container using a 6mm (ID) PVC tube. A solenoid valve placed along the tube enabled the fluid level reservoir in the model container to be controlled manually. The fluid level in the model container was monitored using a pressure transducer. During initial proof tests it was found that, despite the elevation of the tank, only a small amount of fluid flowed to the model before the flow stopped.

Consideration of the centripetal acceleration field is important in deciding the routing of the fluid discharge tube. The fluid pressure in the storage tank and discharge tube can be studied using the equations for a forced vortex. Consider the forced vortex (parabolic water level) in a rotating tank subjected to an angular velocity ω. The variation in the vortex' water surface profile, dH, can be calculated using:

$$dH/dr = (2\omega^2 r)/g \qquad (1)$$

where dr is the change in radius and g is gravitational acceleration. The distribution of potential with radial distance can be calculated using integration as:

$$H = (\omega^2 r^2)/2g \qquad (2)$$

The total head is the sum of the pressure head $\left(h_p = p/\rho g\right)$ and velocity head $(h_v = v^2/2g)$, so that, from Equation 2, the pressure head distribution is described by $h_p = (\omega^2 r^2)/2g$. This equation describes the fluid depth in an open rotating cylinder above the fluid depth at the centreline. The viscous fluid tank used in the experiments measured 0.3 x 0.3 x 0.6m high and was placed in the instrumentation cabinet above the centrifuge with the two side walls between radial distances of 0.3m and 0.6m from the centre of rotation. An angular velocity ω = 14 rad/s is required to provide an acceleration of 60 g at a radial distance of 3m (the radius of the centrifuge). At a radial distance of 0.3m from the centre of rotation the acceleration is 6g, increasing linearly to 12g at 0.6m. With a tank not full and only 1g acting downward, the fluid surface will not merely slant outward, but all fluid will be pushed against the outer sidewall of the tank. (For a full tank, the associated pressure head at a radial distance of 0.3m from the centre of rotation is 0.9m, increasing quadratically to 3.6m at a radial distance of 0.6m.) To ensure free drainage, the tank outlet must therefore be in the outer tank wall. The tube to the model must be routed so that the radial distance measured from the centrifuge rotation axis to any point on the tube monotonically increases with distance from the tank, if the tank is not pressurised. If not, difficulties may be experienced to drain the fluid from the tank to the model.

7 CONCLUSIONS

A series of centrifuge tests were conducted to study failure mechanisms of tailings dam slopes. Several had to be addressed before a successful failure event was modelled:

1. The widely used CMC is shown to be a non-Newtonian fluid, which raises the concern about scaling the viscosity of an appropriate pore fluid during a failure event. Furthermore, at the concentrations used the CMC-water mixtures appeared to clog the tailings matrix comprising the model slopes, preventing seepage. A glycerine-water mixture was adopted as the viscous fluid for subsequent tests.
2. Preferential flow paths caused piping failure of the model slopes. To prevent preferential flow along the model boundaries, a layer of silicon sealant was applied to the bottom boundary of the container, aluminium baffles were installed upstream of the model slope to increase the flow path length along the model boundary and a graded sand filter was placed between the fluid reservoir and the model slope. This allowed the fluid to seep into the slope, preventing piping failure.
3. Chemicals in the tailings caused the aluminium to oxidise, resulting in undesirable boundary effects. An acrylic panel was installed in the model container to prevent the tailings from reacting with the aluminium.
4. When using a tank mounted near the centre of the centrifuge supplying fluid to the model, the tank outlet must be on the outside tank wall and the tube to the model must be routed with radial distance increasing continuously if the tank is not pressurised. If not, difficulties may be experienced to get the entire content of the tank to flow to the model.

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