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Advances in dam breach analysis appropriate for dewatered tailings storage facilities

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Abstract

Dam breach analysis is an instrument that allows owners and designers to assume a failure of the tailings storage facility (TSF) and estimate its impact. The International Council of Mining & Metals recommendation is to base a breach analysis on credible failure modes. Historically the techniques to undertake dam breach analysis have been extrapolated from the water dam industry, assuming that tailings flow like water (i.e. a Newtonian fluid). Nevertheless, hydraulically deposited tailings may be more likely to present non-Newtonian behaviour. In addition, dewatered tailings constitute an additional layer of complexity in tailings flow properties. For example, dewatered tailings are more likely to develop particle-to-particle interaction, and hence, dilative and contractive properties of tailings are expected to play a more significant role during a potential dam breach.

The last decade has seen the flourishing of non-Newtonian techniques and numerical packages. These techniques can better estimate the potential impact of non-Newtonian flows and have resulted in improved breach analysis for conventional TSFs. This study presents the results of a dam breach analysis applicable to dewatered tailings using the mud farming technique. The TSF is a project located in northern Australia. Mud farming was adopted to construct a structural zone upstream of the conventionally built embankments. To investigate the credible failure modes, runout, and loss of freeboard estimation, an emerging technique called the material point method was applied to capture large deformations such as those seen during dam breaching.

Keywords*: mud-farmed tailings, dam breach, liquefaction, tailings, consequence classification.*

1 Introduction

Tailings are waste produced in the mining industry with traditional limited financial value but that can constitute considerable risk to humans and the environment. As such, tailing storage facilities (TSF) are designed for the safe deposition and storage of these materials. Unfortunately, serious and very serious failures of TSFs have increased since 1960, inflicting losses of lives and significant environmental damage (Bowker & Chambers 2015). The upward trajectory of serious TSF failures highlights the need for improvements in the current procedures of tailing dam design and tailings dam breach analysis (TDBA).

Current procedure for design of tailing dams and TDBA relies heavily on the past failures of water retaining dams and extrapolated water dam techniques. These techniques generally apply fluid mechanics concepts and disregard particle-to-particle and particle-to-fluid interactions (Canadian Dam Association 2021). However, particle-to-particle interactions control the behaviour in some tailings (especially when the solid concentration is above 55% by volume). Tailing flows might exhibit highly unsteady flow where standard fluid mechanics concepts do not apply to them. Nevertheless, some practitioners assume that using fluid mechanics and treating tailings like water would lead to more conservative results. This assumption may need to be revised. Modelling tailings like water usually leads to results with low depth and big inundation footprint. The risk profile of such a scenario is radically different from that of several metres thick of displaced tailings and a much smaller footprint near the toe of a TSF, where mining infrastructure is often located (Llano-Serna 2023).

The last version of technical bulletin of the Canadian Dam Association suggests geomechanical numerical methods based on continuum mechanics for unsteady non-Newtonian tailing runout analyses (Canadian Dam Association 2021). These numerical methods are currently being developed and are an active area of research.

The United States Society on Dams (2022) *Guidance on Numerical Modelling* highlights some of the frameworks available for non-linear deformation analyses in dams. These frameworks are generally based on continuum mechanics and apply non-linear constitutive models to capture the response of various materials. United States Society on Dams (2022) mentions common geotechnical tools (e.g. PLAXIS and FLAC) for performing nonlinear deformation analyses that can model dam dynamic motion and soil plastic deformations.

Common geotechnical software (e.g. PLAXIS and FLAC) have important capabilities but also challenges. They are well-tested software based on the finite element method or finite difference method created specifically for geotechnical design. As such, they have advanced constitutive models for capturing the different behaviours of tailings and tools to perform different types of analyses. They can also be used to replicate complex construction sequences. A significant weakness of these software packages is their inability to model large deformations as seen during dam breaches.

The use of material point method (MPM) is relatively new in geotechnical engineering. Nevertheless, it has proved its capability and importance. United States Society on Dams (2022) points to the previous application of MPM for tailings runout analyses and highlights MPM as a numerical method with the potential to be used in large deformation analyses. Llano-Serna et al. (2016), Soga et al. (2016) and Yerro et al. (2019) provide details about the use of MPM in runout analyses and large deformations. Tran et al. (2023) and Seyedan & Sołowski (2021) highlight further potentials and capabilities of MPM in investigating runout analyses. Robertson et al. (2019) applied MPM to model the Brumadinho dam failure in Brazil. Pierce (2021) studied the Cadia failure using MPM techniques. Kafash & Cerna-Diaz (2023) used MPM to analyse the slump runout distance of TSF failure.

This work presents the results of investigations by the authors to study breach scenarios for an upstream TSF in Australia. The TSF includes a structural zone built with mud-farmed tailings. The study explores the effects of key failure modes, such as the breaches in the dam caused by weakness in the foundations of the dam. The need for these investigations was identified in previous studies including the failure modes and effects analysis. These scenarios included the reduction of the strength of materials that could lead to dam instability. The work used the MPM-based software Anura3D for performing its analyses although the analyses completed are 2D sections.

2 Site background

This work investigated a TSF in northern Australia built using the upstream method. The TSF is located in a tropical monsoonal climate with wet and dry seasons and over 2 m of annual rainfall. Each year, approximately 9–10 million dry tonnes of tailings are deposited into the TSF. Tailings are released into the TSF via a series of spigots positioned at regular intervals. The starter dam was completed in 2018 and has stored tailings and decant water throughout its operational lifespan. It consists of about 1,000 hectares of ‘paddock type’ impoundment, surrounded by embankments and has no upstream catchments. The perimeter walls vary in height from 0 to 12 m, with a downstream batter of 2.5H:1.0V and an upstream batter of 2.0H:1.0V. The first upstream raise was built in 2022. The life of facility (LOF) considers there would be 13 embankment raises upstream of the starter embankment. Each lift is planned to be 2 m high. Figure 1 shows a simplifed section in this TSF for the LOF stage.

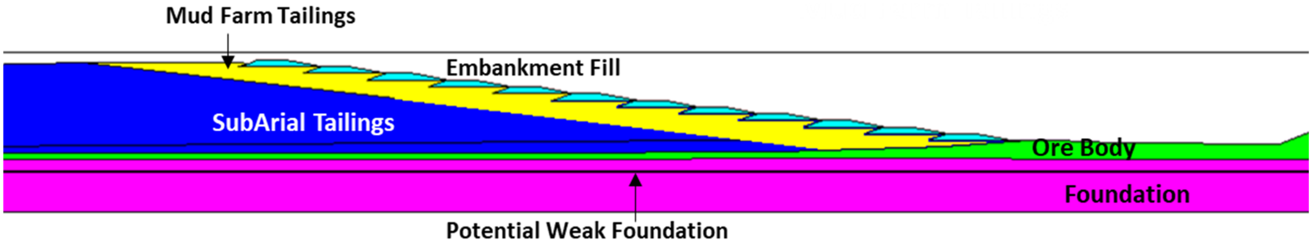

Figure 1 Typical section in the tailings storage facility

2.1 Mud farming

Construction of upstream tailings dams are sensitive to the strength of the underlying tailings. Rock filling is a common way to increase foundation strength for upstream rise when the strength of the existing tailing is low (Smirk & Jackson 2010). This approach is effective costly. In situ dewatering is another practical way to increase the strength of tailings that develop high strength at high density. Conventional methods for dewatering (e.g. drainage) are not always suitable, can restrict access, can be costly, and can delay operations. Due to these limitations, alternative techniques have been developed. One such technique is mud farming, which involves mechanical consolidation to accelerate the dewatering and consolidation of tailings (Munro & Smirk 2018).

Mud farming is the practice of ploughing and harrowing fine tailings using mechanical equipment. It improves tailings management by increasing the density and strength of tailings and reducing the disposal footprint and surface dust generation (Smirk & Jackson 2010). This method evolved from the alumina industry and has been adopted in other industries (Munro & Smirk 2018). Efficient mud farming is usually carried out when 0.8 m deep deposited tailings have shear resistance between 15 to 25 kPa and 60 to 65% of solid content (Cabrera 2020).

The TSF investigated in this site uses mud farming to increase the density and strength of deposited tailings. The high concentration of the solid content in the mud-farmed tailings means that particle-to-particle interactions are significant within the tailings. As such, conventional methods using Newtonian and non-Newtonian rheological formulations present significant drawbacks. The TDBA for this site was considered using large deformation geomechanical numerical methods.

2.2 Foundation

In the site, a kaolinite zone exists beneath the orebody. This zone can be divided into two subgroups: fine grains dominated and granular dominated. These materials are all referred to as ‘foundation’. Extensive cone penetration testing (CPTu) revealed a distinctly voided materials within the foundation. These voided materials are identified in discrete pockets of the foundation. Lines et al. (2023) provide details of a comprehensive soil investigation performed to describe the mechanical behaviour of this potentially weak layer.

3 Material point method framework

This work applied MPM to develop potential dam breach scenarios. MPM has its origins in the nineties. Sulsky et al. (1994, 1995) extended the previously known ‘particle in cell’ numerical method to introduce MPM. MPM is based on continuum mechanics. It can use different constitutive models for capturing the complex behaviour of tailings. MPM is efficient for large deformations and displacement calculations since it does not suffer from mesh distortion. These characteristics makes MPM a suitable method for conducting TDBA of dewatered tailings since it can capture particle-to-particle and particle-to-fluid interactions.

The ongoing developments of MPM improve the method’s accuracy, versatility, and usability (Sołowski et al. 2021). The MPM conventional algorithm ensures the conservation of mass and momentum in calculations. In each step, the algorithm employs a background grid to solve the equation for the conservation of momentum. Then, MPM algorithm saves the time-dependent data on material points and resets the background grid.

This work has employed Anura3D (an MPM engine) to develop TDBA estimates. Anura3D was designed to model large deformation processes. It was developed by an active group of MPM researchers from leading universities. It can employ structured and unstructured meshes. Anura3D provides several constitutive models for capturing soil behaviour and different integration schemes. It works within a practical computer-aided design platform that allows the creation of relatively complex geometries.

Anura3D and other MPM-based programs have important weaknesses. Existing MPM software packages are mainly research-based and do not yet have the powerful and well-tested base of common geotechnical software (e.g. PLAXIS and FLAC3D). Other limitations include difficulties in replicating different stages of construction's history which makes capturing the triggering of the instability challenging. Assumptions based on engineering judgment are often needed to overcome some of these challenges.

Anura3D does not support multi-threading, which means that it cannot execute multiple threads simultaneously. As such, it is not suitable for calculations with a large number of material points that require parallel processing. Although some other MPM software (e.g. MPM-PUCRio and Uintah) can perform multi-threading. This work used Anura3D since its computer-aided design platform was essential for preparing the section geometries.

4 Material point method modelling

4.1 Studied cases

This work investigated different scenarios using MPM. These models used unstructured triangular elements with about 1 m mesh size. The simulations used three material points per element and were initialised to reach a static state. The calculations considered the application of residual strengths for materials. Fern & Soga (2016) demonstrated how this assumption results in conservative estimates. Table 1 presents the parameters used in all the simulations of this investigation.

Table 1 Parameters used in all the simulations

Parameters	Residual friction angle (°)	Residual undrained shear strength ratio	Porosity	Dry density (kg/m^3)	Young's modulus (Mpa)	Undrained Poisson's ratio
Mud-farmed tailing	25	–	0.33	1,501	1.7	0.49
SubAerial tailings	–	0.13	0.39	1,321	1.7	0.49
Weak foundation	–	0.06	0.55	1,055	1.7	0.49
Foundation	6.3	–	0.6	1,546	3	0.49
Sensitive tailings	–	0.1	0.47	1,180	1.7	0.49
Orebody	22	–	0.33	1,546	3	0.49
Embankment fill	24	–	0.3	1,535	3	0.49
Bulk fill	24	–	0.3	1,535	3	0.49

4.1.1 Column collapse modelling

The total released volume during a dam breach depends on the volume of the supernatant pond during the failure, the release of eroded tailings during the discharge of the supernatant pond, and the runout of liquefied tailings in cases liquefaction of tailings is possible (Canadian Dam Association 2021). This work used MPM to estimate the volume of released tailings for this method using the post-failure beach geometry, cone of depression (Figure 2). The column collapse problem has received attention from several researchers because it is a numerical abstraction of a dam collapse that allows focusing on the mechanical properties of tailings. An advantage of using MPM for performing cone of depression calculations is the possibility to include complex tailings layering.

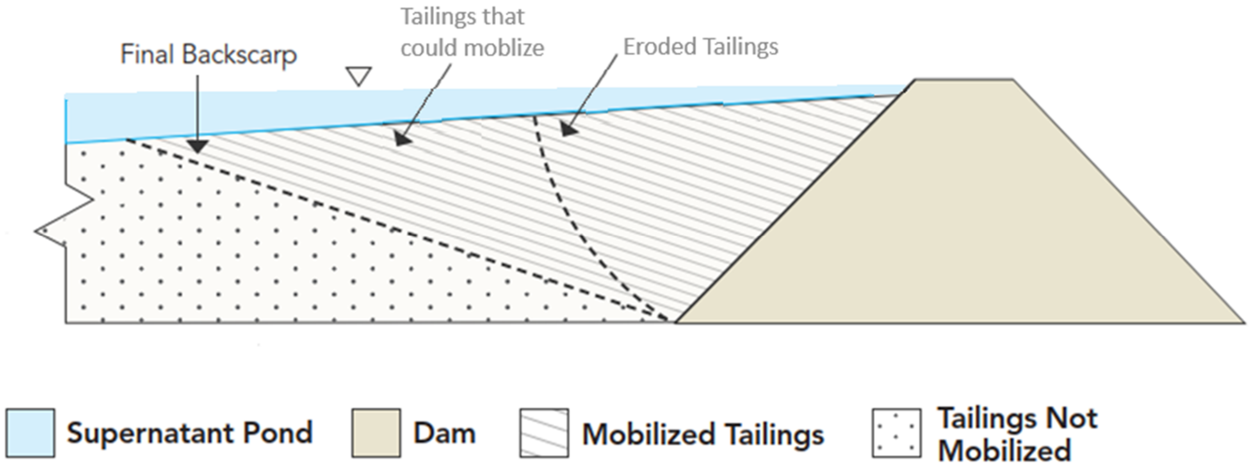

Figure 2 Cone of depression concept within a tailings storage facility (Canadian Dam Association 2021)

To perform such assessments, column collapse models were solved using the material properties presented in Table 1. Figure 3 presents a column collapse model adopted herein with a complex tailing layering. The height of the column in this figure replicates the maximum tailings depth expected during the LOF. The example shown in Figure 3 is hypothetical and does not represent the model used for the project.

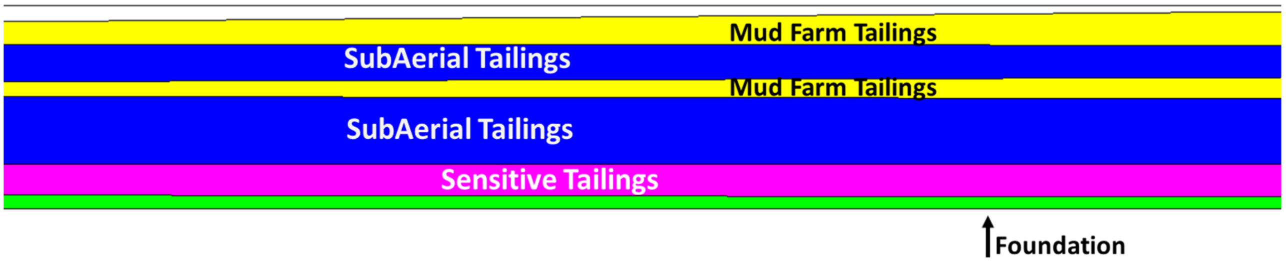

Figure 3 An example of column collapse modelling

A mesh sensitivity analysis was also performed using the column collapse calculation. This analysis used three different mesh sizes of 0.5, 1, and 2 m mesh and compared their runout distances. The analysis indicated that the mesh of 1 m size used in this work results in adequate outcomes.

4.1.2 Weak foundation modelling

A distinctly voided foundation was identified as a potential weak layer that resulted in a credible failure mode. MPM modelling was used to investigate the possible triggering effect of a failure due to residual strengths being mobilised within the weak foundation. The body of work included several calculations in two-dimension for various critical cross-sections and different stages during the dam life span. Figure 4 shows one of these critical cross-sections.

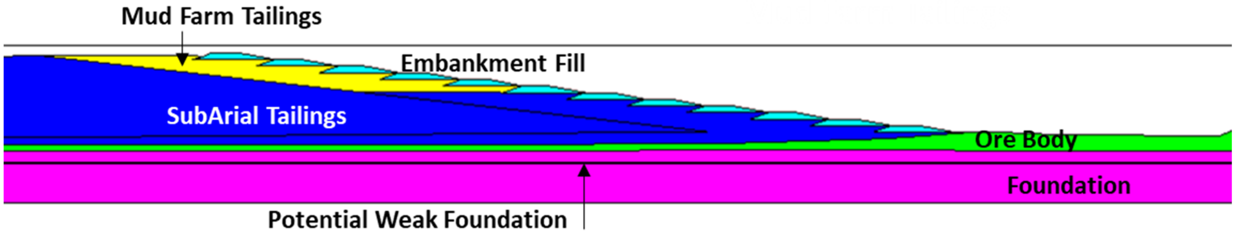

Figure 4 Critical cross-section with a weak layer in the foundation

4.2 Results and discussion

4.2.1 Results of column collapse modelling

Figure 5 displays the results of an MPM calculation performed on a 32 m tall tailings column. See Figure 3 for the initial configuration of the column collapse. The figure plots the deviatoric strain colour map, which can display approximately the location of the failure surfaces. Red shadings indicated failured regions. The result of this calculation estimates a runout distance of 270 m and a post-failure slope of roughly 3.9°.

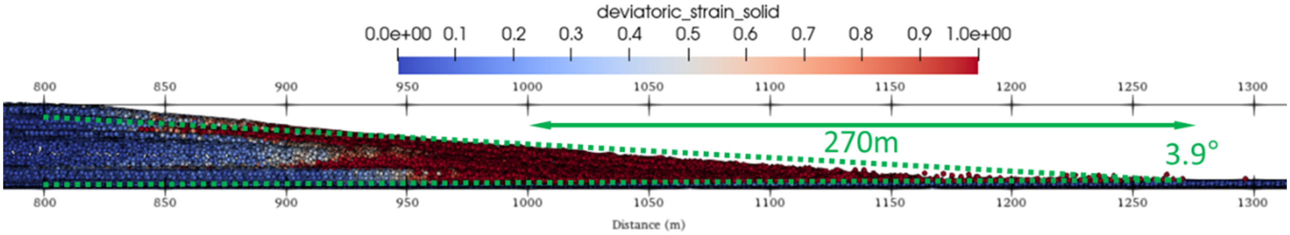

Figure 5 Column collapse of a 32 m tall tailings column with interbedded mud-farmed and subaerial deposited tailings

The column collapse calculations establish that the height of collapse affects the runout distance and depression angles. Higher collapse height leads to longer runout distances and greater depression angles because of higher stresses and accompanying shear resistance. Table 2 shows the historical records of the cone of depression angles reported in the literature. The results of the column collapse calculations in this work using MPM are consistent with these historical records.

Table 2 Summary of the surface slopes observed after flow failures in tailings impoundments, based on Blight & Fourie (2003)

Tailings dam	Post-failure surface slope
Bafokeng	4°
Bafokeng	2°
Arcturus	3°
Saaiplas after rain	3°
Saaiplas no rain	2.3°
Saaiplas no rain	3°
Merriespruit flow slide	1.1°
Merriespruit failure basin	2°

The results of the column collapse calculations were used to calculate the total released volume during a dam breach and complemented other failure mode scenarios.

4.2.2 Results of weak foundation modelling

Several MPM calculations explored the mobilisation of residual strengths in the weak foundation and its possible triggering effects. Figure 6 displays the horizontal displacement colour map for one of the critical cross-sections in the TSF. This figure shows that the maximum horizontal displacement is 45 m and that the displacement colourmap extends around 60 m upstream of the TSF. This information is key because it helps to inform pond operational levels and management during a potential breach scenario.

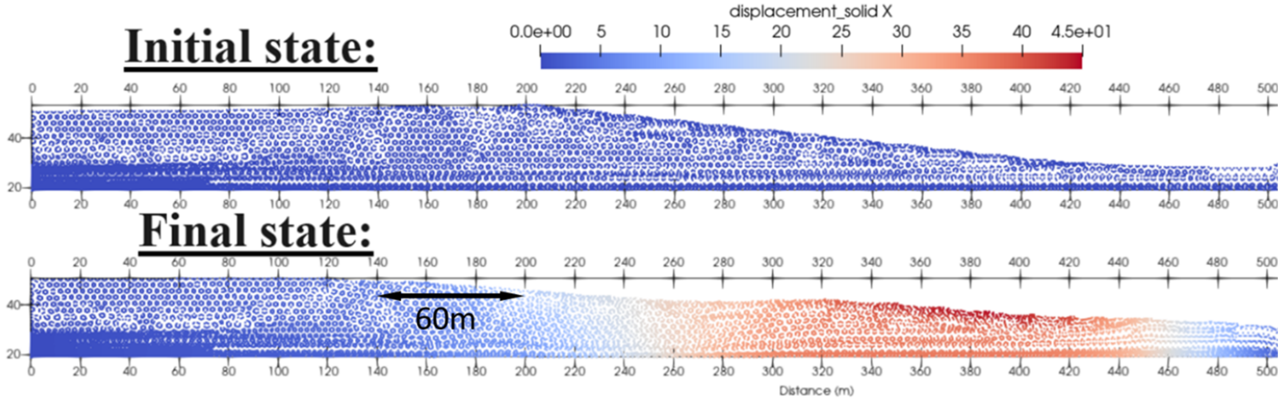

Figure 6 Maximum runout

Figure 7 displays the vertical displacement colour map for the same critical cross-section in the TSF. This figure shows a 10 m loss of freeboard in the dam body. The figure also reveals that at around 60 m upstream from the dam crest the loss of freeboard is negligible.

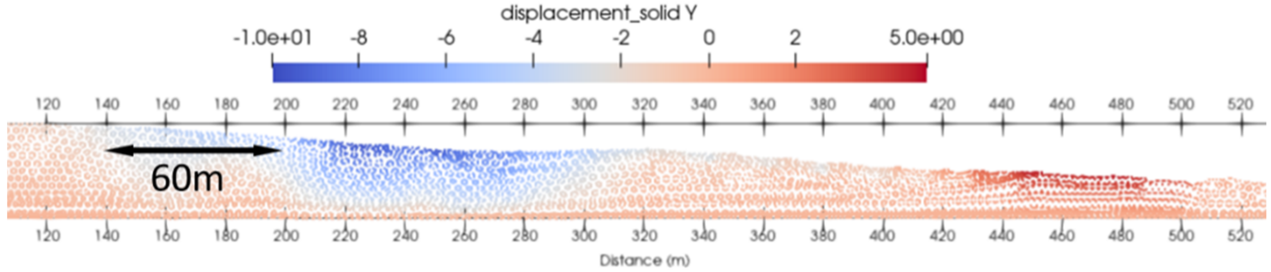

Figure 7 Loss of freeboard

Figure 8 displays a colour map of the deviatoric strain to identify the locations of the failure surfaces. Red shades indicate failed zones whereas blue shades indicate intact regions. The figure shows the high deviatoric strains are concentrated in the dam face and within the weak layer. In this figure, the failed part of the weak layer is highlighted with a dashed green rectangle. Further investigation showed that the initial displacements in the face of the dam would create a failed zone in the weak layer that leads to further deviatoric strains and displacements in the tailings of TSF.

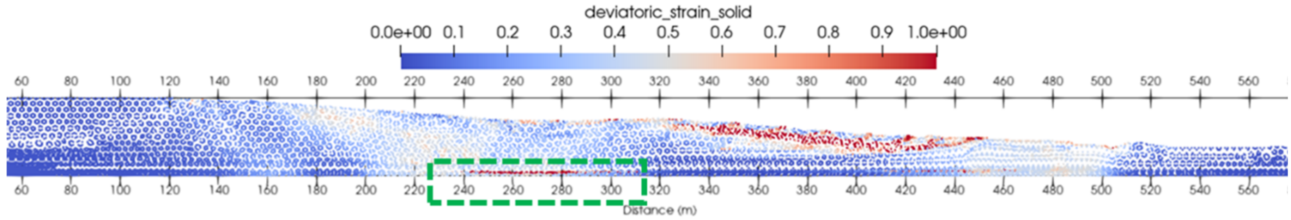

Figure 8 Deviatoric strain colourmap

The results from the analysis were used to estimate the potential loss of freeboard and to predict the possible loss of containment from the pond. Estimates were used to provide valuable information for risk management.

5 Conclusion

This work presents the results of a dam breach analysis for a TSF in northern Australia with a mud-farmed tailings structural zone. The work used MPM, a relatively new method in geotechnical engineering. MPM allows for efficient dam failure modelling of dewatered TSFs, the technique fulfils the requirement set by the most recent technical bulletin of the Canadian Dam Association. MPM has also been highlighted in the guidance of the United States Society on Dams and is increasingly being adopted by engineers and researchers for conducting tailings runout analyses.

The work used Anura3D (an MPM engine) to develop TDBA for breaches in various two-dimensional critical sections of the dam and to investigate potential weaknesses in the dam's foundations. The method was also used to calculate the cone of depression for a complex geology and the results are shown to be aligned with historical records. The results were used to estimate tailing runout, potential loss of freeboard, and predict the possible loss of containment from the pond.

Connecting conventional geotechnical software to MPM engines is crucial for future development. Currently, available MPM engines, including Anura3D, cannot accurately replicate complex stages of construction history, making it challenging to capture the triggering of instability. This work has used assumptions based on engineering judgment to overcome this challenge (e.g. use of residual strengths for materials and simplification of geometries).

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