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Dam breach analysis of a closed facility using the Material Point Method

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Abstract

The Global Industry Standard on Tailings Management *(GISTM) has become a critical benchmark for tailings storage facilities (TSFs), driving mining companies to ensure compliance. This push intensified following the Brumadhino TSF failure with GISTM emphasising the need for accurate dam breach analysis (DBA) to assess potential risks, even after closure.*

Traditional DBA models use rheological properties to characterise the flowability of tailings. However, due to high solids concentrations in closed TSFs, these models might not be representative. Tailings behave more like solids as saturation decreases after closure. Conventional DBA models may overestimate runout distances and underestimate inundation depth, potentially leading to costly, unnecessary mitigation and misallocation of resources.

The Material Point Method (MPM) is one of the techniques recommended by the Canadian Dam Association (CDA 2021) for conducting DBA. It incorporates geotechnical material properties and can be applied to closed facilities, potentially providing more realistic runout estimates. Additionally, MPM is capable of accounting for flow resistance from the embankment, unlike conventional approaches.

This paper presents a case study of a closed TSF using MPM, integrating credible failure modes from the failure modes and effect analysis and residual strength parameters to trigger runout. Additionally, a probabilistic sensitivity study was carried out to account for material strength variability to capture runout behaviour even under extreme conditions. The findings demonstrate that even with unrealistically low strength values for tailings, embankment, foundation and dam materials, the predicted runout distances are limited.

Insights from these models could optimise closure planning, inform more practical post-closure strategies, and improve understanding of failure impact potential. The results demonstrate that dam breach likelihood and tailings runout are highly sensitive to material strength assumptions, with full breach only occurring under extremely low-probability scenarios. Even in these cases, runout distances remained limited, highlighting the ability of the MPM approach to produce more physically representative outcomes, even under extreme conditions. These findings support a risk-informed framework for emergency preparedness and resource allocation, enhancing compliance with GISTM and promoting safer, more sustainable tailings management practices.

Keywords: *Material Point Method, dam breach analysis*

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1 Introduction

The recent catastrophic failures of tailings storage facilities (TSFs) – such as Brumadinho, Samarco, Mount Polley, and Cadia – have catalysed a shift in the mining industry toward more robust tailings governance. In response, the *Global Industry Standard on Tailings Management* (GISTM) was introduced, emphasising a transition from a traditional compliance-based approach to a risk-informed framework (International Council on Mining and Metals 2020). Under this framework, TSFs must be designed, operated, and closed based on the potential consequences of failure, not merely the probability of occurrence. Notably, GISTM is applicable to all TSFs – active, inactive, and closed – irrespective of age or operational status.

A cornerstone of this risk-based framework is DBA, which evaluates the potential impacts of TSF failure under credible scenarios. DBA supports TSF classification and emergency planning by estimating runout extent, inundation depth, and travel time (United States Society on Dams [USSD] 2015). However, conventional DBA models often treat tailings as fluid-like materials using rheological or empirical flow models – an approach that can be reasonable for active TSFs with high water content and surface ponds. For closed facilities without surface ponds, where desiccation reduces tailings moisture content, this assumption becomes invalid. The tailings in such facilities behave more like granular solids, and traditional water-based models may significantly overpredict runout distances and underpredict inundation depths, leading to mischaracterisation of downstream risk.

To address this limitation, MPM has gained prominence as a next-generation tool for simulating TSF breaches. MPM allows for simulation of both solid-like and fluid-like material behaviour, making it uniquely suited for modelling the transitional behaviour of tailings. Recognised by the USSD (2022) and recommended by the National Academies of Sciences, Engineering, and Medicine (NASEM 2021) for simulating soil liquefaction and large deformations, MPM is increasingly used in complex geotechnical applications. Recently, the CDA (2021) also endorsed MPM as a suitable method for dam breach modelling, citing its capability to simulate breach initiation and post-failure flow with a foundation in engineering mechanics.

Over the years, MPM has gained popularity in the field of DBA, particularly for modelling sunny-day failure scenarios. One of the earliest applications of MPM for DBA used the method to simulate a hypothetical TSF failure and demonstrated its advantages over conventional approaches (Zabala et al. 2011). More recently, Anura3D (2022), an MPM-based software, was applied to model the Brumadinho disaster and identify the mechanisms controlling tailings runout (Robertson et al. 2019). The same software was also used to simulate the Cadia TSF breach, offering insights into the factors influencing the extent and nature of post-breach flow (Pierce 2021).

This paper presents a case study of a closed TSF in Australia, where MPM was used to simulate the outcomes of a combination of credible failure modes that had been identified through a failure modes and effects analysis (FMEA). A sensitivity analysis was conducted by defining a series of breach scenarios using strength parameters that were probabilistically varied to reflect uncertainty in embankment material properties. This analysis included five scenarios, ranging from most probable to least probable, in alignment with the risk-based approach promoted by GISTM. While it could be argued that the lowest strength values tested the boundaries of credibility, the objective was not to predict a definitive outcome but rather to study the influence of material strength variability on runout behaviour. By quantifying this influence, the analysis provided a clearer understanding of potential failure consequences, thereby supporting more informed planning and emergency preparedness decisions for the site.

2 Methodology and background

Prior to undertaking this assessment, the existing DBA for the facility was based on a conventional water-based dam breach model. The assessment assumed tailings would behave as a low-viscosity mud and accounted for the presence of a supernatant pond in the breach scenarios. This DBA suggested extensive inundation areas with projections exceeding 200 m downstream.

However, the closure design included deep perimeter drains, the installation of a capping geomembrane and conversion of the facility into a shedding landform. The removal of the supernatant pond, along with deep drain excavations and capping, resulted in a significant reduction in tailings saturation levels. Field investigations during closure revealed that the phreatic surface in the TSF had decreased significantly, which was further substantiated by readings from vibrating wire piezometers following closure. Furthermore, the groundwater models developed for the site corroborated this observation, predicting a continued decline in the phreatic surface over time. Considering these post-closure changes, the dam breach results were reassessed using MPM to obtain a more realistic representation of the extent of inundation under the closure conditions.

MPM is a hybrid Eulerian–Lagrangian numerical method. It combines the advantages of fixed computational grids with those of deformable material points. In each computational step, material point data – such as mass, momentum, and stress – are mapped onto the computational grid where the equations of motion are solved. The updated information is then transferred back to the material points, which carry the material history and properties (Soga et al. 2016; Yerro et al. 2019). This framework allows MPM to simulate large deformations, interface interactions, and material phase transitions, making it particularly well-suited for geomechanical problems involving liquefaction, collapse, and post-failure flow (Arenas & Pereira 2024).

For this study, Material Point Analysis of Continua (MPAC) was used to perform two-dimensional simulations of potential breach scenarios. MPAC is a computational tool based on MPM, developed to simulate large strain geomechanical problems, providing multithreaded performance and coupling with FLAC for hybrid simulations (Purvance & Coetzee 2024). All results presented in this paper were benchmarked against other established MPM tools, including Anura3D (2022) and MPM-PUCRio (Fernandez 2021), and demonstrated good agreement across all cases.

The TSF under investigation is a downstream-raised facility that stores red mud, the highly alkaline waste by-product of alumina refining. The section selected for the study is a relatively localised portion of the TSF which has a slope of 2.5H:1V, with the embankment transitioning to a flatter slope of 7H:1V for the remainder of the facility. For the MPM simulation, a two-dimensional section was selected through the steepest, highest part of the facility. This conservative approach – assuming the steep slope continues across the entire embankment – provides an upper-bound estimate of potential runout consequences in a dam breach scenario. The typical cross-section used for the analysis is presented in Figure 1.

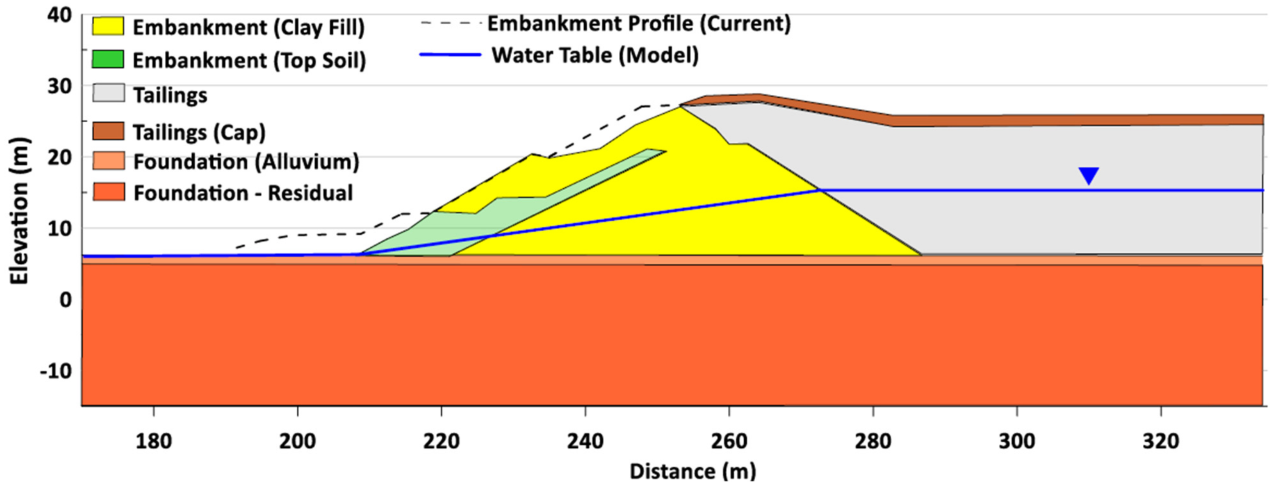


Figure 1 The section chosen for the dam breach analysis

The TSF embankment was constructed using a combination of clay fill and sandy silt alluvial material (historically termed 'topsoil'), placed in controlled lifts during construction. The embankment was founded on a thin, approximately 1 m thick layer of alluvium, herein referred to as the foundation alluvium. This layer consists of soft to medium stiff soils, underlain by a competent residual bedrock, which forms the primary load-bearing stratum and is termed the foundation residual. A closure cap, approximately 2 m thick, was modelled atop the tailings as part of the final landform configuration. This cap comprised 1 m thickness of mechanically dewatered tailings, a geomembrane, and 1 m of vegetated cover soil. The phreatic surface within the TSF, informed by vibrating wire piezometer data, was incorporated into the analysis, and is illustrated in Figure 1.

An FMEA was carried out as part of the closure risk assessment, which identified three credible failure modes for the TSF:

1. excavation-induced instability at the embankment toe
2. foundation collapse due to shear or settlement within the alluvium
3. embankment failure induced by seismic loading.

For this study, all three failure modes were conservatively assumed to occur simultaneously – an extremely low-probability scenario that provides an upper-bound estimate of risk.

These failure mechanisms were incorporated into the MPM model using the following simulation strategy:

1. Excavation at the embankment toe was simulated by removing a 15 m wide and 2 m deep section of material at the toe, representing a potential uncontrolled excavation scenario.
2. Foundation collapse was represented by a reduction in the shear strength of the foundation alluvium layer. This models a situation where the alluvial layer may experience a loss of strength and become unstable due to softening, water ingress, or long-term consolidation.
3. Earthquake-induced failure was incorporated by assigning residual strength parameters to the tailings, reflecting the assumption that the entire tailings mass may undergo liquefaction during a seismic event. This assumption is commonly adopted in preliminary dam breach analyses (e.g. Zhang et al. 2013) and provides a conservative basis for estimating post-failure deformations and flow mobility.

This integrated approach ensures that the model accounts for a comprehensive and conservative set of failure conditions.

3 Material properties

According to the Critical State Soil Mechanics framework (Jefferies & Been 2015), geomaterials exhibit a residual strength when subjected to large deformations, such as those that typically occur during a dam breach. Ideally, simulations of such scenarios should assume residual strength for all materials involved, including the embankment. However, the inherent variability in properties like strength, stiffness, and density introduces uncertainty, raising concerns about the reliability of this assumption.

To address the uncertainty associated with embankment material strength in dam breach modelling, a series of simulation cases was developed using varied strength parameters. These cases were designed to reflect a range of plausible conditions, informed by probabilistic principles, to explore how variability in material properties could influence breach behaviour. Instead of predicting a single definitive outcome, the objective was to assess how runout characteristics respond to variations in strength assumptions. This approach supports a more robust understanding of potential failure scenarios and enhances the basis for risk-informed decision-making.

Based on the cone penetration tests (CPTs) conducted on the tailings to support the closure design and utilising the correlations proposed by Lunne et al. (1997) and Robertson (2010), the residual strength ratio (s_r/σ'_v) of the tailings was assessed to be 0.03. The peak shear strength values for the embankment materials, topsoil and clay fill, were estimated from triaxial tests, which indicated peak friction angles of 36 and 37°, respectively. In accordance with Australian National Committee on Large Dams (ANCOLD 2019) guidelines, a residual strength (hereafter denoted as μ) equivalent to 80% of peak shear strength was adopted for these materials in the MPM model, reflecting their behaviour under large deformations. Similarly, triaxial tests on the foundation alluvium indicated a peak shear strength of 31°, and 80% of this value was considered to estimate the residual strength for this layer, consistent with the approach used for the embankment materials. Additionally, based on the peak shear strength values derived from the CPTs on the tailings, the 1 m crust of the tailings was assigned a peak shear strength ratio (s_u/σ'_v) of 0.16 in the model.

4 Cases considered for the dam breach analysis

Phoon (2008a) noted that soil strength typically follows a normal distribution with a coefficient of variation (COV) of 25%. Based on this, the standard deviation (σ) of residual embankment strengths is calculated as:

$$\sigma = COV \times \mu \quad (1)$$

where μ is the residual strength of the embankment materials and the foundation. Based on these assumptions, the following cases were considered for the analysis:

Case 0 – column collapse: this is the base and most conservative case, where resistance from the embankment is ignored. A column of tailings, equal in height to the TSF, is allowed to flow under its own weight. While this scenario does not reflect realistic conditions, since it assumes the collapse of an isolated column, it represents the maximum possible runout. Its purpose is to validate the model's ability to simulate material flow and deformation, which is essential for more complex and realistic breach analyses.

- Case 1 (μ): residual strength for the embankment materials including topsoil and clay fill.
- Case 2 (μ − σ): residual strength minus one standard deviation for the embankment materials corresponds to the 84.2nd percentile.
- Case 3 (μ − 2σ): residual strength minus two standard deviations for the embankment materials corresponds to the 97.8th percentile.
- Case 4 (μ − 3σ): residual strength minus three standard deviations for the embankment materials corresponds to the 99.9th percentile.

For all these cases, the collapse of the foundation is simulated by reducing the foundation alluvium strength according to these cases. Since the adopted tailings strength is already a lower bound value, it is not reduced further. The corresponding shear strengths of the materials are shown in Table 1.

Table 1 Material properties for all cases considered

Geotechnical unit	Unit weight (kg/m^3)	Cohesion (kPa)	Friction (residual) (Case 1)	Friction (μ – σ) (Case 2)	Friction (μ – 2 σ) (Case 3)	Friction (μ – 3 σ) (Case 4)	s_r/σ'_v residual
Foundation – residual	2,040	NA	NA	NA	NA	NA	NA
Foundation – alluvium	2,140	0	24.8	23.2	15.5	7.7	NA
Embankment – clay fill	1,940	0	30.0	28.1	18.8	9.4	NA
Embankment – topsoil	1,940	0	29.3	27.4	18.3	9.1	NA
Tailings (crust)		NA	NA	NA	NA	NA	0.16
Tailings		NA	NA	NA	NA	NA	0.03

NA = not applicable.

The pore pressures in the model for Case 0 are shown in Figure 2 while pore pressures for Cases 1 through 4 are given in Figure 3. All materials above the phreatic surface were assigned a pore pressure of 0 kPa. The MPM model with all the materials is shown in Figure 4.

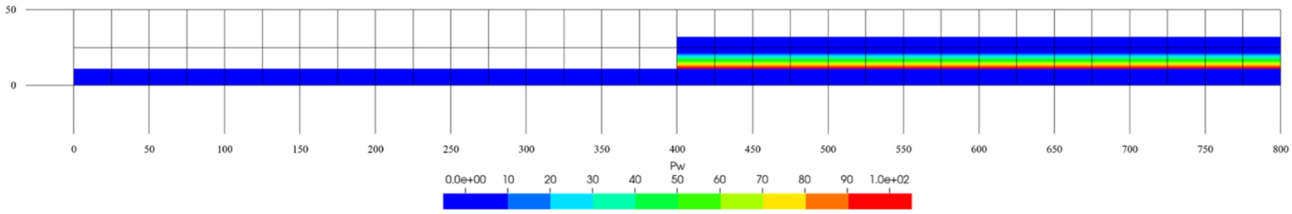


Figure 2 Initial pore pressure distribution in Case 0 in the model in kPa

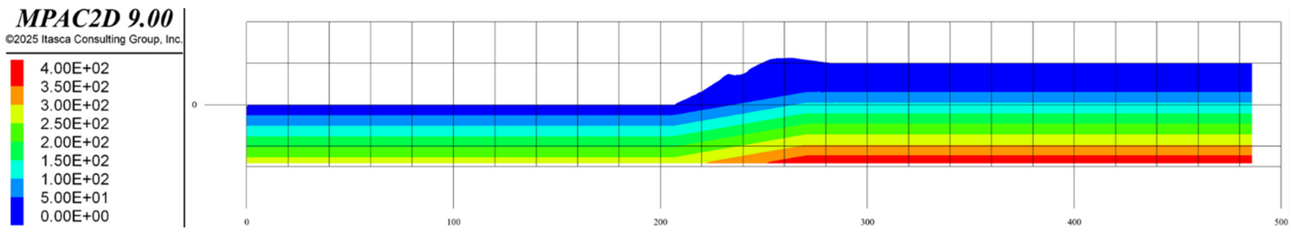


Figure 3 Pore pressure in Cases 1 through 4 in the model in kPa

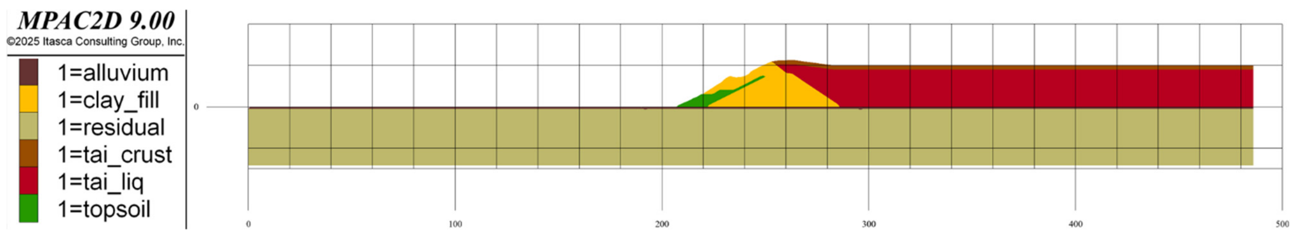
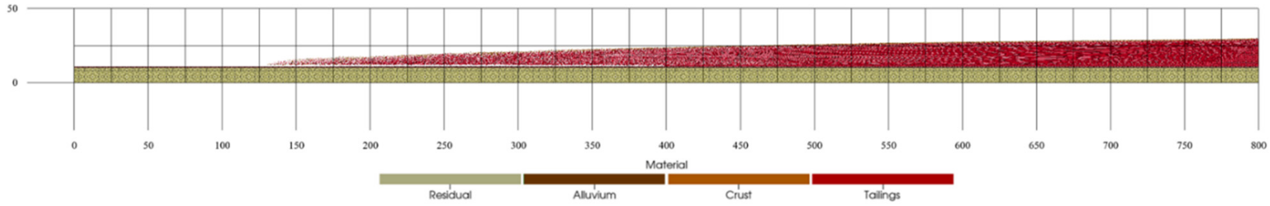


Figure 4 The model with the materials in Material Point Analysis of Continua

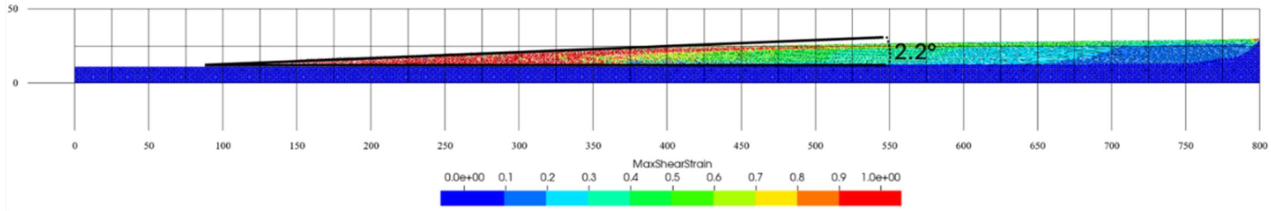
The models were carried out in a 2D section with a mesh size of 1 × 1 m. Each mesh element (1 × 1 m) was populated with a two material points.

5 Results

The results of the column collapse simulation using the MPM model are presented in Figure 3 (displacements) and Figure 5 (shear strains). As shown, a 21 m collapse of liquefied tailings resulted in a runout distance of approximately 240 m, and a post-failure surface slope of 2.2°. This value of post-failure surface slope aligns well with typical post-failure surface slopes observed in documented flow failures of TSFs reported by Blight & Fourie (2005). The ability of the model to reproduce both the runout distance and surface gradient observed in real failures enhances confidence in its predictive capability. This validation is significant, as it supports the model's application in assessments of potential flow failures in similar TSFs.



(a)

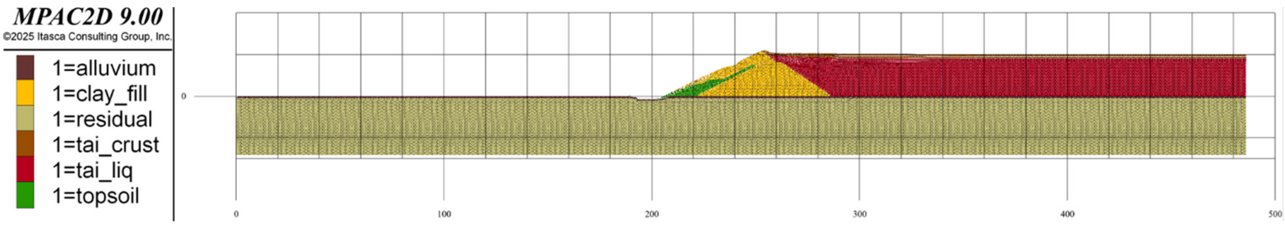


(b)

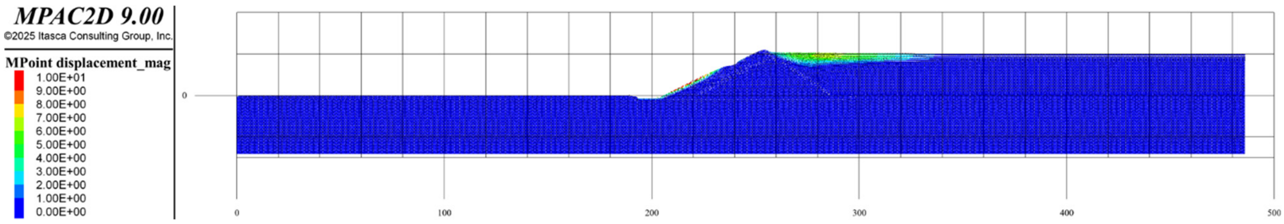
Figure 5 Results from the model for Case 0 showing: (a) Final material positions; (b) Shear strain contours

The results for the various cases are presented in Figures 6 to 9. For each case the upper image in the figure shows the final positions of the respective materials, while the lower image shows displacement contours. The following observations summarise the outcomes for each case:

- In Case 1, the excavation of the toe within the model can be seen in the upper part of Figure 6. The lower part of Figure 6 shows that the maximum horizontal displacement observed is approximately 10 m, primarily due to the downstream movement of the embankment material. Displacements ceased after 30 seconds, and the upper portion of the embankment remained intact, successfully containing the tailings.



(a)



(b)

Figure 6 Results from the model for Case 1 showing: (a) Final material positions; (b) Displacement contours

- In Case 2, a maximum displacement of 11 m was recorded, similar to Case 1, and was attributed to embankment movement. The simulation was halted at 30 seconds with no further deformation observed. Importantly, no breach occurred and tailings remained securely confined.

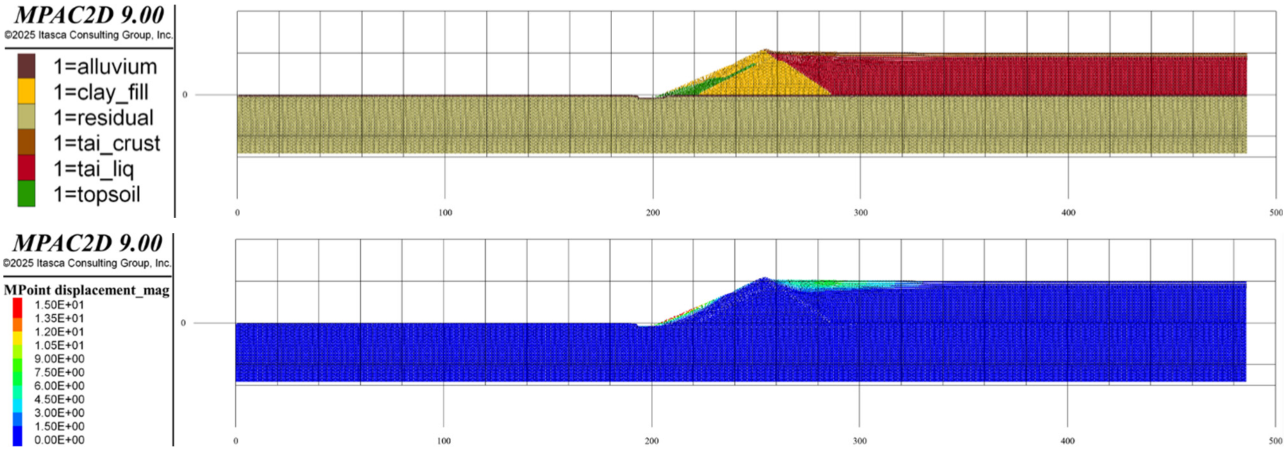
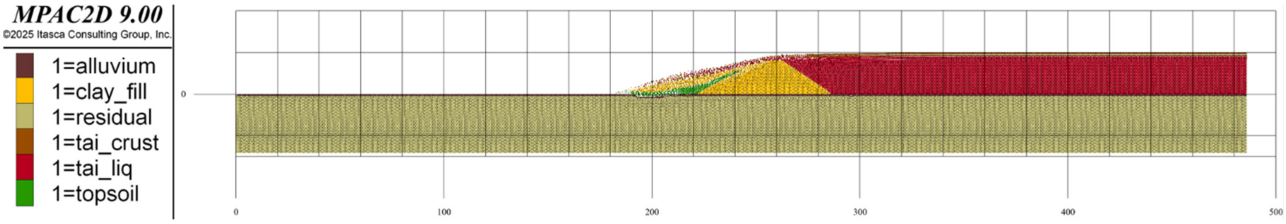
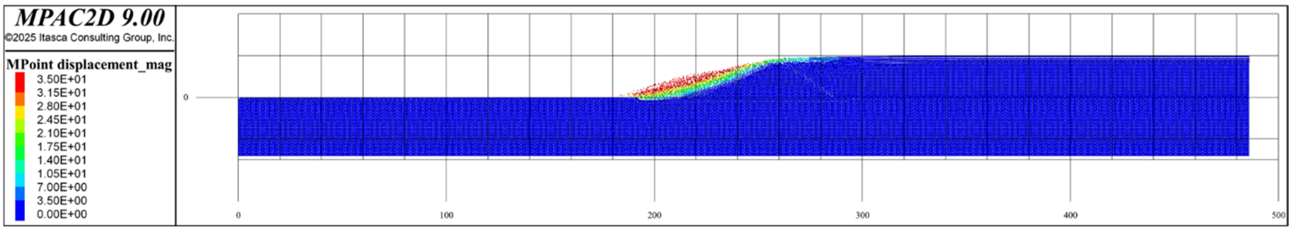


Figure 7 Results from the model in terms of displacements for Case 2

- In Case 3, the maximum horizontal displacement increased to approximately 35 m. A breach in the embankment became apparent, allowing tailings to escape. While the embankment materials exhibited the greatest deformation, there was also a clear loss of containment, as illustrated in the upper image by the red band extending across the slumped embankment batter. The simulation was terminated at 45 seconds, beyond which no further significant movement was detected.



(a)



(b)

Figure 8 Model results for Case 3 showing: (a) Final material positions; (b) Displacement contours

- In Case 4, the most conservative scenario, the maximum horizontal displacement reached approximately 140 m. A breach was clearly identified, and a substantial volume of tailings was released through the failure zone. As with Case 3, the embankment experienced greater deformation than the tailings, but the runout and extent of tailings release were significantly greater than in Case 3. The simulation was stopped at 60 seconds, with the system having reached a new equilibrium. As noted earlier, the Case 4 model was included as a sensitivity analysis to test the outcomes of extremely low residual strength materials in combination with the other two credible failure mechanisms.

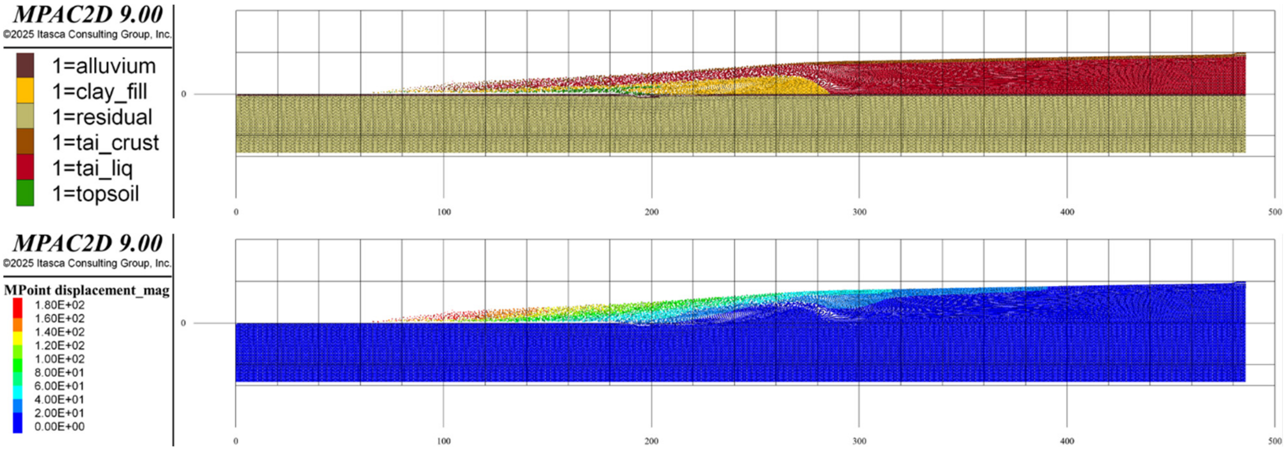


Figure 9 Results from the model in terms of displacements for Case 4

The results of all the cases considered are summarised in Table 2.

Table 2 Results of the Material Point Method models

Cases	Case 0	Case 1	Case 2	Case 3	Case 4
Material properties	μ	μ	μ - σ	μ - 2σ	μ - 3σ
Breach of tailings storage facility	NA	No	No	Yes	Yes
Tailings release	NA	No	No	Yes	Significant
Runout distance	240	10	11	35	140
Time of simulation	NA	30	30	45	60

This analysis confirms that while lower orders of reductions in material strength (Cases 1 and 2) do not compromise dam integrity, more significant reductions (Cases 3 and 4) result in breach and tailings release. Case 4, which represents the 99.9th percentile reduction in residual strength ($\mu - 3\sigma$), defines the statistical limit of credible failure based on material variability as per Phoon (2008b).

The use of this multi-scenario modelling approach, grounded in critical state soil mechanics and probabilistic representation of strength, is critical for risk-informed decision-making, and supports:

- defining operational restrictions under potentially adverse ground conditions
- establishing monitoring thresholds, such as early-warning displacement or strain triggers
- designing and adapting containment structures and downstream protective infrastructure, including emergency preparedness zones.

By capturing the full spectrum of credible behaviour – from containment to breach – the analysis ensures that even low-probability, high-consequence events are explicitly evaluated, as recommended by ANCOLD (2019) and the International Commission on Large Dams (ICOLD 2016).

6 Conclusion

A large-deformation numerical analysis was undertaken to assess the potential for a sunny-day breach of a closed TSF, with the goal of evaluating whether credible failure modes identified in the FMEA could lead to dam failure and tailings release. The modelling adopted a 2D formulation, which is generally considered conservative in predicting runout distances and deformation patterns.

The analysis was carried out in two phases:

1. Model validation: a column collapse simulation was first conducted to establish a baseline and validate the model's ability to replicate typical flow failure behaviour. The resulting post-failure slope of 2.2° was consistent with those reported for liquefied tailings in previous case studies (e.g. Blight & Fourie 2019), providing confidence in the model's calibration.

2. Scenario assessment: the calibrated model was used to simulate a combination of the three previously identified credible failure modes, across multiple scenarios with progressively reduced material strengths. These strength reduction scenarios were defined based on statistical variability of residual strength following the framework of Phoon (2008a), using mean (μ), and μ – σ, μ – 2σ, and μ – 3σ reductions to represent increasing severity. The failure mechanisms incorporated were simultaneous toe excavation, foundation weakening, and tailings liquefaction due to seismic loading.

The results indicated that:

- For strength values at or above μ – σ (i.e. up to the 84^{th} percentile), no dam breach occurred. Deformations were limited, and the embankment continued to contain the tailings.
- At μ – 2σ (97.8^{th} percentile), a localised breach was observed with limited tailings release.
- At μ – 3σ (99.9^{th} percentile), a full breach occurred, resulting in significant deformation and tailings runout.

Case 4 (μ – 3σ) represents an extremely low-probability, high-consequence scenario, considered to be the credible limit of material degradation based on current understanding of soil variability. Including this case ensures the analysis captures the full credible range of performance outcomes, in alignment with risk-informed guidance from ANCOLD (2019) and ICOLD (2016).

This study highlights the value of large deformation modelling in tailings risk assessment, especially when exploring extreme but plausible scenarios. By adopting a statistically grounded approach and providing runout distance for the different scenarios (i.e. Cases 1 through 4), this analysis supports a defensible framework for dam safety and enhances emergency preparedness planning.

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