

Applying the material point method to dam break assessment of a closed tailings storage facility

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Abstract

Tailings dam failures pose a significant hazard to downstream communities and the environment. Effective risk management of dam failures requires accurate assessment. Conventional approaches include widely used empirical, depth-averaged models, as well as simplified continuum-based numerical methods. These conventional approaches are computationally efficient but often rely on significant simplifications, may overestimate runout extent, which is not necessarily conservative and fail to capture realistic flow behaviour.

This study applies the material point method (MPM) and a volume balance-based empirical approach to evaluate potential sunny-day dam breach consequences of a closed tailings storage facility (TSF). Both approaches are intended to represent the same clear-weather failure consequence scenario. The empirical approach provides a simplified estimate of runout based on volume balance assumptions and is not formulated to explicitly represent material strength degradation, pore pressure effects, or progressive deformation mechanisms. In contrast, the MPM simulation incorporates soils shear strength and large-deformation soil–water interaction, thereby providing a more realistic representation of tailings run-out behaviour. The analysis is limited to clear-weather conditions and does not consider additional run-out associated with rainfall or flooding-induced entrainment.

The results of the study show that MPM provides realistic predictions of post-failure deposition patterns while maintaining reliability. These findings highlight the value of MPM as a robust and strong tool for assessing the residual risk of closed TSFs and for bridging the gap between simplified industry tools and real tailings flow behaviour.

Keywords: *tailings storage facility, dam break assessment, MPM*

1 Introduction

Tailings storage facilities (TSFs) represent a critical challenge for mine closure, where long-term stability and risk reduction must be achieved with limited ongoing intervention. Historical failures have demonstrated that TSF breaches can result in severe environmental, social, and economic consequences, reinforcing the need for risk-based closure strategies that explicitly account for both the likelihood and consequences of failure.

Tailings dam breach analysis (TDBA) is central to this process, informing consequence assessments and closure design decisions. However, many conventional approaches – largely derived from water dam practice – do not adequately represent the complex mechanical behaviour of tailings. In particular, simplified fluid assumptions can mischaracterise flow behaviour, leading to uncertainty in predicted inundation extents and impact severity (Llano et al. 2025). Such limitations are especially critical in closure settings, where residual risks must be understood over long timeframes.

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Recent guidance has placed increased emphasis on the identification of credible failure modes, defined as physically plausible mechanisms consistent with site conditions and material response. In this context, the material point method (MPM) provides an advanced numerical approach capable of simulating large deformations and phase transitions associated with tailings failure.

This paper examines the application of MPM to TDBA in a closure context and compared to the conventional approach to improve failure mode definition and enhance the reliability of consequence predictions to support risk-informed mine closure.

2 Case study background

Figure 1a shows the studied TSFs condition over time. The TSF was an open cut pit formed by mining operations in the 1960s. Tailings deposition began in 'Cell 1' in 1993, then flowed into 'Cell 2', ceasing in 1999. Zoned embankments were built on three sides of 'Cell 2' (northern, western, and southern) from 1996 to 1998 to increase storage capacity. A crust layer of tailing formed in both cells by 2004.

The facility was utilised to stockpile the mine-spoil-coarse-rejects material since 2009, and the existing coarse-rejects thickness varies across the facility. Figure 1b presents an interpreted heatmap of coarse-rejects thickness, with the maximum thickness of 28 metres.

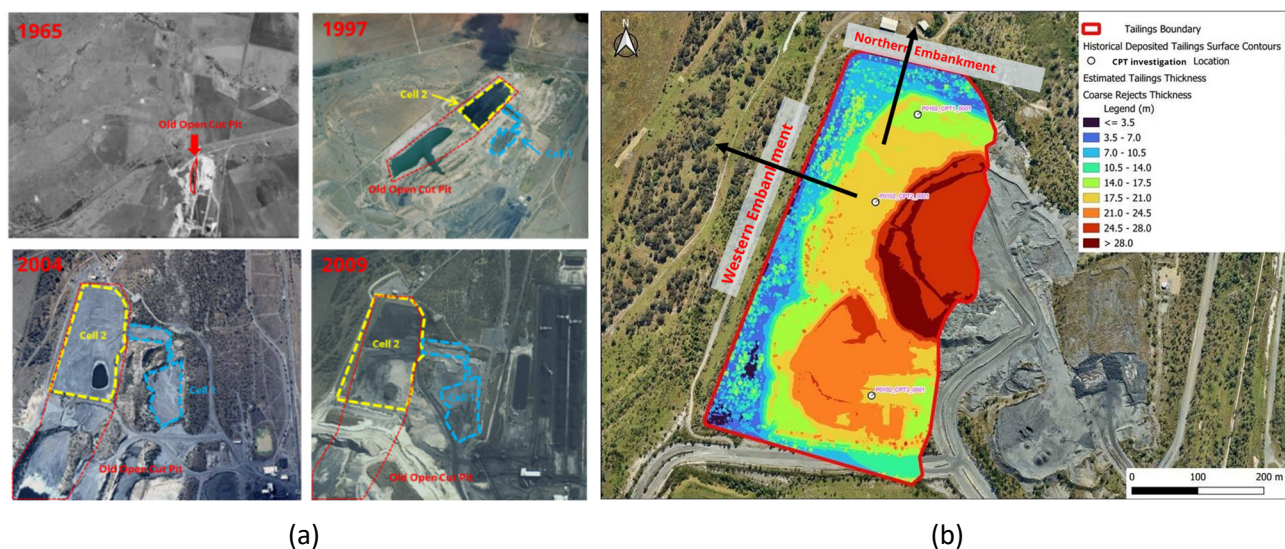


Figure 1 (a) The studied Tailings storage facilities (TSFs) condition over time; (b) The studied TSF current condition with the capping material's thickness

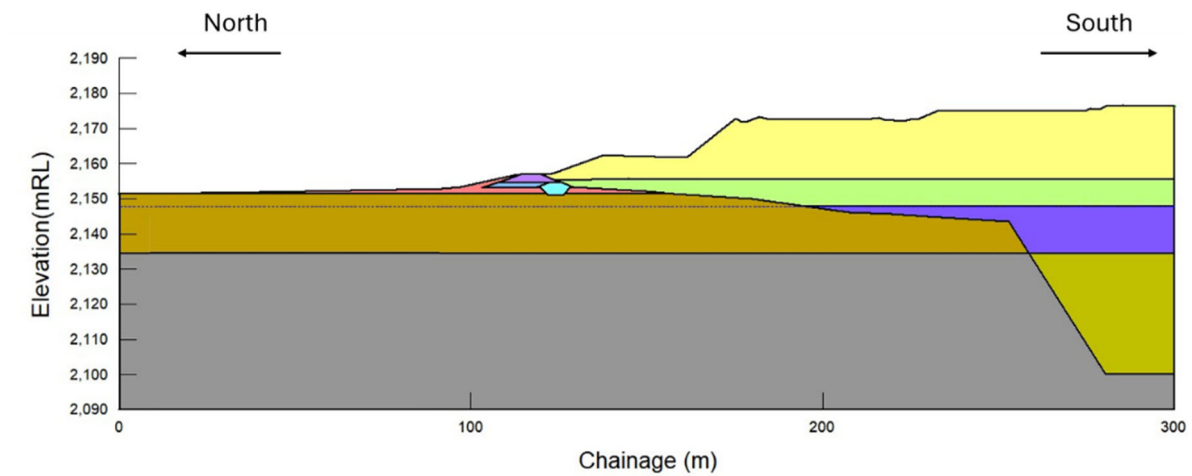
The existing capping geometry is not engineered and does not meet site rehabilitation criteria or free-drainage requirements. A dam break study has therefore been undertaken to assess potential failure consequences and inform the future landform reshaping design.

Two potential breach locations were assessed for the TSF based on consequence-driven criteria:

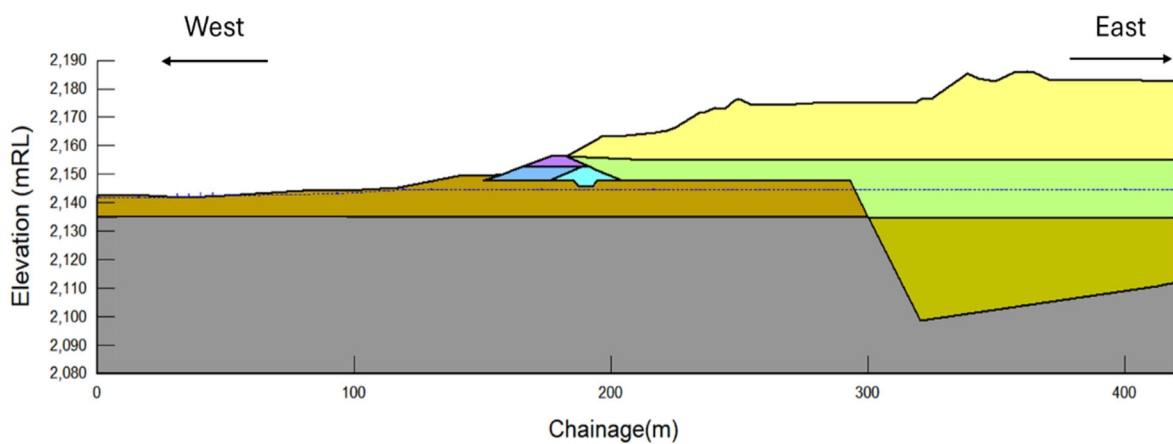
1. Northern embankment: selected due to the minimal separation distance between the facility and the site warehouse, representing the highest fatality risk. The existing cross-section is shown in Figure 2a.
2. Western embankment: selected based on the maximum elevation difference between the coarse particulate capping layer and the downstream terrain, representing the largest potential containments release. The corresponding cross-section is shown in Figure 2b.

The facility comprises a staged embankment constructed with three material zones. The embankment layout is presented in Figure 2c, with zoned material descriptions summarised as follows:

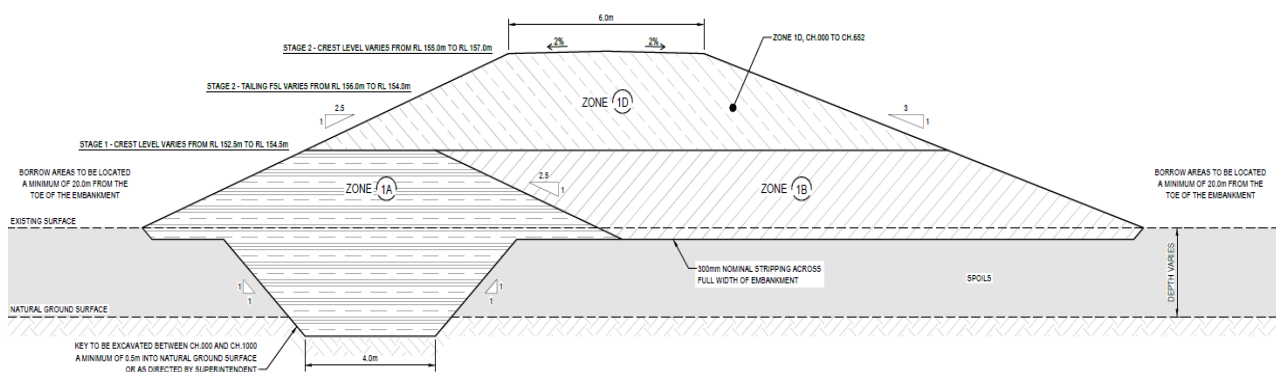
- Zone 1A: predominantly silty, clayey sands and gravels sourced from site borrow materials.
- Zone 1B: semi-pervious, compacted plant rejects derived from the CHPP.
- Zone 1C: low-permeability earthfill forming the core or sealing zone.



(a)



(b)



(c)

Figure 2 (a) Northern Embankment critical cross-sectional geometry; (b) Western embankment critical cross-sectional geometry; (c) Typical zoned embankment cross-sectional layout

3 Dam break study methods

3.1 Empirical method

The volume balance approach, as one of the empirical methods, could be used for simulating clear-weather dam failures. This type of dam breach analysis is based on geometric configuration and is typically designed for simulating a sunny-day tailings dam breach.

The volume balance approach is a geometry-driven method that does not model dynamic breach processes. The breach is defined by its location, elevation, and width, and a failure surface is then projected upstream as an inverted cone at a specified post-failure slope until it intersects the tailings surface (Figure 3).

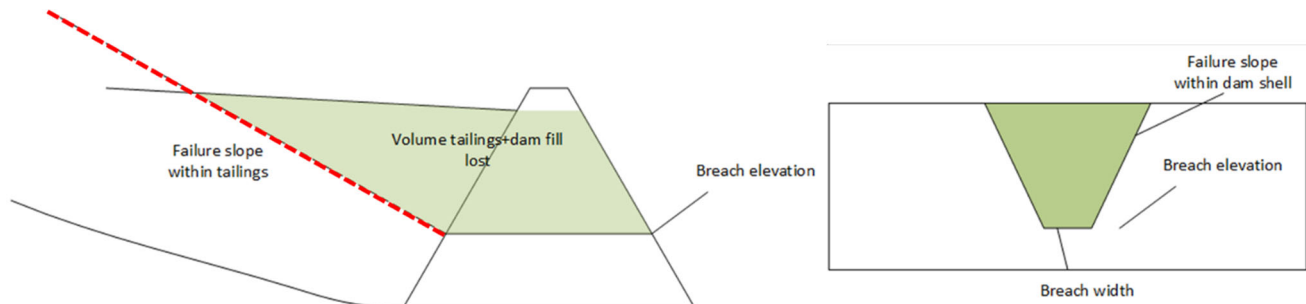


Figure 3 Muk3D Dam break modelling concept (MineBridge 2024)

The released volume is defined by mass balance between the backscarp and the downstream deposit. This volume is then projected onto the terrain using a post-failure surface to generate the flow footprint, enabling rapid estimation of extent and thickness.

3.2 Material point method

MPM is a continuum mechanics-based method proposed by Sulsky et al. (1994). An MPM model is composed of a background grid or and material points. Figure 4 shows the MPM concept and key elements for a structured mesh with square elements. MPM algorithm discretises objects using particles, which store all time-dependent information, and solves the momentum equations on a grid.

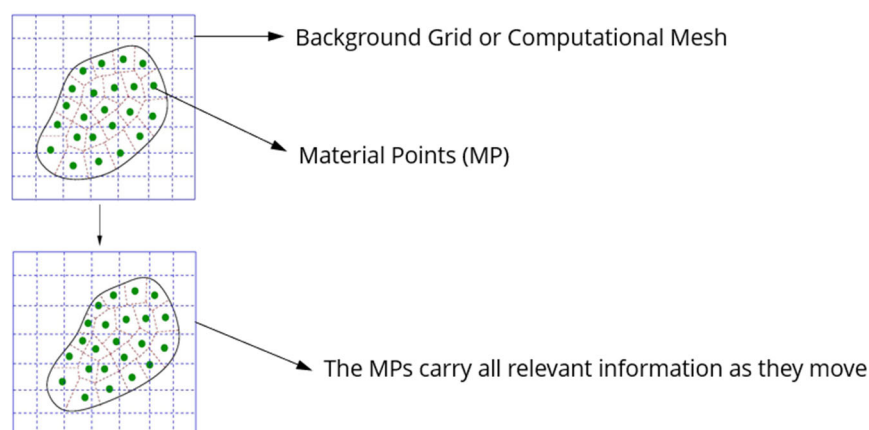


Figure 4 The material point method concept (www.imechanica.org)

For a large deformation process, such as that seen during a tailing dam failure, MPM has some important advantages. First, MPM can handle large deformation without dealing with mesh distortion. Mesh distortion is the problem preventing common numerical methods (for example, the finite element method) from capturing large deformations. Second, the continuum mechanics base of MPM allows it to model large deformations with reasonable computational cost. The continuum mechanics base of MPM enables it to use common and advanced soil constitutive models.

4 Dam break modelling results

4.1 Empirical method modelling

A dam break assessment was carried out using Muk3D before the MPM modelling. Following the introduction of the methodology above, the shape of a potential tailings failure was predicted based on the lower bound of the post-failure surface slope angles detailed in Blight & Fourie (2003) and considered to be 2° . However, due to the presence of approximately 28 m of coarse-rejects above the existing tailings level, a different failure surface was adopted. In the analysis, a residual friction angle of 30° was assigned to the coarse reject capping materials. The dam breach elevation location was assumed at the base level of the embankment.

The volume balance approach was used to estimate the runout distance and inundation extent for breaches at the northern and western embankments. The predicted results are presented in Figure 5a and b, respectively. In these figures, the black dashed line represents the existing facility topography, the solid black line represents the post-failure surface, and the orange line indicates the predicted runout extent.

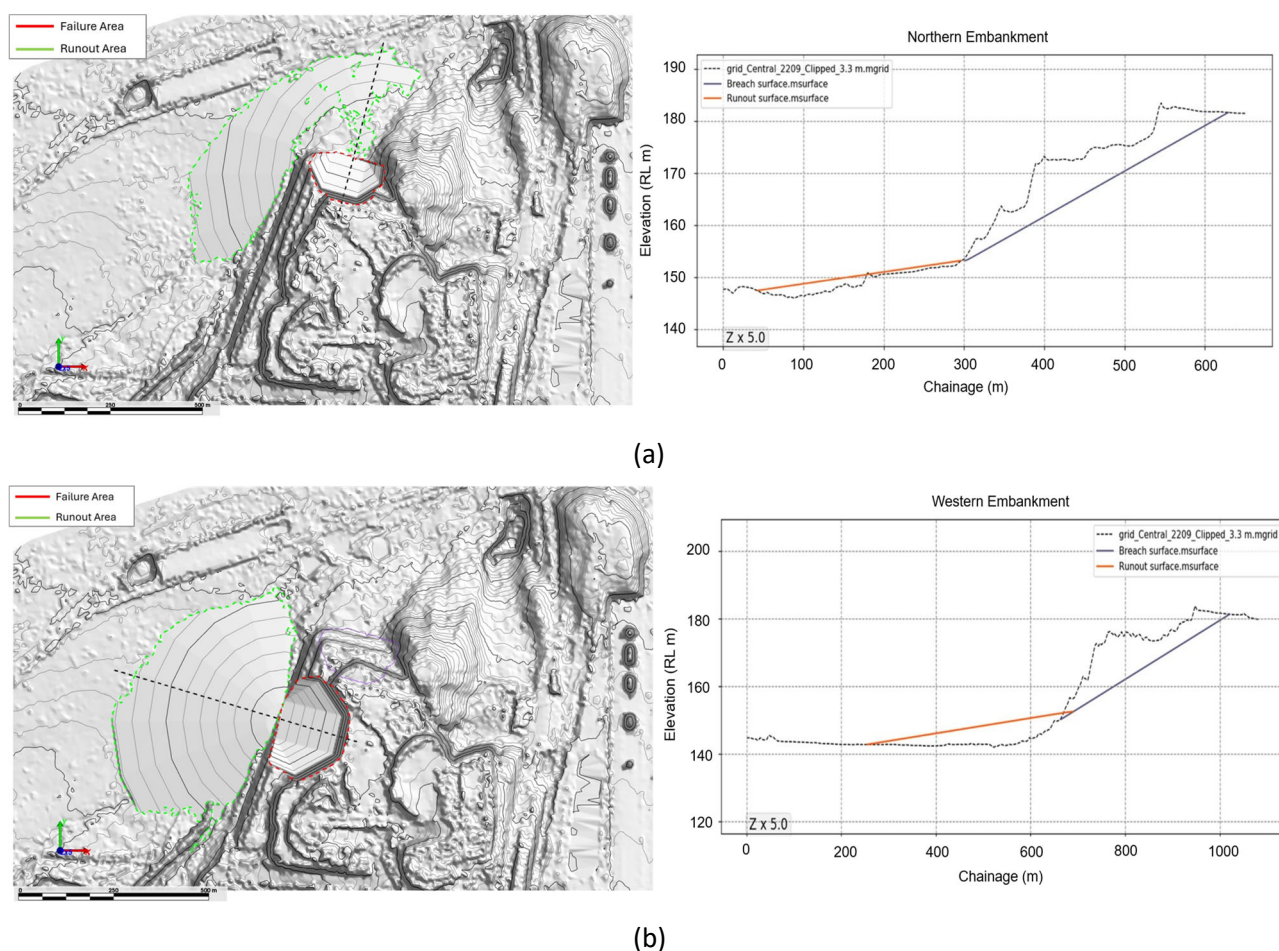


Figure 5 (a) Northern Embankment failure and runout plan view (b) Western embankment failure and runout plan view

4.2 Material point method modelling

Anura3D (www.anura3d.com) was used with the MPM to produce the deformation estimate. The soils in the model were all modelled using the one-phase, single-point formulation following the overview by Yerro & Rohe (2018), with soils assumed to be in either dry or fully saturated status. The models were set up using unstructured triangular elements with a mesh size of 1 m, with three material points per element, and were initialised to reach a static state.

The post-seismic (liquefied) shear strength of the tailings was derived from the 5th percentile lower-bound of cone penetration test based interpretation, representing a conservative approximation of residual strength under contractive, flow-like conditions.

The coarse-rejects are classified as sandy gravel to gravel materials, and it is expected that negligible porewater pressure will develop within the layer. Consequently, the material was assigned a critical friction angle with no further reduction applied. The intact embankment of the facility was simulated to replicate in situ conditions.

An 20% reduction in shear strength was applied to the embankment fill and foundation soils in accordance with ANCOLD (2019) post-earthquake deformation guidance to approximate strength loss associated with excess pore pressure generation under seismic loading conditions. This reduction is acknowledged as a simplified approach and represents a sensitivity-based assumption rather than a rigorously derived parameter. Additionally, considering the credible failure mechanism, it is not expected that the facility failure plane will develop in the rock strata; therefore, an infinite strength is assigned to the foundation rock layer.

Table 1 presents the materials properties that were adopted in this study.

Table 1 Material inputs of the material point method modelling

Material category	Initial porosity	Soil density (kg/m ³)	Poisson's ratio	Young's modulus (MPa)	Residual friction angle (degree)
Coarse-rejects – capping fill	0.25	1,500	0.3	50	27
Post-liquefied tailings	0.40	600	0.49	20	2.3
Spoil	0.3	2,000	0.25	20	–
Alluvial/ residual soils	0.3	1,900	0.2	20	20
Saturated mined spoil	0.4	1,000	0.49	20	18
Embankment Zone 1A fill	0.2	1,900	0.2	50	25
Embankment Zone 1B fill	0.2	1,500	0.2	50	28
Embankment Zone 1C fill	0.2	1,900	0.2	50	25
Bedrock	–	2,650	0.2	100	–

The Mohr–Coulomb constitutive model is assigned to all materials in the simulation. A study by Fern & Soga (2016) revealed that materials using the Mohr–Coulomb model exhibited greater runout distances than those using the Norsand model. This is thought to be because the Mohr–Coulomb criterion is an elastic-perfect plastic criterion with limited representation of plastic hardening and associated energy dissipation. This is because the natural energy dissipation of the materials is not taken into account by the Mohr–Coulomb constitutive model. According to the recommendation of Ceccato & Simonini (2018), a homogeneous local damping coefficient of 0.75 and a small value of 0.05 were adopted to converge to static equilibrium and simulate the natural energy dissipation of the materials.

The deformation modelling was run in time steps and terminated after 20 seconds, once all material points had equilibrated to zero velocity.

Figure 6 shows the runout deformation outcomes for both the northern and western embankments, with a solid deviatoric strain heat map plotted. Regions coloured red indicate potential failure surfaces and predicted critical failure planes are overplotted in white.

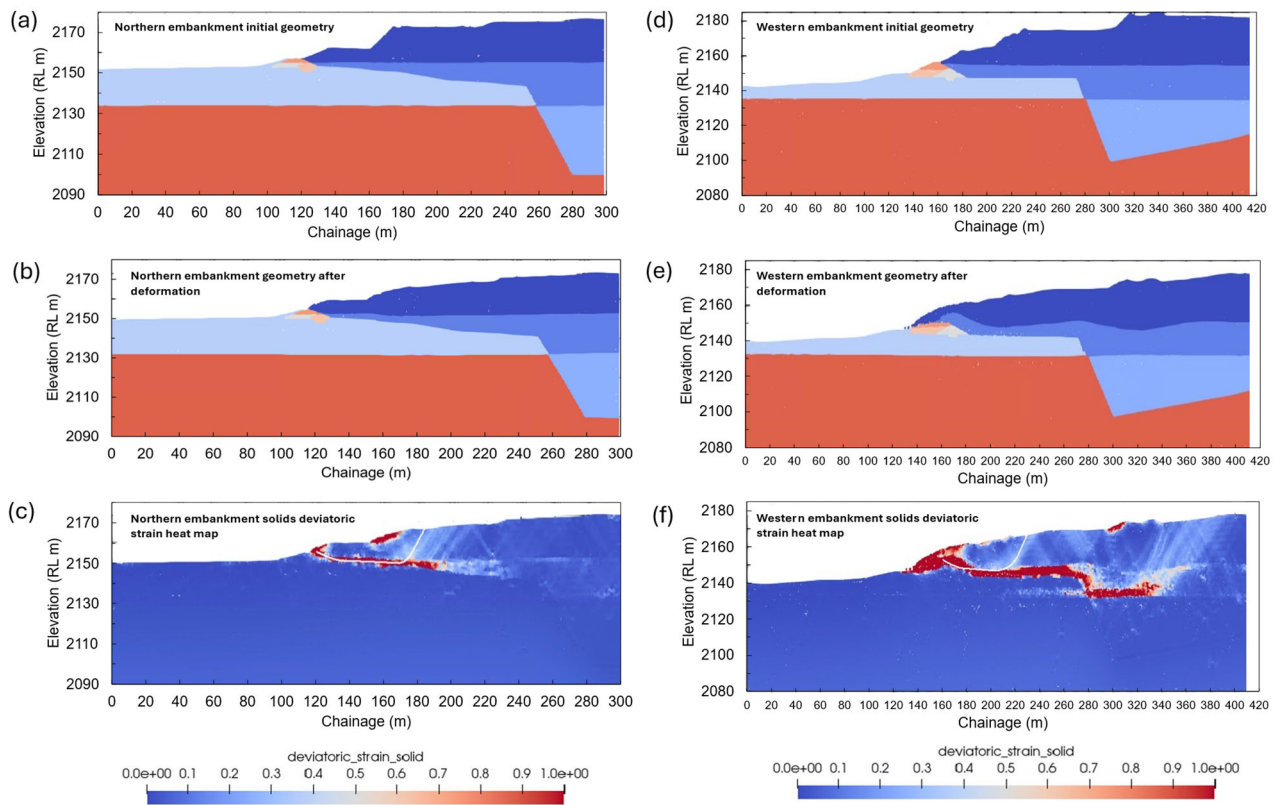


Figure 6 (a) Northern Embankment initial setup; (b) Northern Embankment deformation after 20 seconds; (c) Northern Embankment solids deviatoric strain heat map; (d) Western Embankment initial setup; (e) Western Embankment deformation after 20 seconds; (f) Western Embankment solids deviatoric strain heat map

4.3 Dam break runout comparison

Comparison of the empirical volume balance approach (Figure 5) with the MPM-based large-deformation runout simulations (Figure 6) indicates that the empirical method predicts a significantly greater runout extent, with material extending further downstream and over a wider area.

A key difference between the two approaches lies in their underlying assumptions regarding the dam breach mechanism. The volumetric balance model assumes near-complete geometric mobilisation of the embankment and underlying tailings. A predefined back-failure surface, typically represented by a conservative lower-bound slope of 2° for liquefied tailings, is projected upslope until volume equilibrium is achieved between the displaced mass and the downstream deposition zone. In effect, the dam is assumed to fully disaggregate upon breach initiation, with runout governed primarily by mass conservation. While computationally efficient for preliminary bounding assessments in closed facilities, this approach does not explicitly represent the mechanics of failure, particularly where a thick coarse-rejects capping layer (up to 28 m) overlies the tailings.

In contrast, the MPM simulation captures a more progressive and localised failure process. The zoned embankment and competent coarse-rejects capping layer do not undergo wholesale collapse. Instead, instability is driven primarily by strain localisation within the underlying liquefied tailings. Loss of shear strength in the tailings leads to upward propagation of deformation, resulting in limited instability at the toe and crest and a slump-type failure confined to discrete portions of the slope, rather than global dam-body collapse.

The deviatoric strain distributions from the MPM analysis (Figure 6) show concentrated shear bands (red zones) developing along progressive failure surfaces, predominantly within the tailings. In contrast, the capping materials and most of the embankment retain much of their structural integrity and initial geometry. As a result, the MPM predicts shorter and more spatially constrained runout distances, strongly influenced by local topography and stratigraphy. A comparison of the predicted runout distances obtained from both the MPM simulation and the volume balance-based empirical approach is summarised in Table 2, and the runout distance is defined as the maximum downstream extent of mobilised tailings and capping materials measured from the embankment crest.

Table 2 Comparison of predicted runout distances from material point method (MPM) and empirical volume balance approaches

Embankment critical section	Predicted runout distance (m)	
	MPM	Empirical approach
Northern embankment	N/A	260
Western embankment	25–30	375

This mechanistic comparison demonstrates that the volumetric balance approach, while suitable for conservative screening, is not fully consistent with the observed physics of liquefaction-induced failure in capped TSFs. By explicitly resolving large deformations, material transition behaviour, and strain-driven failure progression, the MPM approach provides a more physically representative prediction of runout behaviour, reducing unnecessary conservatism in residual risk assessment without compromising safety.

5 Conclusion

This case study applied the MPM to assess potential dam break consequences for a closed TSF capped with up to 28 m of coarse-rejects. A comparison between MPM simulations conducted using Anura3D and traditional empirical volume balance modelling via Muk3D indicated that MPM offers more realistic predictions of failure mechanisms, runout distances and patterns.

The empirical approach, while computationally efficient, relies on simplifying assumptions such as predefined post-failure slope angles and depth-averaged flow, often leading to overestimated runout extents and conservative outcomes. In contrast, MPM effectively handles large deformations and the solid-to-fluid transition in liquefied tailings through a particle-based framework, incorporating Mohr–Coulomb constitutive behaviour, liquefaction strength, and appropriate energy dissipation parameters. The resulting simulations revealed shorter, more topography-responsive runouts and progressive failure surfaces that better reflect the in situ conditions of the zoned embankment and thick capping layer.

These findings underscore MPM's value as a robust numerical tool for bridging the gap between simplified industry methods and actual tailings flow behaviour. For closed TSFs in the closure phase, MPM enables more accurate residual risk quantification, supporting improved failure mode and effects analysis, TDBA, and ALARP decision-making. Ultimately, adopting advanced methods like MPM can help avoid overdesign, reduce unnecessary closure costs, and enhance the defensibility of risk assessments while maintaining high safety standards for downstream communities and the environment.

In this study, single-phase MPM is used for post-failure behaviour, with pore pressure effects approximated through parameter selection rather than explicitly modelled. And the future work could extend this approach by incorporating two-phase formulations for explicit soil–water coupling and optimising the model inputs using a constitutive model that accounts for both strain softening and hardening.

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