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A hybrid FLAC3D-MPM approach for post-failure slope behaviour

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Abstract

Simulating large-strain behaviour in rock slopes poses significant challenges for traditional continuum modelling methods, primarily due to mesh distortion leading to numerical instabilities. While mesh remeshing can mitigate this issue, it becomes computationally intensive and technically complex in 3D, especially for irregular geometries. Meshless methods such as the Material Point Method (MPM) and Smoothed Particle Hydrodynamics (SPH) offer an alternative by avoiding mesh distortion entirely; however, they often come with drawbacks including longer run times and difficulty applying boundary conditions.

This paper presents a hybrid modelling approach that combines the efficiency of a finite-volume meshed continuum with the flexibility of MPM for simulating large deformations. The model uses traditional finite-volume zones in regions of low strain, while areas expected to undergo large deformation are handled with material points. The interface between the two domains allows for information transfer through an overlapping region. Material point regions can be defined at the outset or generated dynamically when deformation thresholds are exceeded, enabling a responsive and efficient modelling framework.

To evaluate performance, a rock slope failure with significant runout is simulated using three configurations: fully meshed (FLAC3D), hybrid FLAC3D-MPoint, and fully meshless (MPoint). Displacement patterns and computational times are compared across all cases.

This hybrid formulation is particularly relevant for risk and reliability assessments of rock slopes, where post-failure deformation and runout are critical to consequence estimation. By capturing large displacements without compromising computational efficiency, this approach improves runout predictions and supports risk-informed slope design.

Keywords

Numerical Modelling, Material Point Method, FLAC3D, Slope Stability, Runout Analysis

1 Introduction

Assessment of rock slope stability traditionally focuses on the onset of failure, often quantified through factor of safety or strength reduction methods. However, for high-consequence slopes, prediction of post-failure deformation and runout is equally critical, as it directly governs hazard extent and infrastructure exposure. Conventional continuum methods such as finite difference or finite element approaches are effective in simulating pre-failure stress redistribution and progressive strain localization. Their applicability diminishes once deformation becomes very large, where mesh distortion can lead to numerical instability and artificial resistance.

Meshless methods, including the Material Point Method (MPM), provide an attractive alternative for modelling extreme deformation and flow-like motion. By decoupling material motion from the computational grid, MPM avoids mesh distortion and enables robust simulation of large displacements. However, fully meshless models can be computationally expensive when applied to large three-dimensional domains in which significant portions remain in low-strain conditions.

This paper presents a hybrid numerical framework that combines FLAC3D (Itasca, 2026a) with MPoint (Itasca, 2026b), the commercial implementation of the Material Point Method formerly known as MPAC (Purvance and Coetzee, 2024). The objective is to unify progressive failure modelling and post-failure runout within a single mechanically consistent framework. A benchmark is carried out using a case study of a slope failure in an open pit, in order to compare fully meshed FLAC3D, fully meshless MPoint, and hybrid approaches. The case study allows to demonstrate practical applicability in large-scale engineering problems.

2 Numerical Framework

2.1 Continuum Formulation (FLAC3D)

FLAC3D employs an explicit finite-volume formulation for solving the equations of motion in a Lagrangian framework. It is well suited for modelling stress redistribution, progressive strain localization, and structural control through zone joints or ubiquitous joint formulations. For rock slopes, it enables realistic representation of geological domains, fault geometries, and strain-softening behaviour. The limitation arises when shear localization evolves into large displacement, where element distortion reduced numerical accuracy and may require artificial damping or remeshing when large-strain mode is enabled.

2.2 Material Point Method (MPM)

The Material Point Method represents material as a set of Lagrangian particles carrying state variables such as stress, strain, and density. These material points interact with a background Eulerian grid on which momentum equations are solved. Because the grid is reset each timestep, large deformations do not cause mesh distortion. MPoint provides robust simulation of large strain shear localization, fragmentation-like behaviour, flow-like post-failure motion, etc. However, full-domain MPM simulations can be computationally demanding for large models with extensive low-strain regions.

2.3 Hybrid Coupling Strategy

The hybrid approach combines both formulations within a single model. Regions expected to remain stable are represented by FLAC3D elements (zones), while regions undergoing large deformation are represented by material points. An overlapping transition region allows stress and velocity transfer between the two formulations. The coupling is achieved using the approach of Lian et al. (2012), where “hybrid” points exist at each FLAC3D zone gridpoint within some distance of the material points and these hybrid points act as a bridge passing information between gridpoints and the background MPM grid.

3 Case Study: Open PitStability

3.1 Background

This case study focuses on the stability of the north wall of an open pit mine in Peru. The slope was monitored using ground-based radar, which identified deformation at an inter-ramp scale extending over approximately eight benches above the nearest ramp (Figure 1). Displacement rates increased

significantly, reaching velocities of up to 54 cm/day in August 2019. Subsequently, between November 2019 and April 2020, rainfall events contributed to continued slope movement, resulting in cumulative displacements exceeding 1 m. These observations raised concerns regarding the potential for further acceleration and propagation of the instability under additional precipitation events. As a result, evaluating the potential runout associated with a progressive or fully developed failure became critical to support safe continuation of mining activities at pit bottom.

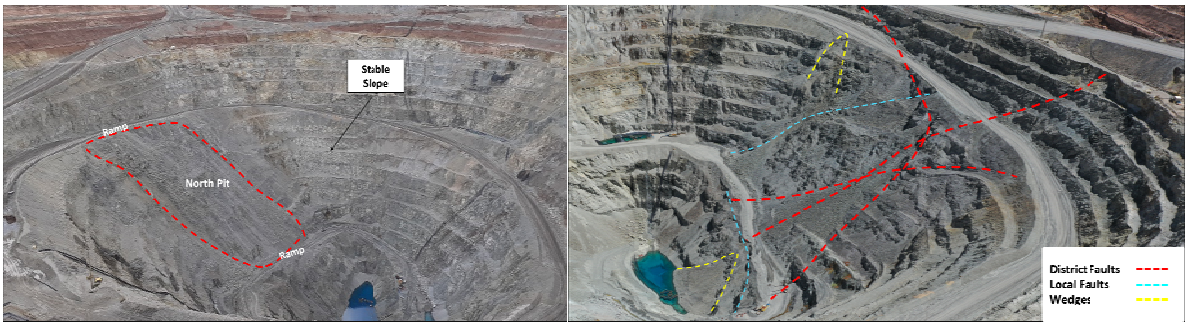


Fig. 1Photos of the North Wall by April 2020, condition after large deformations.

3.2 Model Definition

A three-dimensional FLAC3D model was constructed for this case study, initially calibrated in small-strain conditions and subsequently evaluated in large-strain mode. The element size in the area of interest was 6 m approximately. The rock mass was represented using a Hoek-Brown model with perfectly plastic behaviour. Weaker materials, including damage zones associated with fault halos, were modelled using a Mohr-Coulomb criterion with a cohesion of 10 kPa and a friction angle of 29°. The failure mechanism was interpreted to be strongly controlled by the intersection of major structures forming wedges, combined with elevated pore pressures near the slope face.

Figure 3presents the safety factor (FS) contours obtained from the calibrated small-strain model, compared with an I-site scan of the observed failure. The model captures the location and general extent of the instability, providing a basis for subsequent large-deformation analyses.

Three additional simulations were performed to evaluate post-failure behaviour:

- Fully meshed FLAC3D in large-strain mode
- Fully meshless approach where the entire volume is represented by material points
- Hybrid approach with material points in the region of interest and FLAC3D zones outside of that

The objective of the study was to determine if the runout would reach the bottom of the pit. The three methods above were used for the evaluation. Runout distances and computational efficiencywas compared across the different modelling approaches.

In the following models, the material was weakened by a factor of 1.1 (relative to the model in Figure 2) to promote unstable failure of the volume at marginal condition (FS ~1.1). This potentially represents an extreme rainfall event of another scenario that may further destabilize the slope.

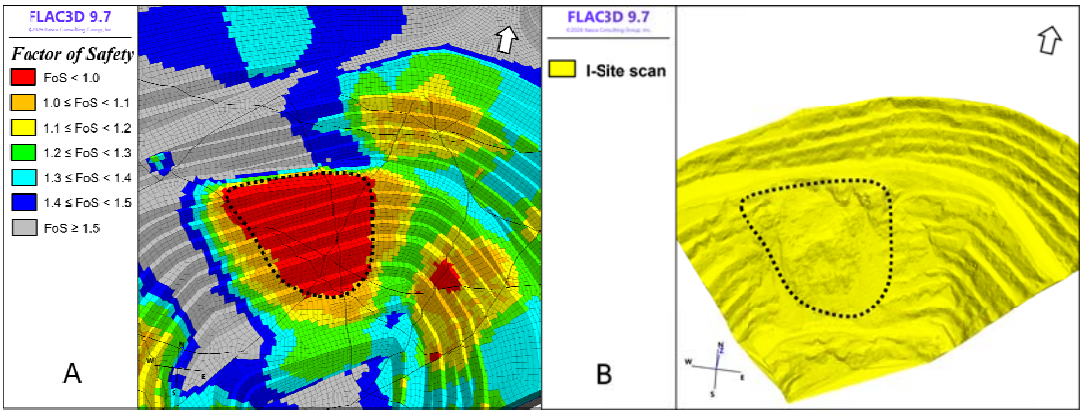


Fig. 2Factor of safety contours from calibrated model in small-strain (A) compared against I-site scan from the failure (B). Dotted black line delineates the area of high deformations identified by radar.

3.3 Methodology

When run in large-strain mode, the finite volume formulation eventually produces zones with highly distorted geometries (illegal geometries), at which point numerical stability is compromised and the calculation cannot continue. To overcome this limitation, the simulation was halted and "rewound" to a stage immediately prior to the onset of mesh degradation.

From this state, two alternative approaches were implemented:

- Meshless method: All zones in the model were converted to material points prior to continued simulation.
- Hybrid method: A predefined volume encompassing the region expected to undergo large deformation was converted from zones to material points prior to continued simulation.

In both approaches, the conversion from zones to material points is performed by directly transferring state variables, including material properties, stresses, and displacements. This allows continuity of the mechanical response during the transition.

3.4 Post-Failure Response

3.4.1 Fully meshed FLAC3D

In the fully meshed FLAC3D model operating in large-strain (Figure 3), numerical stability deteriorated rapidly once displacement exceeded approximately three times the element size (~20 m). Mesh distortion limited reliable prediction of runout extent. This limitation is common in FLAC3D models run in large-strain mode with complex meshes such as open pit geometries.

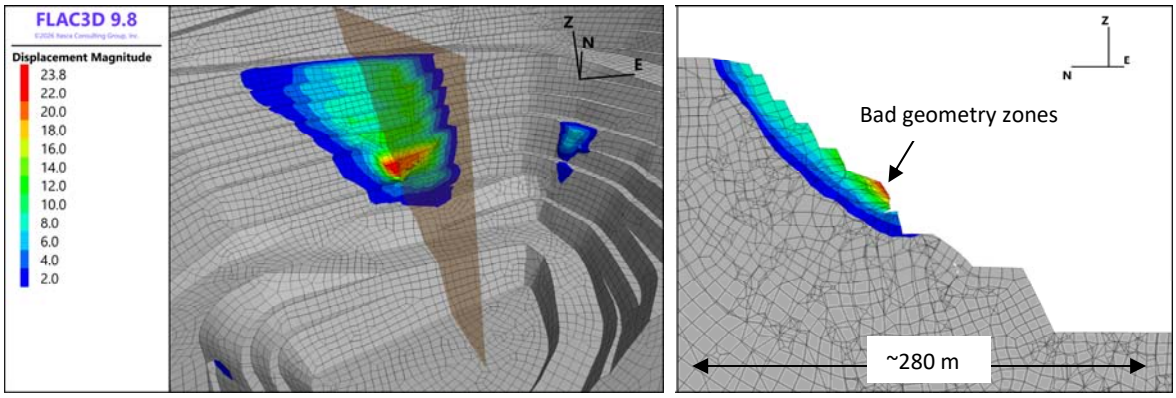


Fig. 3 Fully meshed FLAC3D model results in terms of total displacements (m). The semi-transparent brown rectangle in the left plot shows the location of the cross-section in the right plot.

3.4.2 Fully Meshless Method

The MPoint simulation, in which all zones were replaced by material points, reproduced continuous acceleration, flow, and deposition of the failed rock mass (Figure 4). The results demonstrate that the material point method can simulate large deformations and runout behaviour, which cannot be captured using a purely meshed approach without remeshing.

The model shows that most of the failed material is contained in the ramp below rather than on pit bottom. An interesting observation is the apparent gap between the failing material and the bottom of the pit. There is not a true gap here, there is a specified interaction between the material points that prevents them from interpenetrating. As material points come close together, they are considered part of the same continuum, even though in reality there is probably a sliding contact between the two materials. This problem is addressed in the hybrid model of the next section.

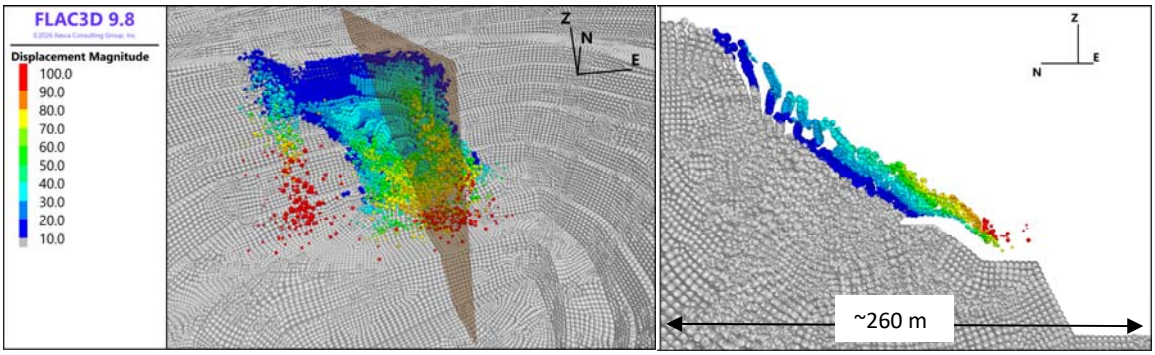


Fig. 4 Fully meshless MPoint model results in terms of total displacements (m).

3.4.3 Hybrid Method

In the hybrid FLAC3D-MPoint simulation, zones within the region of expected large deformation were replaced by material points. Zones adjacent to the material points interact with the material points by using hybrid points as described above. To prevent the unrealistic merging of material in the sliding mass and the bottom of the pit, hybrid points were not added to the zones below the failure region. Instead, a frictional wall was placed on the surfaces of the zones. The wall prevents penetration of the material points into the zones and also offers a frictional surface on which the failing material can slide. The model set up is shown in Figure 5.

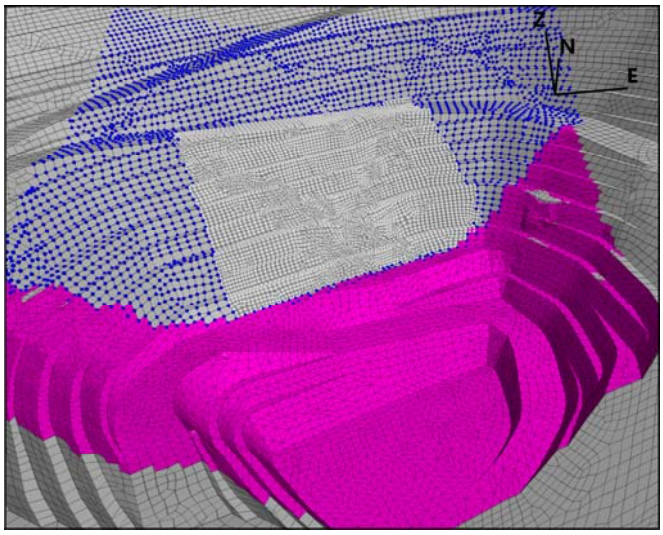


Fig. 5. Hybrid model prior to solving. Blue spheres show the location of hybrid material points used in coupling the FLAC3D zones and the material points. The pink surface represents the frictional wall attached to the zone faces at the bottom of the pit.

Displacement results are shown in Figure 6. In this model, the failure is contained in the ramp below the failure. The advantages of this approach are (a) the spurious "merging" of material at the bottom of the pit can be prevented (b) the calculation is significantly faster (~ 10x).

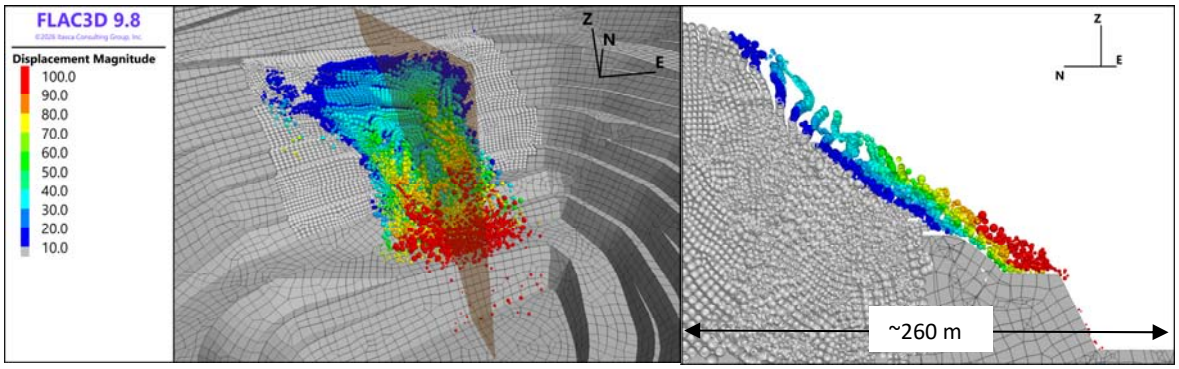


Fig. 6 Hybrid FLAC3D-MPoint model with area of interest replaced by material points. Results in terms of total displacements (m).

4 Discussion and Conclusions

The results demonstrate that the hybrid formulation retains the ability of continuum-based methods to represent progressive failure while enabling simulation of large deformation and post-failure behaviour. The case study shows that this approach can be applied to realistic three-dimensional geometries, including complex open pit configurations. In this case, the MPoint-based simulations indicated that most of the failed material would be contained on the ramp below, with only a limited volume potentially reaching the pit bottom if the failure were to progress during more intense rainfall events.

A key advantage of the FLAC3D-MPoint approach is the use of a consistent numerical framework to assess both slope stability and post-failure response. Conventional workflows typically rely on separate tools for factor of safety calculation and runout analysis, which introduces additional assumptions and potential inconsistencies between the two stages. In addition, modelling the rock mass with finite volume zones away from areas of high deformation and material points only where large strains develop provides significant calculation efficiencies compared with representing the entire domain using material points. The hybrid FLAC3D-MPoint framework allows progressive failure development, velocity evolution, and deposition geometry to be simulated within a single analysis.

The example presented here answers the practical question of whether a slope failure could reach the bottom of the pit. However, more reliable predictions of runout distance, deposition geometry, and failed volume require calibration of the post-peak material behaviour against observed failures whenever such data are available. As with any numerical assessment, calibration remains essential for establishing confidence in the predicted response.

Although the MPoint and hybrid FLAC3D-MPoint approaches successfully extend the analysis beyond the limits of traditional continuum methods, further development and validation are required before the methodology can be routinely applied for quantitative prediction of post-failure behaviour. Future developments should focus on improving numerical robustness and the representation of material separation and deposition processes, enabling more reliable quantitative predictions of final runout extent.

Overall, the methodology provides a practical framework for linking stability analysis with consequence assessment. This capability is particularly relevant for high-consequence slopes, where consistent representation of failure mechanisms and runout behaviour is required to support hazard assessment and risk-informed decision-making.

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