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Cave-scale 3D finite discrete element method modelling

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Abstract

The reliable prediction of caveability, cave breakthrough and subsequent subsidence is critical for cave mining. While continuum-based numerical methods are computationally efficient for large-scale analysis, they are often limited in their ability to explicitly simulate the complex kinematic and fracturing mechanisms associated with cave propagation, large-scale displacement, and the transition from relatively intact rock to a mobilised caved mass. This paper presents a 3D finite discrete element method (FDEM) approach to simulate the complete caving process, from initiation and propagation to surface breakthrough and crater formation. By integrating fracture mechanics principles, the proposed 3D FDEM framework explicitly models the progressive degradation of the rock mass from a continuum to a discontinuum state through stress-induced fracturing and the mobilisation of discrete blocks. The model incorporates a discrete fracture network (DFN) to represent the inherent structural heterogeneity of the rock mass, allowing for the simulation of realistic failure mechanisms. The results highlight that explicit consideration of brittle fracture processes and structural kinematics is essential for reliable forward analysis of the caving process.

Keywords: *cave mining, cave-scale modelling, 3D FDEM, discrete fracture network*

1 Introduction

Block or panel caving is increasingly the method of choice for extracting large, low-grade orebodies at depth. As mines transition into deeper and more competent rock masses, the uncertainty surrounding cave initiation and propagation increases significantly. The primary geomechanical goal is to ensure that once the undercut is established, the cave propagates upward in a controlled manner until it reaches the surface. However, the industry still grapples with 'stalled' caves or unexpected subsidence profiles that deviate from empirical predictions. This paper explores how advanced numerical frameworks can move beyond empirical charts to provide a physics-based forecast of cave evolution.

2 Critical brief review of cave-scale modelling

Cave mining is the primary underground method for extracting large Cu-Au porphyry deposits. These orebodies are broadly characterised by jointed to massive rock masses composed of a range of weak to hard intact rock blocks, often intersected by healed defects such as veinlets. This geomechanical variability presents significant challenges in the simulation of cave initiation, propagation, subsidence, and fragmentation. Furthermore, it directly impacts the effectiveness of preconditioning strategies, such as hydraulic fracturing, intended to assist the caving process. A generalised concept of the cave mining process is illustrated in Figure 1.

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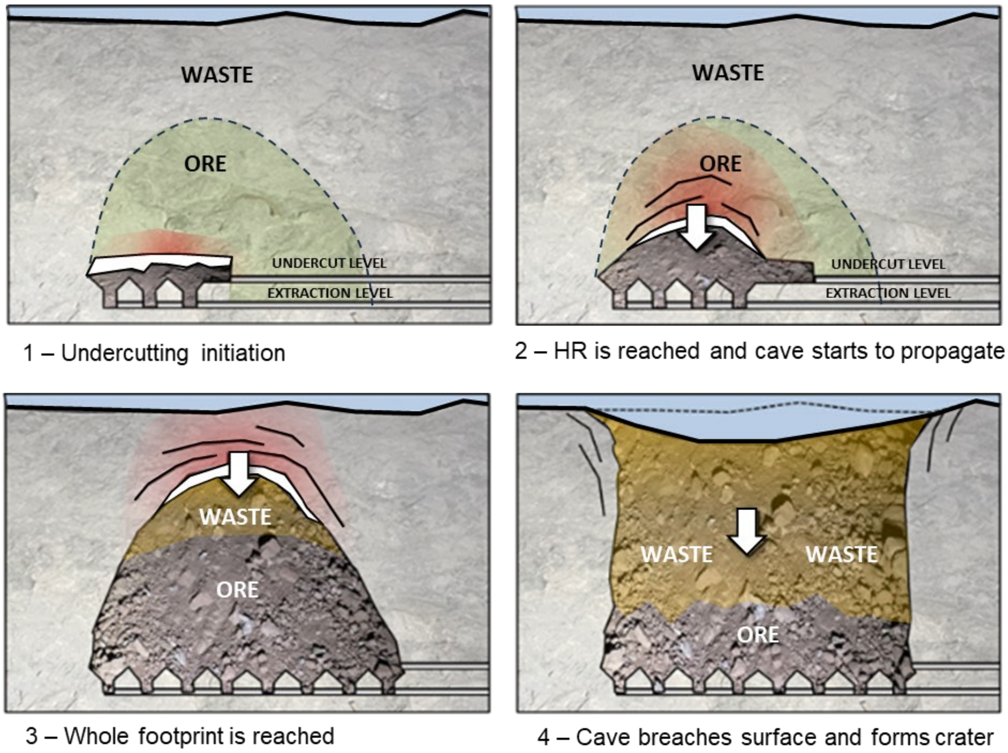


Figure 1 Cave mining process. HR = hydraulic radius

2.1 Rock mass characterisation for caving design

The increasing demand for high reliability in upfront rock mass characterisation, coupled with the ever-increasing depth of modern caving operations, further complicates the engineering design. Factors such as the critical hydraulic radius (HR) required to initiate continuous caving, the rate of cave propagation, reliable estimates of primary and secondary fragmentation, and predictions of surface breakthrough all introduce critical uncertainties. These complexities have a significant impact on operational safety (e.g. airblast risk from stalled caves) and project economics.

In the authors' view, a primary challenge for the cave designer is to be "roughly right rather than precisely wrong." This philosophy should apply to all design aspects, from critical hydraulic radii to the ultimate surface subsidence profile. Caving mechanics and cave behaviour are governed by the interaction of in situ and induced stress fields, rock block strength, and discontinuities. Discontinuities in a geological sense affecting the caving process can range from large-scale features like faults and dykes to smaller-scale stochastic features such as open joints and defects.

Traditional rock mass classification systems used for drillcore logging often ignore or misinterpret critical features of the rock mass fabric. While field or laboratory strength testing of hand-sized rock specimens is standard, it is impossible to directly test the strength of rock blocks or the rock mass in situ. Consequently, characterisation relies on drillcore data, which is a poor predictor of large-scale behaviour due to scale effects and drilling bias (e.g. orientation bias). These challenges can introduce systematic errors in geotechnical characterisation and bias in rock mass parameters. Furthermore, the necessary simplification of geotechnical domains for modelling purposes can further erode the reliability of inputs before simulation begins. These shortcomings can partially be rectified with a well calibrated discrete fracture network (DFN) model, which itself also carries limitations that are not detailed in this paper.

2.2 Modelling challenges of the caving process

While a rock mass may be treated as a continuum for stress analysis, it undoubtedly behaves as a discontinuum once caving is initiated. Therefore, discontinuum-based modelling, specifically hybrid modelling approaches, offers a distinct advantage over pure continuum methods in simulating the transition from a continuous solid to a mobilised caved mass.

Continuum-based modelling approaches can face challenges when simulating the transition from small-strain to large-strain regimes (Figure 2). In the small-strain regime, the rock mass remains largely intact, and deformation is governed by the elasticity of the rock materials and the stiffness of closed discontinuities. However, as caving progresses, the rock mass enters a large-strain regime characterised by the initiation of new fractures and the mobilisation of newly formed rock blocks. Continuum codes rely on compatibility equations that assume displacement is continuous across element boundaries. When fragmentation occurs, these assumptions are violated because the rock mass experiences sudden jumps in displacement and kinematic rotation. While continuum models can approximate damage through plastic strain or isotropic property reduction, they cannot explicitly capture the bulking and detachment of rock mass that define the caving process.

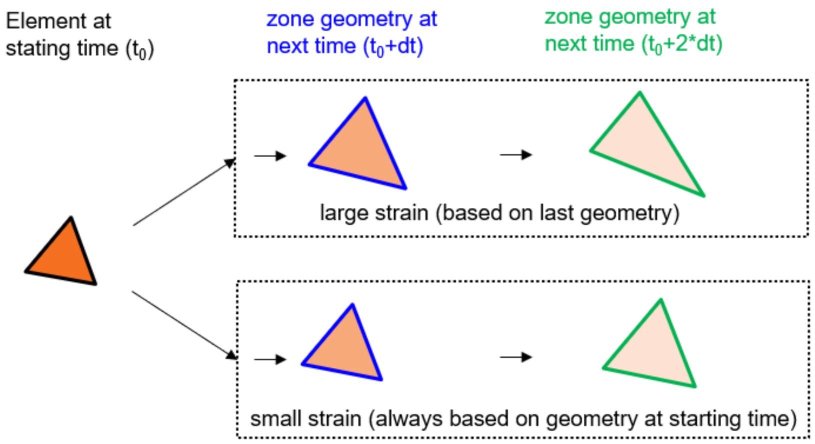


Figure 2 Small-strain versus large-strain modelling challenges in continuum modelling

The dominant mechanism driving cave propagation, whether gravity driven or stress assisted, is the shearing or extension of pre-existing discontinuities and the brittle breakage of rock bridges or asperities. Capturing these discontinuous processes explicitly is essential for more realistic cave modelling. In addition, the caving process is inherently 3D, as is the heterogeneity of the rock mass. Caving is influenced by 3D stress redistribution, cave geometry, and mining direction. Thus, 3D modelling is necessary for cave-scale analysis. While 2D or elastic modelling remains useful for rapid sensitivity checks, 3D discontinuum modelling more closely reflects the physical reality of rock engineering.

The hybrid finite element/discrete element method (FDEM) provides a fracture mechanics based numerical modelling code designed to model the fracture and fragmentation process of brittle materials (Munjiza 2004). FDEM can explicitly model the transition from intact rock material to discrete fragments through the generation of new fractures within a previously continuous material, with or without DFN. However, adhering to rigorous fracture mechanics principles (e.g. cohesive zone modelling) requires complex contact detection and nonlinear separation logic in a complex 3D FDEM model, which increases computational demand.

In practice, integrating stochastic DFNs into 3D meshes introduces significant obstacles, including geometric complexity and non-manifold topological issues. Ensuring the mesh conforms to the complex, intersecting surfaces of a DFN often leads to excessive element counts or degenerate mesh geometries. To address this, the application of parametric mesh generation and General-Purpose computing on Graphics Processing Units (GPGPU) acceleration (Zhu et al. 2024; Wang et al. 2025) offers a path forward. These techniques optimise element shape, eliminate degenerate elements, and allow for the dynamic scaling of mesh density, significantly reducing the computational cost of field-scale 3D FDEM simulations.

3 Framework for cave-scale 3D finite discrete element method modelling

This study employs parallel continuum-discontinuum code (PCDC3D), a graphics processing unit (GPU) accelerated FDEM program, to simulate the rock mass fracturing process. In PCDC3D, the fundamental computational entity consists of tetrahedral finite elements, which are governed by an elastic constitutive model. The interaction between elements at contact interfaces is simulated using the Mohr–Coulomb (M-C) constitutive model. Crack initiation and propagation are explicitly modelled using the Extrinsic Cohesive Zone model (ECZM, Geomechsim 2025), intrinsic cohesive zone model (ICZM, Munjiza 2004), or unified cohesive zone model (UCZM, Lei et al. 2024) grounded in fracture mechanics theory.

3.1 3D finite discrete element method based representative rock mass simulation

In the hybrid FDEM modelling, fracturing is represented by the insertion of face-joint elements between adjacent finite elements, as shown in Figure 3. The mechanical behaviour of these joint elements follows a traction-separation law derived from fracture mechanics. While they can be modelled using either the intrinsic (ICZM), extrinsic (ECZM), or UCZM approach, the UCZM is utilised here to ensure that the initial elastic stiffness of the rock is not artificially reduced by the presence of unbroken cohesive elements and ensure time continuity (Papoulia et al. 2003).

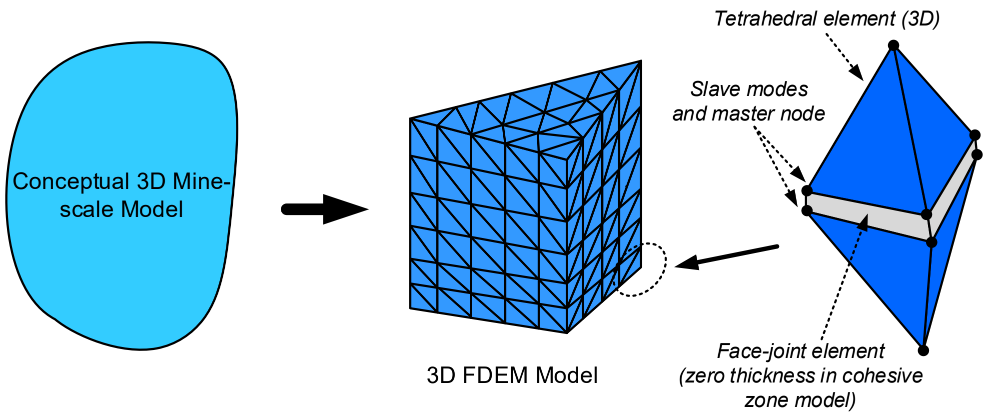


Figure 3 Face-joint elements and tetrahedra elements in a 3D finite discrete element method (FDEM) model

In cave mining engineering, discontinuities exist across 4 distinct scales, each influencing the rock failure process under varying loading conditions. These include:

- Large-scale or major geological structures, such as faults and shear zones, which extend beyond the mine scale and dominate large-scale deformation.
- Intermediate-scale features, including long persistent joint sets and bedding planes, which define the representative rock mass anisotropy. In the field, one or 2 dominant sets often control behaviour, contradicting the isotropic assumptions inherent in systems like the geological strength index (GSI).
- Macro-visible defects, such as veinlets, which are observable at the rock block scale. Besides their impact on the rock mass, they control rock block strength (RBS) and directly affect primary and secondary fragmentation.
- Micro-defects, such as microcracks or foliation, which affect the laboratory sample scale and impact intact rock strength.

The concept of weakening defects was introduced by Laubscher & Jakubec (2000). Each of these scales contributes to the overall rock mass response, requiring a multi-scale upscaling scheme (Figure 4). It is important to note that reliance on the GSI system alone may introduce errors because it often fails to account for rock block defects and inherent structural anisotropy.

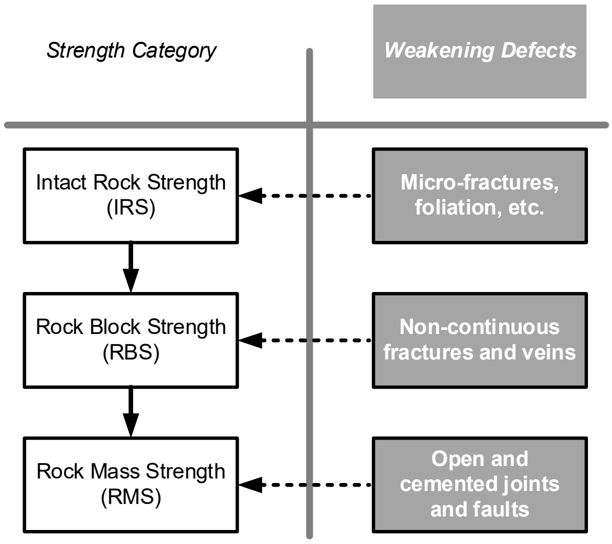


Figure 4 Impact of various rock defects (Laubscher & Jakubec 2001)

Before conducting cave-scale simulations, representative intact rock samples are collected for laboratory testing. 3D FDEM modelling is employed to calibrate the derived mechanical properties. Standard tests, such as uniaxial and triaxial compression and Brazilian tension, are used to derive input parameters, including fracture energy. The calibration process establishes a distribution of parameters that encapsulate the natural variability observed in laboratory tests. For FDEM-based modelling following the UCZM approach, most input parameters have direct physical correspondence. Fracture energy can be inferred from fracture toughness tests, while contact interface properties can be parameterised using M–C or equivalent Hoek–Brown criteria. To ensure model validity, it is crucial that numerical simulations replicate characteristic rock failure modes, such as spalling or extensional fracturing at low confinement, and shearing under confined conditions (Stacey & Wesseloo 2022).

The second step of the workflow is to estimate rock-mass-scale properties. For a given caving project, rock mass behaviour varies across geotechnical domains. As a result, both size effects and heterogeneity become more pronounced. Once modelling parameters are calibrated at the laboratory scale, they should be extrapolated to represent rock mass behaviour at larger scales, up to a size where the influence of size effects stabilises. The strength and deformation behaviour of large-scale rock masses remains an area of ongoing research without a single industry consensus. To guide the upscaling of 3D FDEM parameters, empirical scaling laws such as the generalised Hoek–Brown criterion and mining rock mass rating (MRMR) scheme provide a useful starting point for estimating large-scale RBS. These include datasets such as those compiled by Yoshinaka et al. (2008) (refer to Figure 5, hence up to about 0.5 m sized scale). Additionally, large-scale sample testing results, especially those back-analysis results from site rocks or geomechanically similar rock types serve as a benchmark for validating upscaling results up to the scale of several metres.

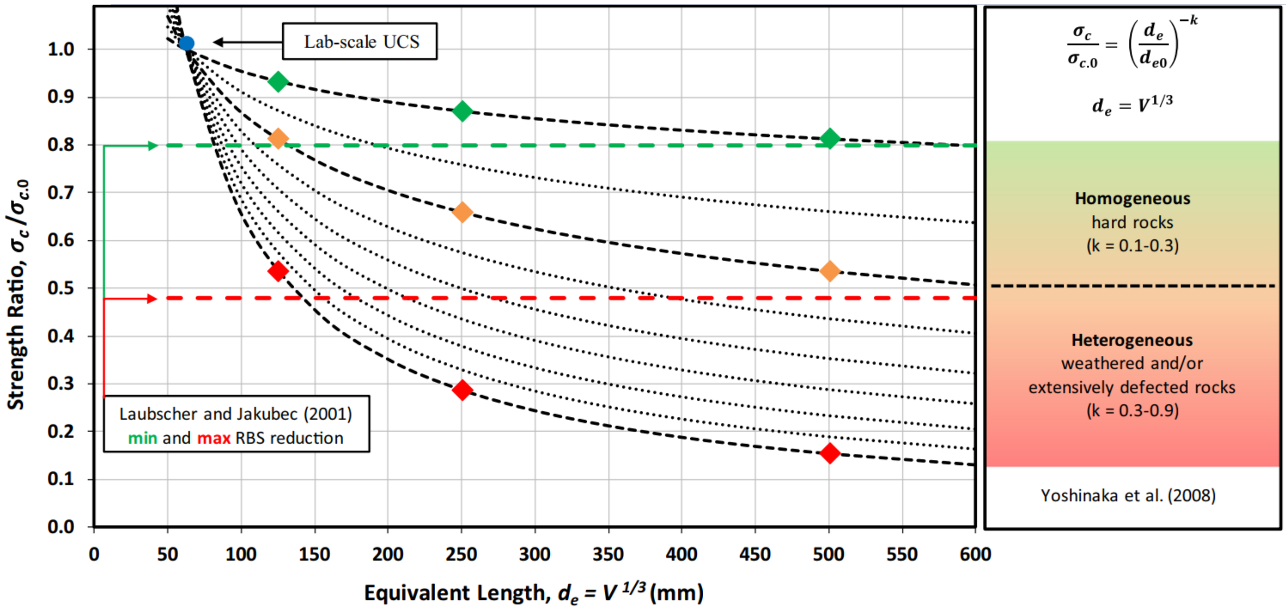


Figure 5 Scale-effect relations, from Stavrou et al. (2019), adapted from Yoshinaka et al. (2008)

This process is termed representative rock mass simulation (RRMS). While conceptually similar to the synthetic rock mass (SRM) approach (Pierce & Fairhurst 2011), it differs in 2 key aspects:

- Instead of using the term 'synthetic', this approach emphasises that the rock mass is being 'simulated' through a structured upscaling framework.
- One single numerical algorithm is applied consistently across all 3 scales, from the laboratory to the cave scale. This preserves the theoretical continuity of fracture mechanics throughout the model hierarchy for upscaling rock mass properties in 3D FDEM simulations.

It is critical to note that RRMS is not intended to diminish the established application and emergent capabilities of the SRM approach. While RRMS enforces algorithmic consistency across scales, its implementation remains model-form dependent, and theoretical consistency does not automatically guarantee absolute physical correctness. In practice, parameters such as fracture energy and cohesion remain inherently scale-dependent, and mesh-size effects must still be accounted for. Nevertheless, the primary advantage of RRMS lies in its alignment with the chosen 3D FDEM computational architecture. By establishing a single upscaling pathway, it can enhance computational efficiency and eliminate the necessity of cross-calibrating rock properties across different numerical codes.

In the third stage, these calibrated parameters serve as the foundation for full cave simulation. Additional large-scale structural features and long persistent joint sets are explicitly incorporated via cave-scale DFN models or interface geometries. Undercut geometry is introduced to align with the production schedule, focusing on the attainment of a sustained HR.

3.2 Short summary of proposed 3D finite discrete element method modelling cave-scale modelling

Figure 6 summarises the proposed 3D FDEM workflow to achieve RRMS for cave design.

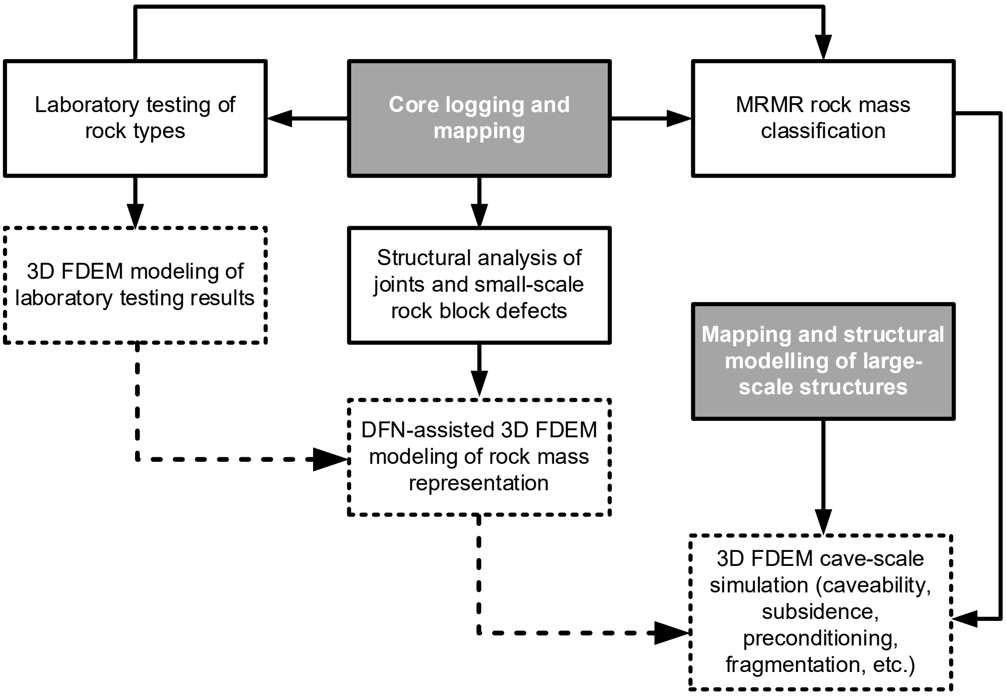


Figure 6 Proposed framework of 3D finite discrete element method modelling (FDEM) based cave-scale modelling

To address the limitations of applying discontinuum-based methods, including hybrid modelling for cave simulations discussed in Section 2.2, Figure 7 summarises the tools and technologies utilised in our workflow. This includes the high-end GPU acceleration required to achieve cave-scale modelling. In particular, sound numerical modelling that fulfills engineering requirements should not only be theoretically viable but must also match real field observations to verify its validity. The proposed modelling framework was first tested against physical centrifugal testing results (Section 4.1) using a large-scale 3D FDEM conceptual model (Section 4.2), then checked against MRMR caving chart (Section 4.3).

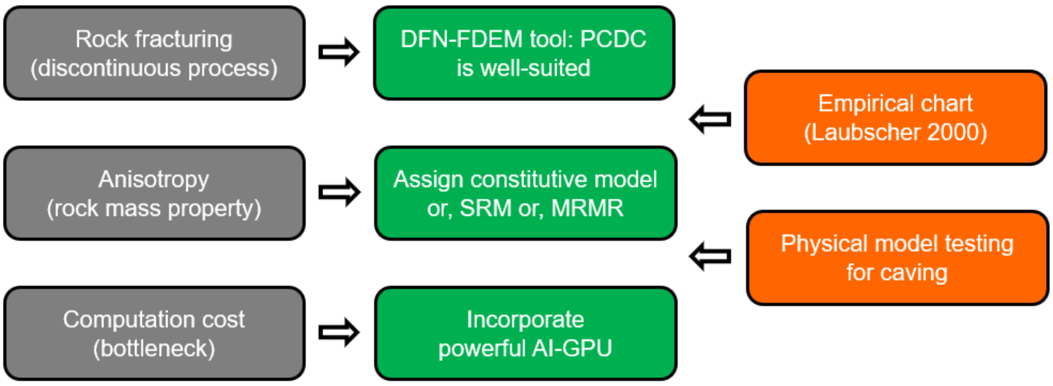


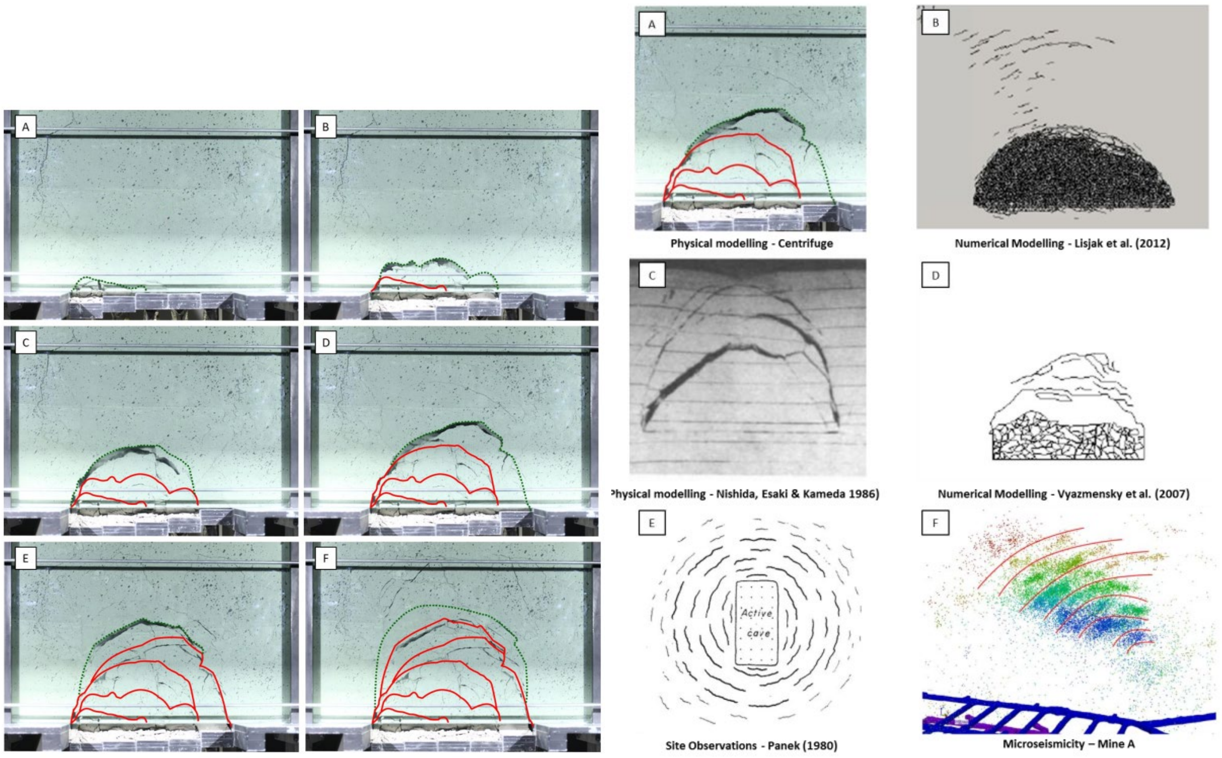
Figure 7 Summary of tools and technologies adopted in the 3D finite discrete element method modelling (FDEM) workflow to achieve cave-scale modelling

4 Simulation of the caving process

4.1 Recent refined findings on the caving process

Research by Cumming-Potvin (2018) and Wesseloo (2021), sponsored by Newcrest Mining , was initiated to address the limitations of existing conceptual models, particularly as cave mining operations transition into deeper and more competent primary rock masses. These findings challenge the industry-standard Duplancic (2001) model, which posits that rock mass damage ahead of a cave back is a continuous process that decreases monotonically with distance from the cave surface. Utilising centrifuge physical modelling at scale factors up to 119 g, Cumming-Potvin (2018) proposed an update to the understanding of failure mechanics. The results indicate that cave propagation in competent rock is not always a continuous degradation process but often occurs through a discontinuous mechanism termed ‘fracture banding’ (Figure 8a).

In this refined conceptual model, the cave back progresses vertically in discrete ‘jumps’ rather than through steady block fallout. Failure is driven by successive extensional fractures oriented parallel to the cave surface, which form bands of intense fracturing separated by relatively intact zones of rock, and it does not appear to be an unique feature from physical modelling of caving process (Figure 8b).



(a) (b)

Figure 8 Centrifuge physical modelling of block caving supported by other evidences (Cumming-Potvin 2018). (a) Centrifuge physical testing results; (b) Evidence of ‘fracture banding’ from different sources

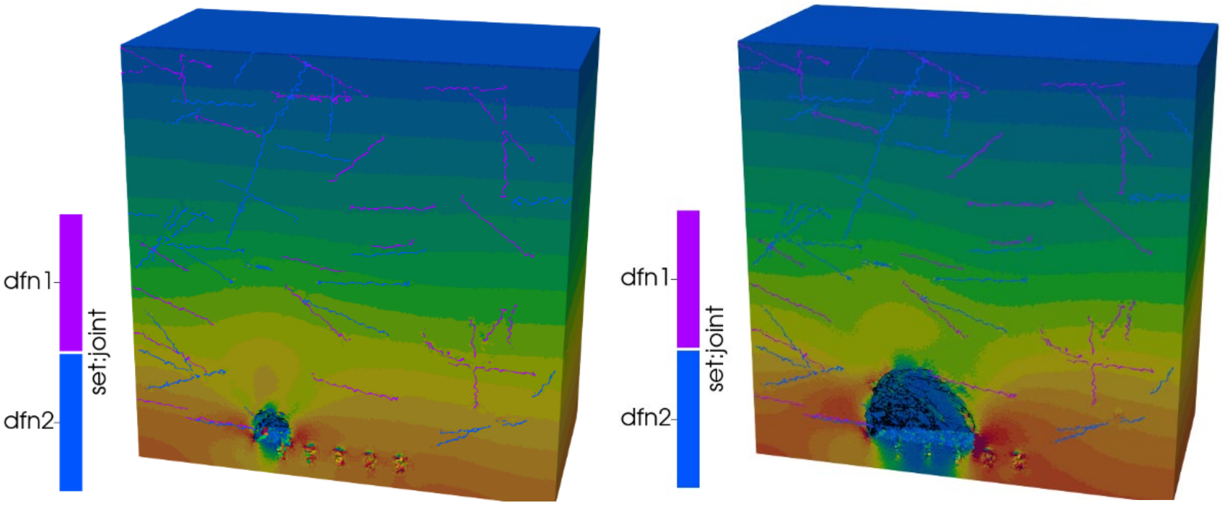
This extended conceptual model is further supported by the synthesis of multi-source instrumentation data from Kamp et al. (2024). By reconciling microseismic clusters, time domain reflectometry measurements, and smart marker data, Kamp et al. (2024) provided operationally proven evidence of these discontinuous failure profiles across several major cave operations, including New Afton, Cadia East, Carrapateena, and El Teniente. In fact, this failure mode might be universal, applying to competent rock mass failure in low confinement (see the anecdotal illustration in Figure 9, where a natural rock bridge collapsed).

(a) (b)

Figure 9 Snapshot of the collapse of Australia's London Bridge (Darrington 1990). (a) Small pieces of rock tumbling from London Bridge; (b) London Bridge the moment it collapsed

4.2 A conceptual model of cave-scale 3D finite discrete element method case

To evaluate the feasibility of the proposed 3D FDEM workflow, a high resolution model comprising more than 12 million elements was developed. The model simulated a 250 × 250 m footprint within a 500 m cubic domain. Two sets of DFNs, each including 100 features representing persistent joints, were introduced. Utilising a NVIDIA H100 GPU, the simulation of the complete undercutting sequence took less than 24 hours. As illustrated in Figures 10 and 11b, the snapshots capture the progressive upward advance of the cave, clearly delineating the evolution of both the caving zone and the overlying seismic (damage) zone.



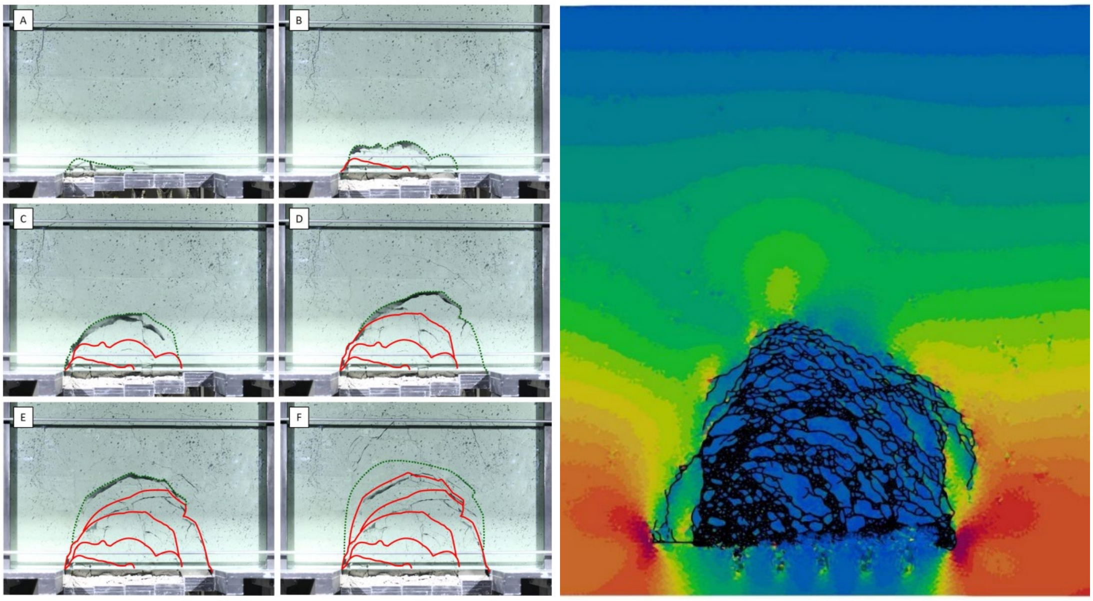
(a) (b)

Figure 10 A conceptual cave-scale 3D finite discrete element method model simulating caving process. (a) Start of undercutting; (b) Undercutting continued

In this framework, regions that have entered the post-peak deformation stage but have not yet reached the residual strength state are interpreted as the seismic zone. In contrast, fully fractured and mobilised material defines the caving zone. Fracturing blocks collapsing into the undercut were assumed to be removed, representing material extracted from the drawpoints and simulated through zone removal. In particular, the modelled fracture modes ahead of the cave propagation direction resemble the 'fracture banding' observed from the physical centrifuge modelling results (Figure 11).

Overall, the simulation demonstrates that the 3D FDEM approach is capable of conceptually reproducing large-scale caving processes with fine element discretisation. this overcomes key limitations associated with earlier

2D or simplified 3D DEM and FDEM methods. the results successfully replicate fundamental features of block caving, including cave initiation, upward propagation, the formation of caving and seismic zones, and the development of stress abutments surrounding the cave. these outcomes provide validation of the proposed 3D FDEM framework as a practical tool for analysing caveability and simulating complex caving processes.



(a) (b)

Figure 11 Comparison of caving failure modes between physical centrifugal modelling and 3D finite discrete element method modelling. (a) Physical centrifugal modelling; (b) Section view of completion of undercutting

4.3 Calibration of Laubscher's caving chart

A simplified conceptual block cave model was established following the same model setup as outlined in Sainsbury (2010), featuring a mining footprint with dimensions of 120 × 120 m (HR = 30 m) at a depth of 600 m below the surface. The maximum principal stresses are horizontal and twice the magnitude of the vertical stress. Production draw was simulated to a total height of 10 m. Four rock masses of varying strength (RM1, RM2, RM3, and RM4), representing 4 distinct rock mass MRMR values were defined and mapped onto Laubscher's caving chart in Figure 12.

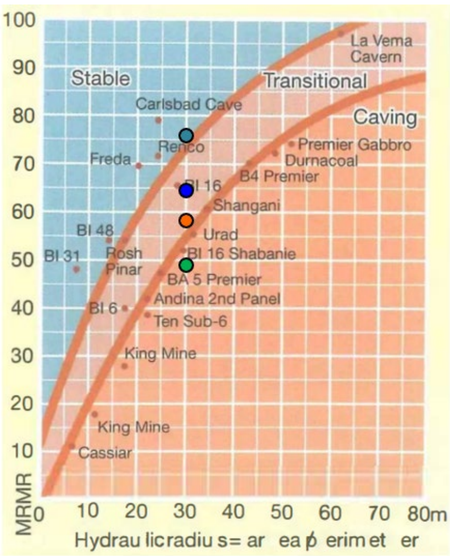


Figure 12 Laubscher's caving chart mapped with 4 rock mass types in circles (RM1 to RM4 from bottom to top)

The cohesion and friction angles used in the UCZM were estimated through a series of numerical uniaxial compression strength (UCS) tests conducted with different block sizes and the average element size adopted in the actual model. The fracture energy assigned to the rock blocks at the average element size was scaled based on the fracture energy of the intact rock. Referring to Figure 13, RM4, representing the strongest rock mass properties, did not initiate caving. RM3 stalled very quickly after undercutting. RM2 propagated to a certain height before stalling. In contrast, RM1, which possesses the weakest rock mass properties, caved continuously and propagated up to a height of 150 m, measured from the broken zone height. The modelled results match the Laubscher's caving chart (Figure 12) broadly well.

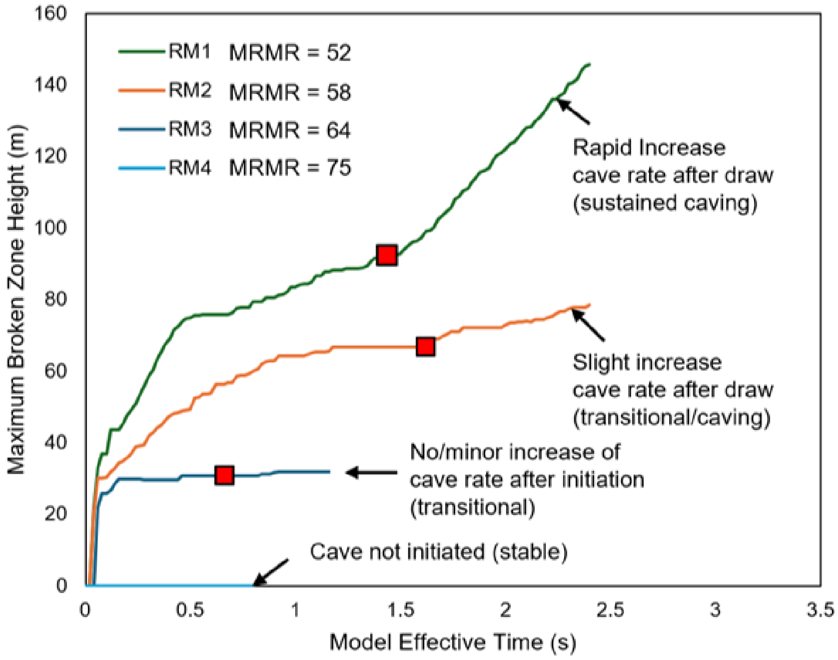


Figure 13 The evolution of the broken zone height over model time across the 4 rock mass types

5 Conclusion

The application of a hybrid 3D FDEM framework to cave mining addresses the limitation of continuum-based methods by explicitly modelling the rock mass transition from a continuous solid to a mobilised, fragmented medium. By integrating fracture mechanics principles with stochastic DFN representations, the proposed workflow captures the kinematic processes of block mobilisation and 'fracture banding' identified in recent centrifuge physical modelling and field observations. The ability to simulate the sudden jumps in displacement and rotation characteristic of the large strain regime allows for a more realistic prediction of cave propagation, seismic zone development, and surface breakthrough. This physics-based approach provides a high-fidelity alternative to empirical design charts, offering a robust foundation for forward analysis in deep, high-stress, and competent rock masses where structural heterogeneity governs the failure mechanism.

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