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Modelling of rock mass fracturing, fragmentation and preconditioning to assist in caving design

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Abstract

The transition to deep, competent orebodies in block caving operations presents significant challenges regarding caveability, primary fragmentation, and seismic hazard management. However, quantifying the mechanistic interaction between stress-induced fractures and the natural discontinuities remains complex. This paper presents the application of the hybrid finite-discrete element method (FDEM) to simulate these coupled processes. Unlike conventional continuum or purely discrete approaches, FDEM explicitly models the transition from continuous to discontinuous media, allowing for the rigorous simulation of fracture propagation through intact rock. This study utilises 3D FDEM to integrate discrete fracture network (DFN) representations of in situ rock fabric with fracture propagation logic. Simulation results demonstrate that FDEM effectively captures the reduction in rock block volume resulting from progressive fracture initiation and coalescence under increasing loading levels, representing either caving-induced stress or hydraulic pressure in cave mining operations.

Keywords: *block caving design, fragmentation, stress or hydraulic fracturing, 3D FDEM*

1 Introduction

Block or panel caving is increasingly the primary underground method for extracting large, low-grade porphyry deposits. These operations are transitioning into deeper and more competent primary environments characterised by massive rock masses where natural jointing is sparse or 'healed' by veinlets. In these settings, the success of the cave depends on the transition from a relatively continuous in situ state to a fully mobilised medium through the brittle fracturing of intact rock bridges. The traditional reliance on empirical charts and continuum-based numerical tools is often insufficient for these jointed hard rock mass environments, where the dominant failure mechanism is the brittle fracturing of intact rock bridges or shearing of joint asperities.

This paper utilises a hybrid finite-discrete element method (FDEM) to simulate these coupled processes. Grounded in the unified cohesive zone model (UCZM) (Lei et al. 2024), the framework explicitly tracks the development of the fracture process zone to ensure time continuity and energy consistency. By integrating stochastic discrete fracture networks (DFN) with energy-based fracture logic, this study demonstrates how 3D FDEM can assist in estimating fragmentation and preconditioning design by modelling rock mass fracturing.

2 Rock mass fracturing process in caving and modelling

Rock masses in nature are intersected by discontinuities. While it may be arguable to treat the rock mass as a continuum in situ or in the far field of mining, the rock mass involving the caving process behaves as a discontinuum once sustained caving is initiated. The caving process is complex because it involves a

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multi-scale transition of the rock mass. At the cave back of deep caving operations, the rock mass is subjected to high caving-induced stresses, leading to the formation of new fractures and the reactivation of natural discontinuities. Primary fragmentation tends to initiate at the weakest points or where stress concentrations occur. Hydraulic fracturing can further complicate the process, whereby fluid pressure actively reduces the effective normal stress on pre-existing joint sets and drives the propagation of new tensile fractures through intact rock bridges. Locally, this leads to progressive fragmentation, dilation, and block fallout. These mechanisms together drive cave propagation and, eventually, surface breakthrough at the cave scale.

Discontinuum-based modelling tools can capture essential aspects of this transition. These include fracture initiation, coalescence, and propagation along pre-existing discontinuities or through intact rock bridges. To capture the rock fracturing mechanisms for cave modelling, a 3D continuum degradation approach is insufficient on its own. Standard continuum models, such as the geological strength index (GSI), typically apply isotropic strength or equivalent reduction to mimic damage. However, they cannot reliably account for the transition of in situ rock mass to the primary fragmentation process because of the sudden increase of rock mass displacement and kinematic rotation at the fracture interface.

A primary challenge of conducting discontinuum-based modelling lies in the dynamic nature of fracture growth. Accurate simulation requires a mesh size small enough to satisfy the requirements of the cohesive zone length as defined by fracture mechanics. This ensures that the energy dissipation during the fracturing process is captured correctly and is not artificially influenced by the element size. Consequently, these high resolution requirements demand substantial computational resources.

3 Comparison of conventional constitutive models and finite-discrete element method modelling

3.1 Conventional constitutive model for rock mass

The simulation of the caving process following conventional continuum-based models requires the description of the post-peak deformation behaviour of the rock mass or a complete stress–strain constitutive model. At scales relevant to rock and mining engineering design, the GSI, which was primarily developed for the Hoek–Brown (H–B) failure criterion (Hoek & Brown 2019), the modified rock mass rating (MRMR) (Laubscher & Jakubec 2001), and the Q-system approach (Barton et al. 1974) are the most commonly used empirical rock mass classification methods. These approaches are widely applied because they provide practical estimates of rock mass strength (Barton 2013), which laboratory testing alone often struggles to achieve due to scale effects. The generalised H–B criterion, in particular, offers a means to describe the complete stress–strain behaviour of a rock mass by incorporating GSI and Factor D (Hoek & Brown 2019) to account for strain-dependent degradation in the post-peak stage.

A major challenge in reliably predicting post-peak deformation in rock masses lies in the scarcity of field monitoring data, which limits confidence in selecting appropriate H–B parameters (or equivalent Mohr–Coulomb [M–C]) for both peak and post-peak rock mass strength. This often results in a wide range of input parameters, with practitioners relying on experience and engineering judgment to estimate material and numerical parameters. This limitation is supported by ongoing debates regarding the extent of the rock mass disturbance zone due to stress relaxation in open pit mining, as well as the precise boundary between seismic and aseismic zones in cave mining and deep open stope mining, where stress-induced fracturing can occur.

It is important to note that numerical models employing the H–B or M–C failure criteria are typically constrained to continuum-based modelling approaches, aiming to capture the global response of intact rock failure and discontinuity-related degradation. However, these models are inherently limited by the assumption of an equivalent isotropic continuum, which does not fully account for structurally controlled failure mechanisms. While ubiquitous joint sets and DFN can sometimes be incorporated explicitly or implicitly, these methods may still oversimplify the inherent heterogeneity of rock mass behaviour.

3.2 Finite-discrete element method modelling algorithm for stress fracturing

The hybrid FDEM is a fracture mechanics-based modelling algorithm designed to model stress fracturing of brittle materials (Munjiza 2004). This approach combines the strengths of the finite element method for modelling continuum mechanics and the discrete element method for handling discontinuities and large deformations. FDEM can explicitly model the complete fracturing process by generating new fractures with or without incorporating pre-existing fractures (e.g. DFN) and ultimate material failure, thereby capturing the transition from continuum to discontinuum mechanics.

However, to strictly adhere to the principles of fracture mechanics that govern intrinsic rock failure, the contact detection and separation behaviours of discretised elements become highly complex and nonlinear, increasing computational demands compared to regular discontinuum codes. While FDEM tools typically employ explicit time integration schemes, these complexities present additional challenges in terms of computational efficiency.

In the intrinsic cohesive zone model (ICZM) approach (Figure 1), which is the classic model for FDEM, crack elements must be pre-inserted prior to computation. The constitutive behaviour follows a nonlinear elastic response from the initial loading state (O_0) to the peak stress point (O_p), beyond which the material transitions into a softening phase (O_p to O_r), and fracture energy G_{fI} (mode I) and G_{fII}.(mode II) governs softening phase. The initial elastic response is controlled by 3 penalty parameters: normal penalty, tangential penalty and fracture penalty. The normal penalty primarily controls the material Young's modulus (*E*); tangential penalty affects the material strength; and fracture penalty controls the stiffness of crack element in tension. Theoretically, penalty parameters tend to be infinite; however, in numerical simulation, smaller time step and longer computational time are required with larger penalty. Therefore, finite value (e.g. 10 times *E*) was suggested to balance computational efficiency and accuracy (Munjiza 2004). Note that the suggested value was limited to millimetre-scale models and requires calibrations in metre-scale models.

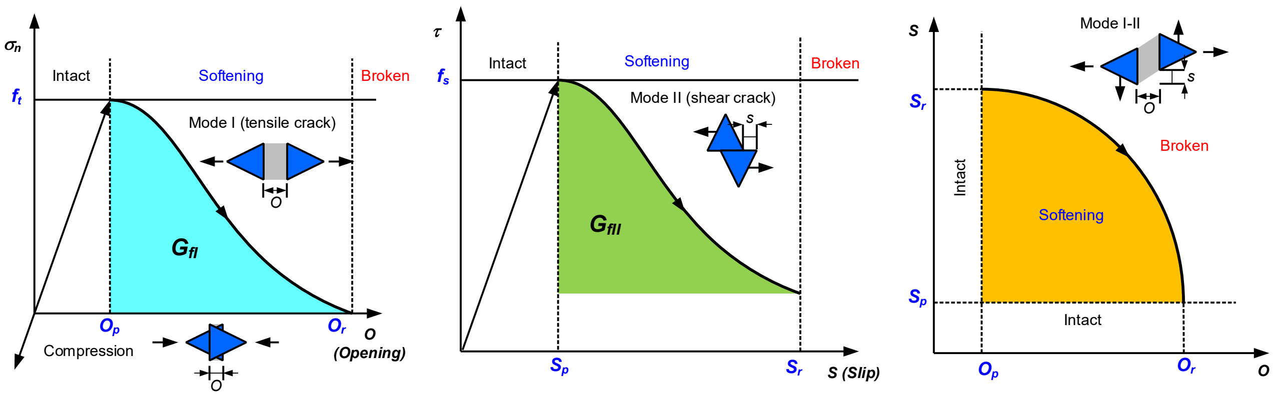

Figure 1 The intrinsic cohesive zone model constitutive relationship between normal stress and opening distance of crack elements

Unlike ICZM, the UCZM approach (Figure 2) does not require predefined crack elements. Instead, crack elements are dynamically inserted when the normal stress (σ_n) or the shear stress (τ) at the interface between adjacent elements exceeds a predefined failure threshold, governed by Equations 1 and 2:

$$\sigma_n \geq f_t \tag{1}$$

$$\tau \geq f_s = \sigma_n \tan\emptyset + c \tag{2}$$

where:

σ_n = normal stress

τ = shear stress

f_s = tensile strength

$\emptyset$ = friction angle

c = cohesion.

At the moment of insertion, the material transitions directly into the softening phase, bypassing the artificial penalty stage. This way, the material stiffness and strength are no longer controlled by penalty parameters (i.e. no calibration needed in any scales), making it a more practical tool in engineering applications.

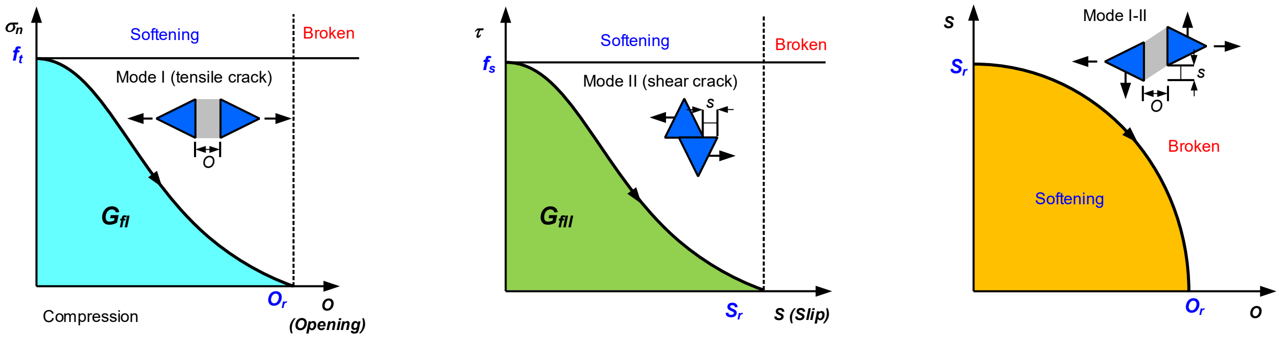

Figure 2 The unified cohesive zone model constitutive relationship between normal stress and opening distance of crack elements

This study employs PCDC3D (Parallel Continuum–Discontinuum Code), a GPU-accelerated FDEM program, to simulate the rock mass fracturing process. PCDC3D integrates the UCZM in a manner that preserves 'time continuity' (Papoulia et al. 2003), following the algorithm proposed by Lei (2024). By leveraging massively parallel GPU computing, the approach significantly reduces computational time compared with traditional CPU-based FDEM simulations while enabling substantially larger model sizes. In the current implementation, simulations involving millions of tetrahedral elements and explicit fracture propagation can be performed efficiently on a single high-performance GPU, making large-scale three-dimensional caving simulations computationally feasible. This capability represents a major advantage over conventional CPU-dependent approaches, which are often limited by computational cost and model scale.

Note that while the UCZM logic successfully bypasses the artificial elastic stiffness reductions and rigorous parameter calibrations traditionally associated with the classic ICZM approach, certain inherent numerical and geomechanical limitations must still be managed. Specifically, because fracture propagation remains bound to the topologies of the finite element mesh, localised mesh dependency can introduce artificial directional bias if not mitigated by a sufficiently refined discretisation. Furthermore, fundamental input properties, especially fracture energy and joint cohesive strength, remain inherently scale-dependent. Consequently, transferring these parameters from laboratory-scale tests to field-scale mine simulations still require upscaling frameworks and/or empirical scaling laws to ensure the model remains reasonable for practical engineering design.

3.3 Mechanical-fluid coupling

The absence of pre-inserted crack elements allows PCDC3D to perform conventional finite element calculations until fracture conditions are met, at which point crack elements are dynamically introduced. This approach not only enhances numerical accuracy but also accelerates the simulation, making it well-suited for large-scale rock mass modelling where complex fracturing behaviour needs to be captured efficiently.

The coupling between fracture fluid pressure and solid deformation is a key feature of the simulation:

- The fluid pressure in the flow channels exerts forces on the solid structure, leading to deformation.
- The deformation affects the flow channels by modifying their opening, which subsequently influences the fluid flow and its pressure on the solid structure.

This interaction represents the fluid–solid coupling effect, where the flow of fluids and the mechanical response of the rock mass are interdependent. A case example is further detailed in Section 4.3.

4 Modelling approach and case studies

The following modelling results illustrate the feasibility of the proposed 3D FDEM workflow for simulating representative rock mass failure processes in cave mining. By integrating DFN, this approach provides more fundamental geomechanical estimates than those typically provided by empirical methods or conventional continuum modelling codes. Detailed information regarding the logic and implementation of this proposed large-scale 3D-FDEM modelling workflow is provided in Xu et al. (2025).

4.1 Mine-by tunnel case

The Underground Research Laboratory (URL) in Canada, managed by Atomic Energy of Canada Limited between 1985 and 2003, served as a landmark facility for investigating geomechanical responses in deep nuclear waste repositories. One of the significant contributions from the URL was the Mine-by Experiment (MBE), which characterised the development of the excavation damaged zone (EDZ) around a 3.5 m diameter tunnel within the Lac du Bonnet granite. Observations documented by Martin (1997) revealed that the failure was dominated by brittle spalling in the roof and floor, leading to the formation of characteristic V-shaped notches in areas subjected to the highest tangential stresses (Figure 3b).

In the context of numerical simulation, the MBE results are widely used as a benchmark for validating constitutive models in brittle rock engineering. To further demonstrate the capability of the 3D FDEM approach, a tunnel excavation model with a radius of 1.75 m was developed in the model. The initial stress field was defined based on values measured at the site such that the intermediate principal stress was aligned with the tunnel axis, while the maximum and minimum principal stresses were 60 and 11 MPa, respectively. Maximum principal stress plunges at 20° with trends of 270°, and minimum principal stress plunges at 70° with trends of 90°. The material behaviour was described using the UCZM model with a friction angle of 40°, cohesion of 25 MPa, tensile strength of 8 MPa, and fracture energies of 42 N/m (mode I) and 420 N/m (mode II). As shown in Figure 3, the simulated fracture zone develops preferentially in orientations perpendicular to the maximum principal stress, and fractured depth is about 0.7 m, broadly consistent with theoretical expectations and field observations of brittle failure around underground openings.

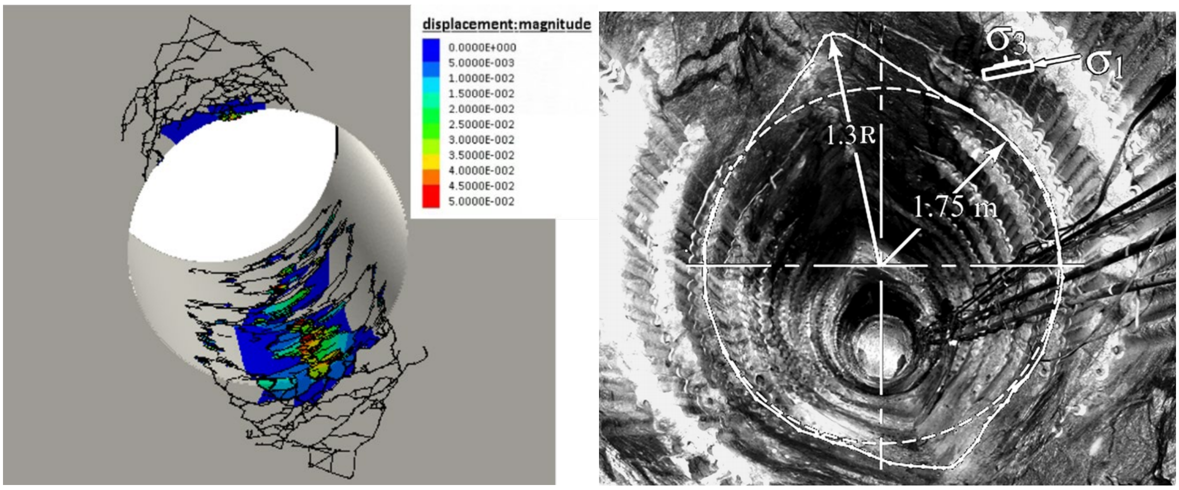

Figure 3 Calibration of Mine-by Experiment (MBE) excavation damaged zone (EDZ) using 3D FDEM model. (a) Oblique view of EDZ in 3D finite-discrete element method model; (b) Photograph of interpreted EDZ from MBE (after Diederichs 2007; modified from Martin 1997)

4.2 Stress-assisted primary fragmentation

Realistic fragmentation estimation is a critical requirement for block cave mine design, as it directly impacts drawpoint productivity, secondary breakage costs, and the selection of material handling systems. Despite its importance, predicting the size distribution of rock fragments remains a significant challenge. Traditional empirical methods often struggle to account for the complex interaction between in situ discontinuities and stress-induced fracturing, particularly in deep and competent rock masses. Furthermore, the lack of high quality field data from operating caves often leads to the underestimation of smaller fragments and fines, which are crucial for assessing gravity flow and dilution.

To address these challenges, whereby improving the estimates of caving-induced fracturing, the authors have been working with the Block Caving Fragmentation (BCF) software developer to advance the new BCF-V4 (Esterhuizen 2026), through the integration of stochastic DFN and FDEM techniques. This collaboration focuses on incorporating operationally proven field data from diverse cave mines, such as those with varying rock mass characteristics, to improve the reliability of prediction logic. A specific workflow has been developed for projects where the rock mass is expected to undergo significant stress-assisted fracturing. This approach serves as a modelling alternative to the standard primary fragmentation module within BCF-V4, following the steps illustrated in Figure 4:

- Step 1: construct and calibrate an in situ rock mass DFN model of the geotechnical domain at a scale comparable to several draw column widths.
- Step 2: develop a 3D FDEM model that integrates the calibrated DFN. This model simulates the progressive fracturing behaviour of the rock mass as it is subjected to the loading levels expected at the cave back. As shown in Figure 5, the growth of stress-induced fracturing is tracked as a fracture intensity parameter (P32) relative to the increasing load levels.
- Step 3: use the quantitative insights of fracture growth from the 3D FDEM results to construct a modified DFN that represents the products of primary fragmentation. The resulting block size distribution of this updated DFN then serves as the inputs for the secondary fragmentation estimates within BCF-V4.

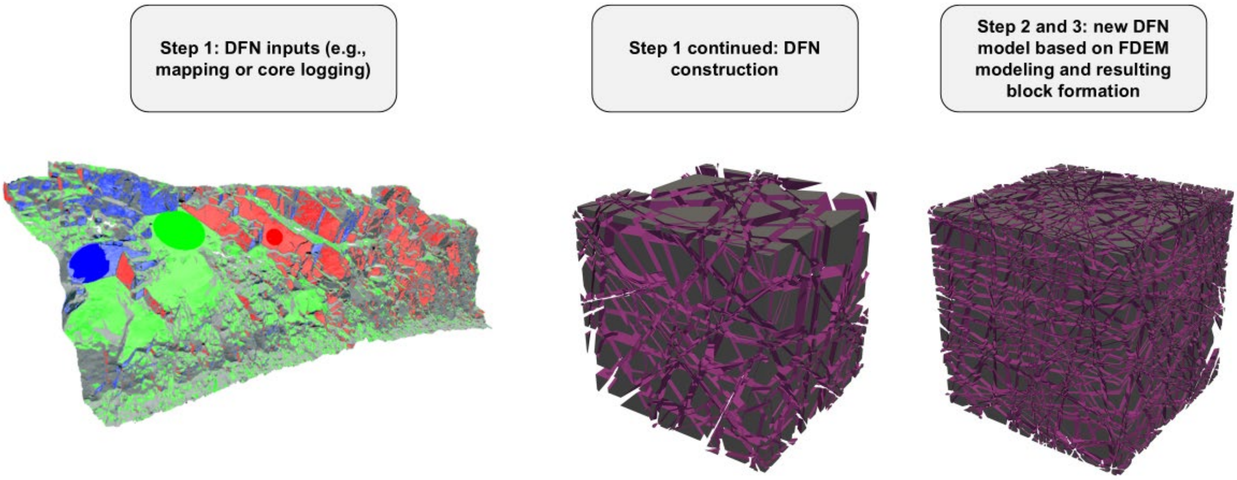

Figure 4 Applying discrete fracture network and finite-discrete element method as inputs for the BCF-V4 primary fragmentation module

While many software packages exist for fracture modelling, few possess the computational efficiency required for rapid DFN construction alongside the identification of thousands of discrete blocks. For this workflow, the developing DFN and block identification modules within mXrap (Harris et al. 2024), supported by the Australian Centre for Geomechanics (ACG), were utilised. These tools allow for the rapid identification of over hundreds of thousands of fragment population within minutes, providing the necessary resolution for cave-scale analysis.

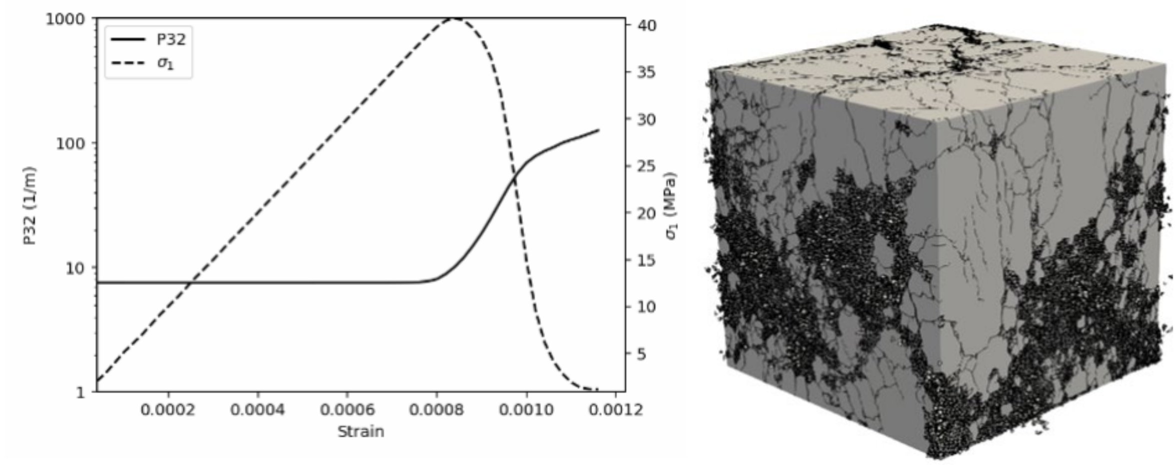

Figure 5 **Growth of stress-induced fracturing using the 3D finite-discrete element method (FDEM) model (1 m cubic model with over 1 million elements as an example). (a) P32 strain curve overlays stress–strain curve; (b) Corresponding 3D FDEM model**

The ultimate goal of this integrated approach is to develop quick reference charts to assist in caving design. These charts estimate secondary fragmentation based on established rock mass ratings, such as the MRMR or fracture frequency, alongside operational parameters like mining depth or height of draw (Figure 6). By grounding these reference tools in high resolution 3D FDEM and BCF-V4 simulations, practitioners can obtain quick forecasts of fragment size distributions across rock mass domains of wide range.

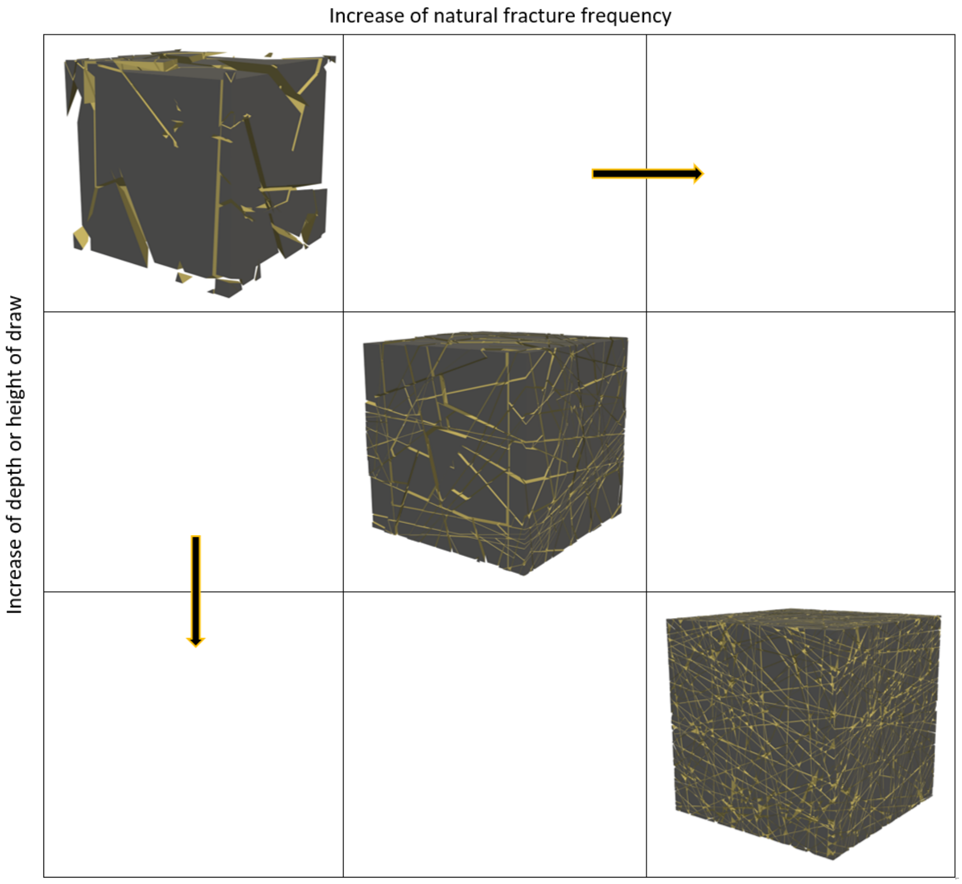

Figure 6 **Conceptual fragmentation estimate chart derived from integrated 3Dfinite-discrete element method and Block Caving Fragmentation**

4.3 Hydraulic fracturing preconditioning

In PCDC, fluid flow through both channel types is governed by Darcy's law. Fluid loss into the host rock mass is incorporated via normal leak-off along the channels using Carter's equation (Valko & Economides 1997), representing pressure- and time-dependent dissipation into a porous medium. The hydro-mechanical (H-M) interaction is implemented in a fully coupled framework. At each time step, mechanical deformation alters fracture apertures and network connectivity, updating the fluid flow field; concurrently, changing fluid pressures modify the stress distribution and solid deformation.

To demonstrate this framework, a 0.3 m cubic specimen subjected to an initial in situ stress field is simulated. As illustrated in Figure 7a–d, fluid is injected into a borehole packer with a radius of 0.01 m and a length of 0.03 m at a constant injection rate of 3.33×10^{-8} m³/s. Because the initial vertical stress (10 MPa) is lower than the horizontal stress (30 MPa), near-horizontal hydraulic fractures are initiated and propagated once the fluid pressure exceeds the strength of the intact rock under in situ stresses. Meanwhile, the fracture intensity (P32) of the rock mass evolves progressively with injection time. The results demonstrate that fracture initiation and propagation are governed by the combined influence of the in situ stress state and the evolving fluid pressure field.

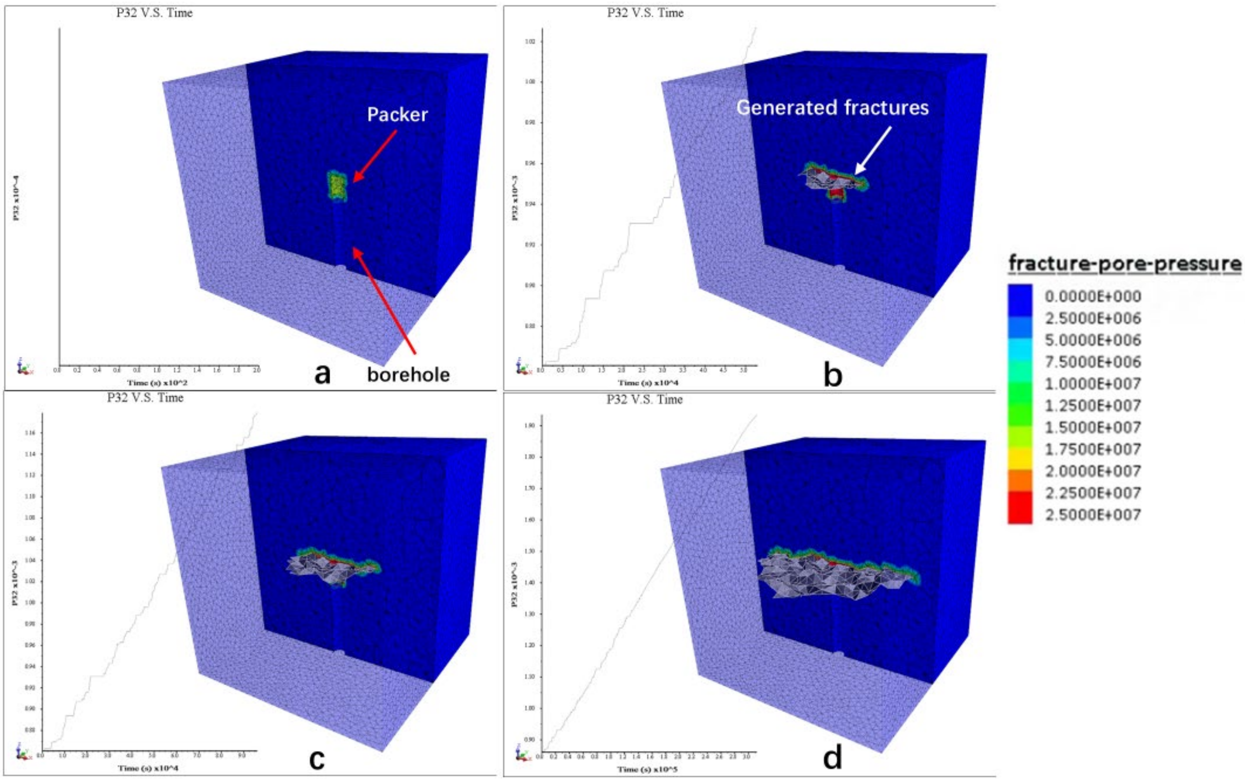

Figure 7 Initiation and propagation of hydraulic fractures induced by fluid injection into a borehole packer

The application of this fully coupled H-M modelling approach is particularly valuable and has potential for optimising cave preconditioning design. By explicitly simulating the interaction between hydraulically driven fractures and the stochastic DFN, the model enables quantitative assessment of the shielding and diversion effects imposed by natural discontinuities on hydraulic fracture propagation. In the context of cave preconditioning, this capability is critical for determining the optimal borehole spacing and injection sequence required to achieve effective rock mass weakening. Furthermore, the model provides a physics-based framework for forecasting the reduction in rock mass strength and the enhancement of primary fragmentation, thereby improving the likelihood of achieving a stable and reliable cave propagation rate in competent orebodies.

5 Conclusion

This study demonstrates the utility of a 3D FDEM framework to assist in rock stress damage, fragmentation estimate and preconditioning design for block cave mining. By employing the UCZM, the simulation effectively captures the transition from intact rock to a fragmented medium. The results from the Mine-by tunnel case and rock mass scale cubic models validate the framework's ability to replicate brittle spalling and fracture coalescence, which are the dominant failure modes in deep, competent orebodies. The integration of fully coupled hydro-mechanical logic provides a modelling tool to study the effectiveness of hydraulic preconditioning. Engineers can utilise this framework to determine optimal borehole spacing and injection parameters by observing the physical interaction between fluid-driven fractures and natural discontinuities. Furthermore, the ability to track stress-induced fracture intensity (P32) provides a rigorous input for advanced fragmentation tools like BCF-V4. Ultimately, this fracture-mechanics-based approach allows practitioners to move beyond empirical proxies, offering alternative numerical codes to model the behaviour of representative rock mass in the caving process. Further work is still required to advance the practical application and predictive reliability of the proposed 3D FDEM framework. The primary objective moving forward is to validate the simulated fragmentation and preconditioning outcomes against actual field data from operating cave mines to refine parameter upscaling logic.

Acknowledgement

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