Caving 2010 — Y. Potvin (ed)
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doi:10.36487/ACG_rep/1002_46_Rogers

Simulating the impacts of hydraulic fracture preconditioning on caveability and fragmentation at the planned Cadia East panel cave

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Abstract

The caving process relies significantly on the natural fragmentation of the rock mass created by the network of fractures and faults. In order to help mitigate the risk associated with unfavourable cave propagation and fragmentation in stronger or less fractured rock masses, the use of preconditioning through hydraulic fracture (HF) generation has increasingly been used. In an attempt to provide a quantitative evaluation of the likely impact of various preconditioning strategies, a combination of discrete fracture network (DFN) and hybrid finite/discrete element method (FEM/DEM) numerical simulations have been undertaken. DFN simulations provide a means to develop an accurate description of the in situ fragmentation. The impact of preconditioning can then be included by adding to the model stress parallel HF of a certain design size and interval spacing. The resultant fragmentation resulting from both natural and induced fractures can then be determined. This can include both the full fragmentation curve as well as the proportion of the rock mass forming large residual blocks of poorly fragmented rock that represent an increased risk of oversize potential. Volumes of the rock mass prone to significant residual block formation can be identified from cave scale DFN modelling, allowing the mapping of these potentially problematic zones of the rock mass. The DFN models can be transferred to a stress analysis method to directly simulate, through synthetic rock mass testing, the impact of preconditioning on rock mass strength. By using a cave-induced stress-path history, synthetic testing of simulated rock samples with and without preconditioning provides a clear indication of the impact of preconditioning on rock mass strength and primary fragmentation. Large scale models are used for simulating cave initiation and growth using embedded DFN fracture traces, to investigate the effects of preconditioning upon caveability.

1 Introduction

With ever-increasing global demand for mineral resources, numerous mines are moving towards mass mining methods (e.g. block and panel caving). A large-scale block or panel cave mine constitutes an example of rock-factory, whose success and economic viability are dependent to a large extent on the fragmentation of the ore material. The capacity of understanding in situ fragmentation and predicting primary and secondary fragmentation requires an intrinsic knowledge of the natural rock fracture network and of the processes occurring in the draw column. In order to help mitigate the risk associated with unfavourable cave propagation and fragmentation in stronger or less fractured rock masses, the use of preconditioning through HF generation has increasingly been used. This paper attempts to provide a quantitative evaluation of the likely impact of various preconditioning strategies, using a combination of DFN and hybrid FEM/DEM numerical simulations.

2 DFN modelling

Rock mass characterisation is a fundamental component for many applications in both mining and rock engineering practice. Fundamental aspects of rock mass characterisation include: (i) definition of an accurate geological model; (ii) geotechnical data collection; (iii) assessing the role of major geological structures; and (iv) determination of rock mass properties. Recent advances in the field of data capture and synthesis have allowed the derivation of more accurate 3D models of naturally jointed rock masses, overcoming some of the limitations inherent in an infinite ubiquitous joint approach.

The volume, shape, and removability of rock blocks within the rock mass depend on the characteristics of the natural rock fracture network. Theoretically, the predicted rock block volume may be expressed as a function of fracture intensity (e.g. fracture spacing), fracture orientation, fracture length, fracture termination mode and size and geometry of the excavation. Using probability density functions to describe discontinuity orientation, spacing and persistence, the DFN approach represents an ideal numerical tool with which to synthesise realistic fracture network models from digitally and conventionally mapped data. The FracMan code (Golder Associates, 2009; Dershowitz et al., 1998) is used in the current study to build a truly spatially variable model of the Cadia East rock mass (Rogers et al., 2010).

The code FracMan allows the 3D visualisation of blocks defined by intersecting discontinuities in the DFN model by employing either an implicit cell mapping algorithm or a more conventional explicit block search algorithm (Dershowitz and Carvalho, 1996). Whereas the latter provides an accurate estimate of block shape and volume, its use is better suited for the kinematic assessment of block stability. The cell mapping algorithm is optimised to provide an initial estimate of the rock natural fragmentation. As shown in Figure 1 the cell mapping algorithm works by initially identifying all the fracture intersections with the specified grid elements. This results in a collection of grid faces and connection information, which is then used to construct a 'Rock Block' of contiguous grid cells. Work is ongoing to further develop the cell mapping algorithm to obtain an explicit representation of the block volumes by unfolding the implicit block to the fracture element mapped on the grid cell elements.

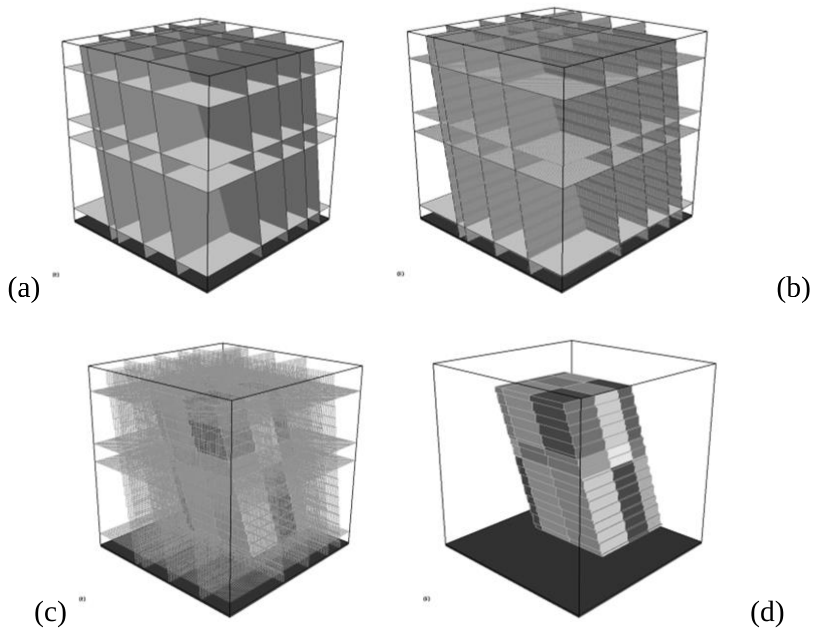

Figure 1 Cell mapping algorithm: (a) initial DFN; (b) fractures are mapped to the specified grid; (c) regular blocks are formed along the grid cells; and (d) final rock block model

Only blocks internal to the fracture model (i.e. not intersected by an external face) should be considered when assessing the size and shape distributions of jointed rock masses. This argument originates from the critical concept of mobile and residual blocks (Figure 2). A mobile block is a fully defined block within the search volume of the model, whilst a residual block is the volume remaining within the search volume where blocks have not been explicitly identified. However, for a sufficiently large rock mass volume, residual blocks effectively represent one or more mega blocks with potentially complex, non-convex geometries. Whether residual blocks are included or not in the fragmentation, analysis completely alters the fragmentation results significantly as at lower fracture intensities, less than 20% of the volume of the rock mass may form discrete mobile blocks.

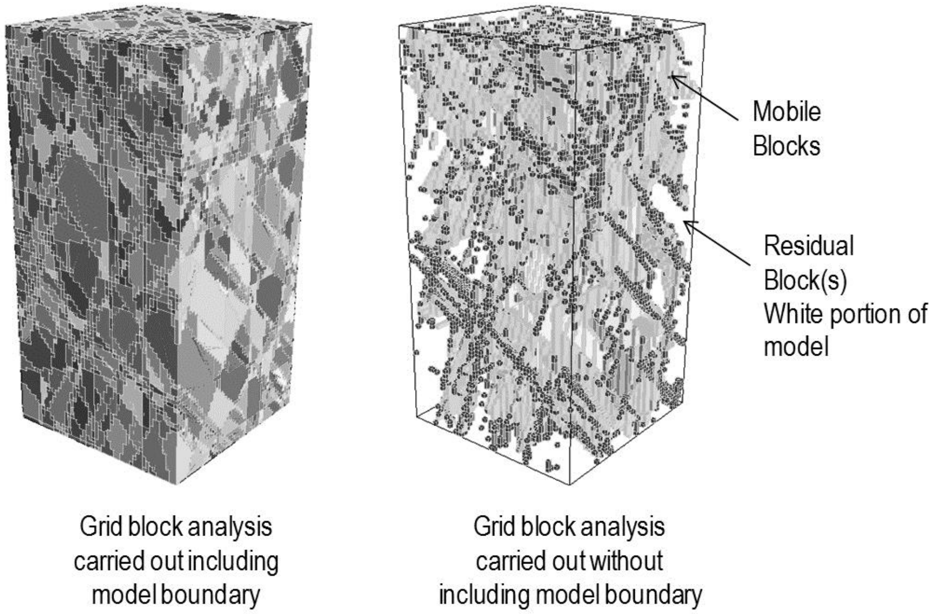

Figure 2 Illustration of the concept of mobile and residual blocks

3 The hybrid FEM/DEM approach

From a modelling perspective, caved induced brittle fracturing corresponds to a transition from a continuum to a discontinuous state. To satisfy this condition, the current modelling employs a state-of-the-art hybrid continuum/discrete technique (ELFEN code; Rockfield Software, 2009), incorporating fracture mechanics principles to simulate caving process in a more realistic manner than one approach alone. The computational methodology of the FEM/DEM approach has been extensively tested and validated fully against controlled laboratory tests by Yu (1999), Klerck (2000) and Klerck et al. (2004). There are several examples in the literature of block cave modelling using the hybrid FEM/DEM approach, including Pine et al. (2007), Elmo et al. (2008) and Vyazmensky et al. (2009). The approach has been successfully applied to modelling the interaction between open pit and block cave mining at Palabora mine (Vyazmensky et al., 2009), whilst Elmo et al. (2010) has used the integrated FEM/DEM–DFN technique to model cave development and subsidence for the prefeasibility study of the Cadia East project.

4 The Cadia East panel cave mine

The Cadia East underground project involves the development of the massive Cadia East deposit into Australia’s first panel cave. Located within the Cadia Valley Province in central New South Wales, Australia, the Cadia East underground project is based on a porphyry zone of gold-copper mineralisation adjacent to the eastern edge of the Cadia Hill orebody and extending to up to 2.5 km east. The system is up to 600 m wide and extends to 1.9 km below the surface. Figure 3 shows a 3D illustration of the main geological domains for the Cadia East project, a typical west–east cross section through the orebody is also shown (Catalan et al., 2008).

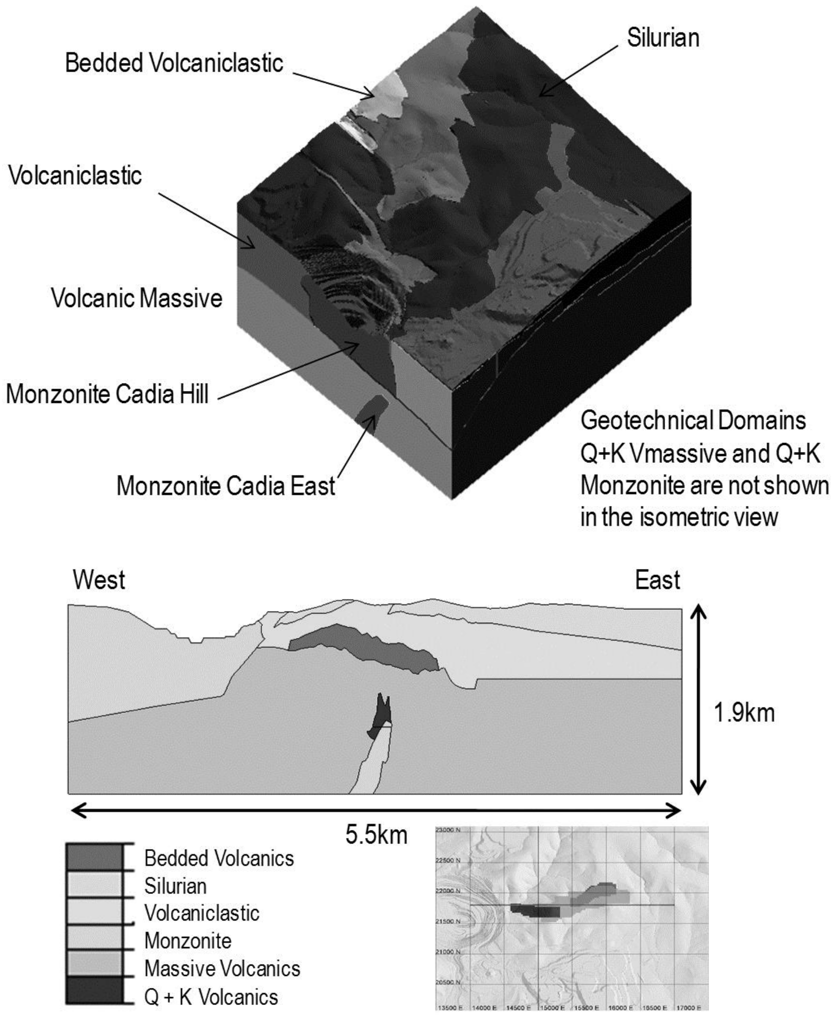

Figure 3 (top) 3D illustration of the main geological domains for the Cadia East project; and (bottom) typical west–east cross section through the orebody

The in situ stress field is defined according to virgin rock stress measurements by CSIRO hollow inclusion stress cell undertaken at the Cadia East Mine (Hulls et al., 2008). A summary of these in situ stress measurements are indicated in Figure 4 (Catalan et al., 2008). This figure includes the vectorial average values by each site which were calculated in terms of their stress components as well as their principal stress magnitudes. From the 10 tests undertaken, the maximum principal stress (σ_1) is subhorizontal and trending approximately east. The intermediate principal stress (σ_2) plunges gently north and the minimum principal stress (σ_3) plunges steeply south-southwest. The measured vertical stress component magnitudes varied both below and above the estimated magnitude based on depth and rock density.

The maximum to minimum principal stress differentials have a mean of 2.6 with a standard deviation of 0.9 (range between 1.6 and 4.7). The mean value is considered typical of eastern Australian conditions. Field measurements have allowed estimating the relationship between principal stress magnitude and depth, accordingly the principal stress differentials are calculated as 2.12 and 1.24 for σ_1/σ_3 and σ_2/σ_3 (out-of-plane) respectively.

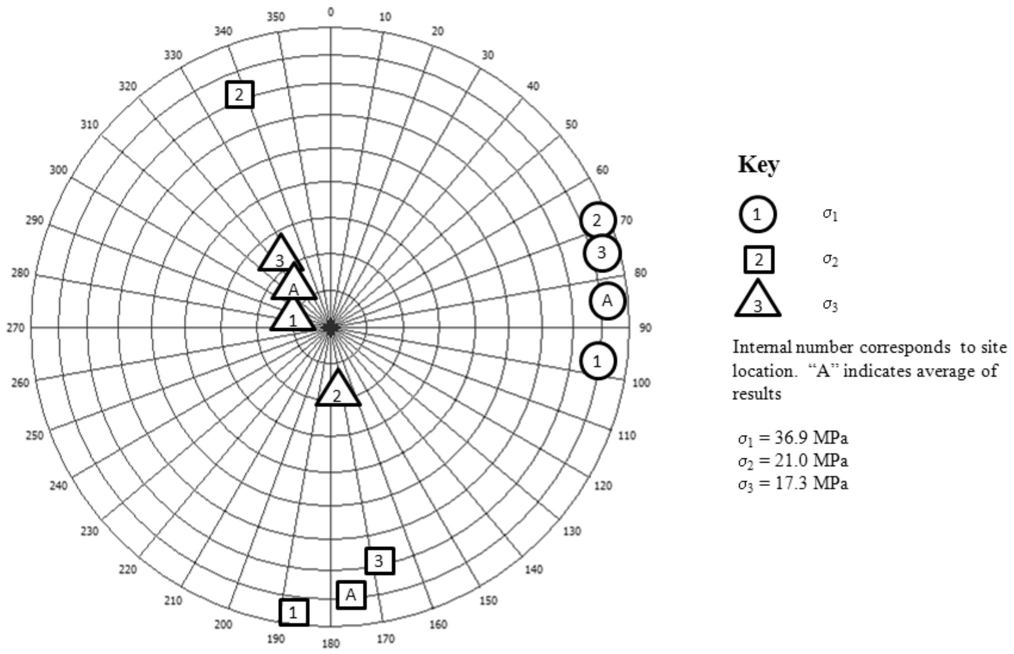

Figure 4 Stress measurement vectorial average values for the Cadia East project

5 Assessment of hydraulic fracturing impact on fragmentation

Hydraulic fracturing (HF) works on the principle that, when fluid pressure is increased within a section of a borehole isolated by packers, the stress around the borehole boundary is modified and application of sufficient pressure induces tensile circumferential stress over limited sectors of the borehole boundary (Brady and Brown, 1993).

Fracturing is initiated when the induced tensile stress exceeds the tensile strength of the rock material, and the orientation of the fracture plane is defined by the orientation of the minimum principal stress whilst the propagation of the fracture into the rock mass will continue as long as the pumping rates exceeds the rate of fluid loss into the rock and as long as the pressure in the fracture exceeds the far-field minimum stress magnitude. Ideally, if the hole is orientated parallel to the minor principal stress, these induced fractures should be propagated perpendicular to the hole boundary and parallel to the major principal stress.

Several authors (e.g. Mahtab et al., 1973; Kendorski, 1978) have recognised that the fracture system most favourable for caving includes a well developed low dipping joint set and at least two prominent subvertical joint sets. Propagating HF in a rock mass prior to caving therefore represents a valid preconditioning technique to improve rock mass caveability. Because of the anticipated stress field at Cadia East, it is planned to drill subvertical boreholes located at 80 m centres. The planned HF will be approximately 80 m across (i.e. 40 m radius) with an inclination of 5° to the east (azimuth = 090), see Figure 5.

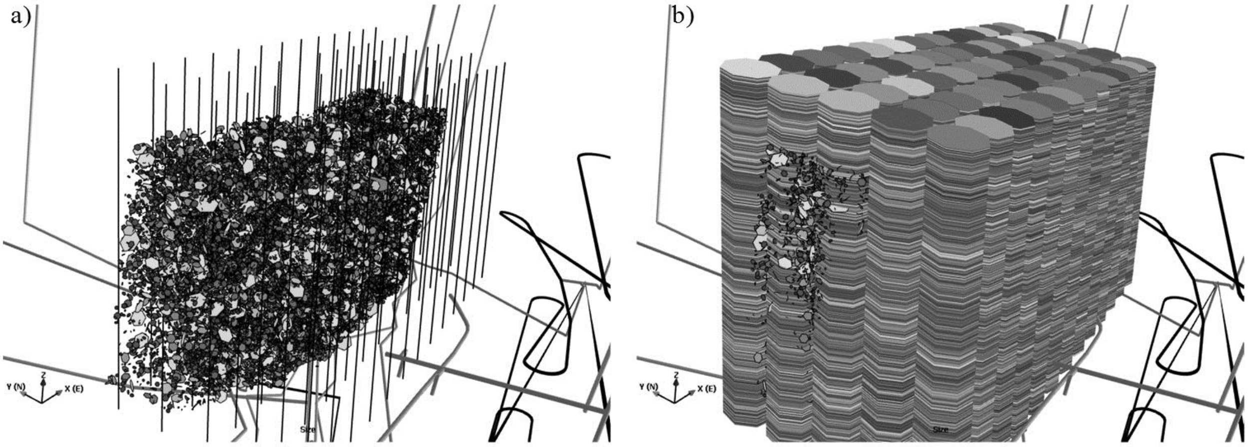

Figure 5 (a) Preconditioning boreholes configuration through one of the lift volumes; and (b) simulated HF array on those boreholes. View looking northeast

5.1 Impact on situ fragmentation

The effects of adding a variety of HF spacings on the in situ fragmentation was assessed using FracMan. DFN models were generated within a 50 × 50 × 50 m region for a range of P32 values to represent the distribution of P32 for a particular domain (see Rogers et al., 2010), where P32 represents the fracture area per unit volume of rock (volumetric fracture intensity). HF of a 40 m radius are then added to the model, spaced according to the particular preconditioning strategy being examined. Using the block searching methodologies described in Section 2, the distribution of block size is determined within a 15 × 15 × 15 m subregion for each P32 model to define in situ fragmentation curves. Subsequently, the modified percent passing curves including the effects preconditioning are calculated using the same block search methodology. These modified curves represent the HF enhanced in situ fragmentation. The modelling methodology is illustrated in Figure 6, whilst examples of the HF enhanced in situ fragmentation curves for a selected domain is shown in Figure 7(a).

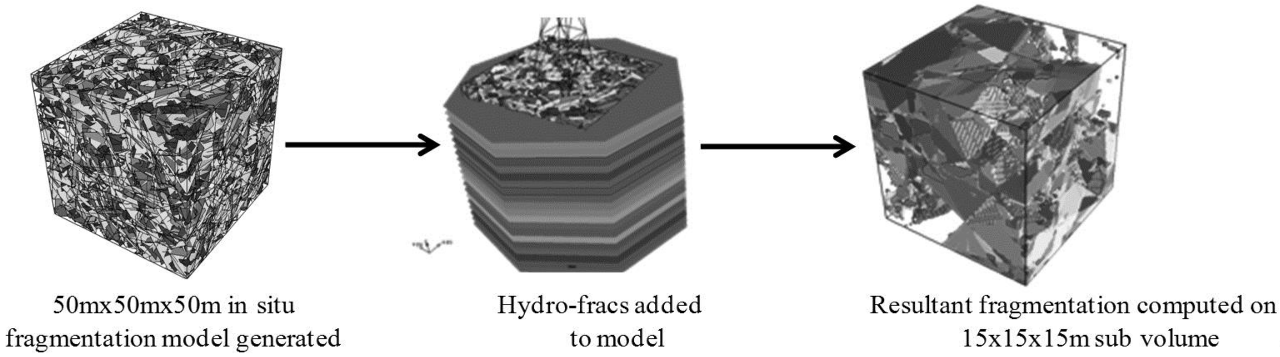

Figure 6 Illustration of the DFN method for in situ fragmentation determination

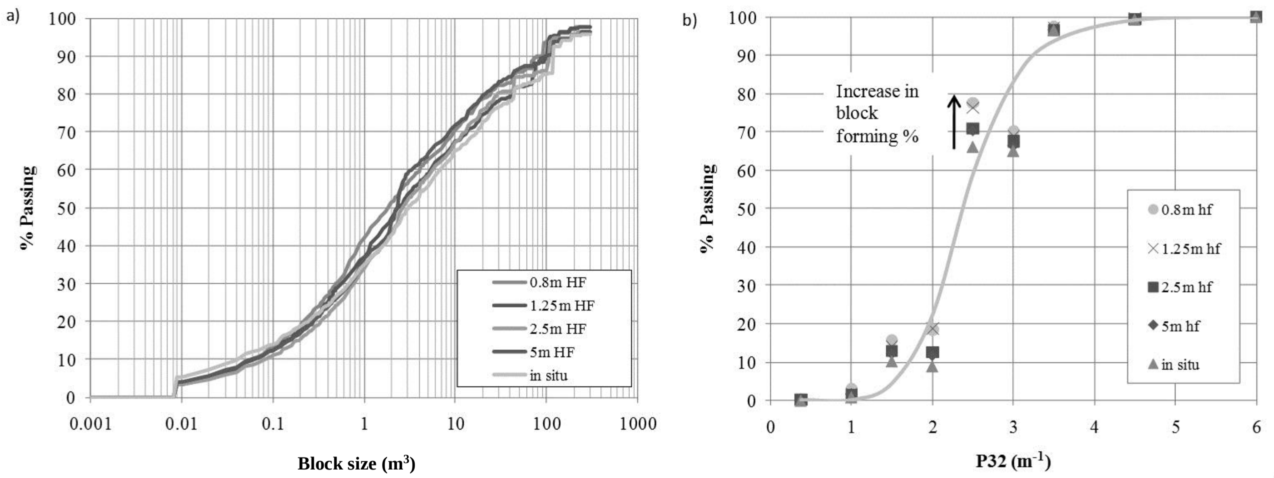

Figure 7 (a) In situ fragmentation curves for two domains for a range of HF spacings; and (b) graph of the percentage of total volume forming blocks plotted against fracture intensity P32 for varying HF spacings

As can be seen from Figure 7(a), there is a discernible reduction in the overall in situ fragmentation as a result of the preconditioning. The mean particle size is reduced from a size of 3 m^3 to a post-preconditioning size of 2.5 m^3 with 2.5 m spacing and 2.25 m^3 with 1.25 m spacing. As is to be expected, the preconditioning is seen to be affecting primarily the larger block sizes. One of the main impacts observed in the modelling is the decrease in the proportion of large residual blocks and a measurable increase in the proportion of the rock mass mobilised into kinematic blocks, see Figure 7(b). Obviously it is probable that many residual rock mass blocks will break up upon caving. However, Elmo et al. (2010) showed that under certain stress conditions, large strong residual rock mass blocks can exist intact within the cave volume for considerable time/distance. Therefore any reduction in the proportion of residual blocks will have a positive impact on reducing hang-ups and other material handling problems. These results are also seen in Table 1 which shows the proportion of the rock mass blocks greater than 2 m^3 in volume. The results indicate a reduction of approximately 10% of the rock mass volume being over sized at the in situ fragmentation stage.

Table 1 Percentage of rock mass with in situ block size > 2 m^3 for a number of different domains

		HF Spacing			
% > 2 m^3	**No HF**	**5 m**	**2.5 m**	**1.25 m**	**0.8 m**
Domain 1	60.7%	50.5%	60.8%	55.6%	52.3%
Domain 2	57.1%	53.5%	56.2%	52.6%	48.6%
Domain 3	57.1%	58.2%	57.3%	51.9%	48.2%
Domain 4	56.5%	50.6%	54.1%	50.5%	47.7%

At this stage, the geometric analysis has assumed that all HF are fully extending and the interaction between HF and in situ fractures has been ignored. In reality this will not be the case, with the in situ fractures often stopping the growth of HF extension or providing conductive pathways allowing the leaking off of pressure and reducing ultimate fracture length.

5.2 Impact on primary fragmentation

The methodology for assessing the impact of HF preconditioning on primary fragmentation includes embedding a representation of both the in situ fracture system and a given HF fracture pattern within the hybrid FEM/DEM code ELFEN. The combined fracture assemblage is subsequently loaded to explicitly simulate fracturing of the rock mass according to a modelled excavation sequence (Figure 8). In the current analysis, a 20 m wide × 10 m high DFN model representing the in situ fragmentation is initially built using a

P32 of 2.7 (mean value for domain). East–west sections are then taken through the model, by including only fracture whose dip direction is within 20° of the trace plane orientation (Moffitt et al., 2007; Elmo et al., 2007). Trace planes corresponding to varying HF preconditioning scenarios are finally added to the in situ fracture model. HF fractures spaced at 2.5, 1.875, 1.5, 1.25, 0.8 and 0.625 m have been used in the current study. The complete fracture assemblage is loaded assuming the simulated rock mass sample is located at a depth corresponding to the 5050RL level in the mine plan scenario as part of the Prefeasibility Study (PFS) of Cadia East panel cave project.

To replicate the effects of undercutting, the initial structural fixities assumed at the bottom of the model are progressively removed. Rock mass material properties for the massive volcanics domain are assumed in the analysis (see Elmo et al., 2010). As shown in Figure 9, the in situ fracture system yields a limited number of fully formed blocks. As the simulation of undercut excavation is fully completed in the model, stress induced fractures are responsible for the progressive breakage of the initially large portion of intact rock material. However, only relatively large blocks are mobilised in the model without HF included. The amount of induced fracturing diminishes as increasingly closely spaced HF traces are included in the model, and the shape/size of the mobilised blocks is clearly a function of the assumed HF scenario, see Figure 10.

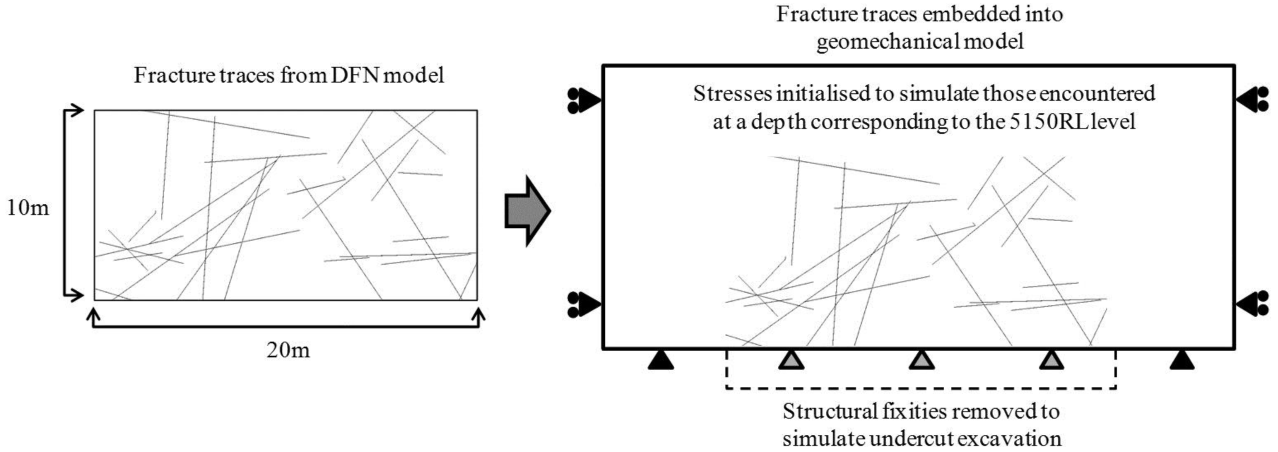

Figure 8 Modelling methodology used to assess the HF impact on primary fragmentation

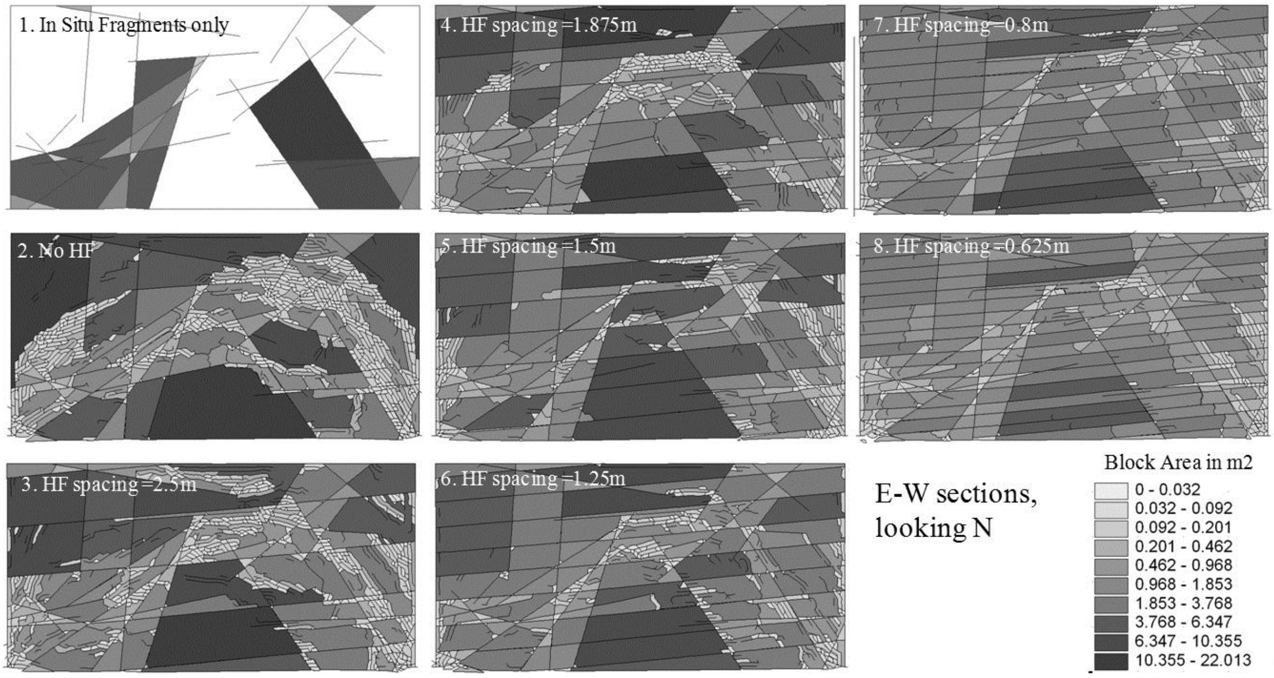

Figure 9 Simulations of primary fragmentation development as a function of HF spacing. The top left model shows the in situ fragmentation prior to primary fragmentation commencement. The blocks are shaded by area

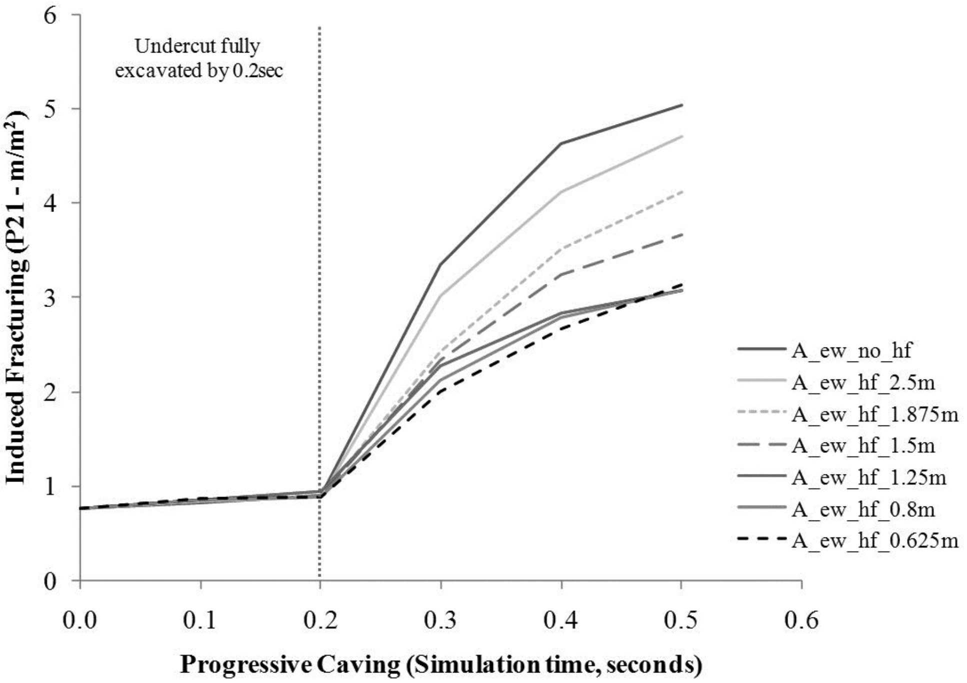

Figure 10 Evolution of fracture intensity (P21) during primary fragmentation simulations for varying HF spacing. Note that full undercut excavation is completed by 0.2 sec

6 Modelling the impact of preconditioning on cave evolution

Whereas the size of the model used in Section 4.2 represents an ideal balance between accurate fracturing simulation and computational times (associated with the mesh discretisation), the model cannot provide indications with respect to the impact of HF preconditioning on cave development. To answer this question a large scale model was used instead, building on work described in Elmo et al. (2010), see Figure 11. Currently, the analysis has been performed for a 5 m HF spacing scenario. In the model, the excavation of 100 m wide undercut is simulated and the overlaying rock mass is then allowed to naturally cave in by gravity. The extent of the caved zone is assumed to be represented by the -1 m vertical displacement and no draw of material is modelled at this stage.

Two major observations are seen from the modelling results:

- A relatively higher degree of cave shape asymmetry is observed for the model without HF traces, in which the cave development is greatly controlled by the in situ fracture system. In accordance with observations in the literature, the presence of the subhorizontal HF fractures favours a more vertical, symmetrical, cave advance.
- For an equivalent time step in the model, the presence of HF fractures results in a more extended caved region, indicating the beneficial impact of HF preconditioning with respect to limiting the risk of cave stalling.

The authors recognise that further analysis is required to include varying the in situ DFN pattern and HF scenarios.

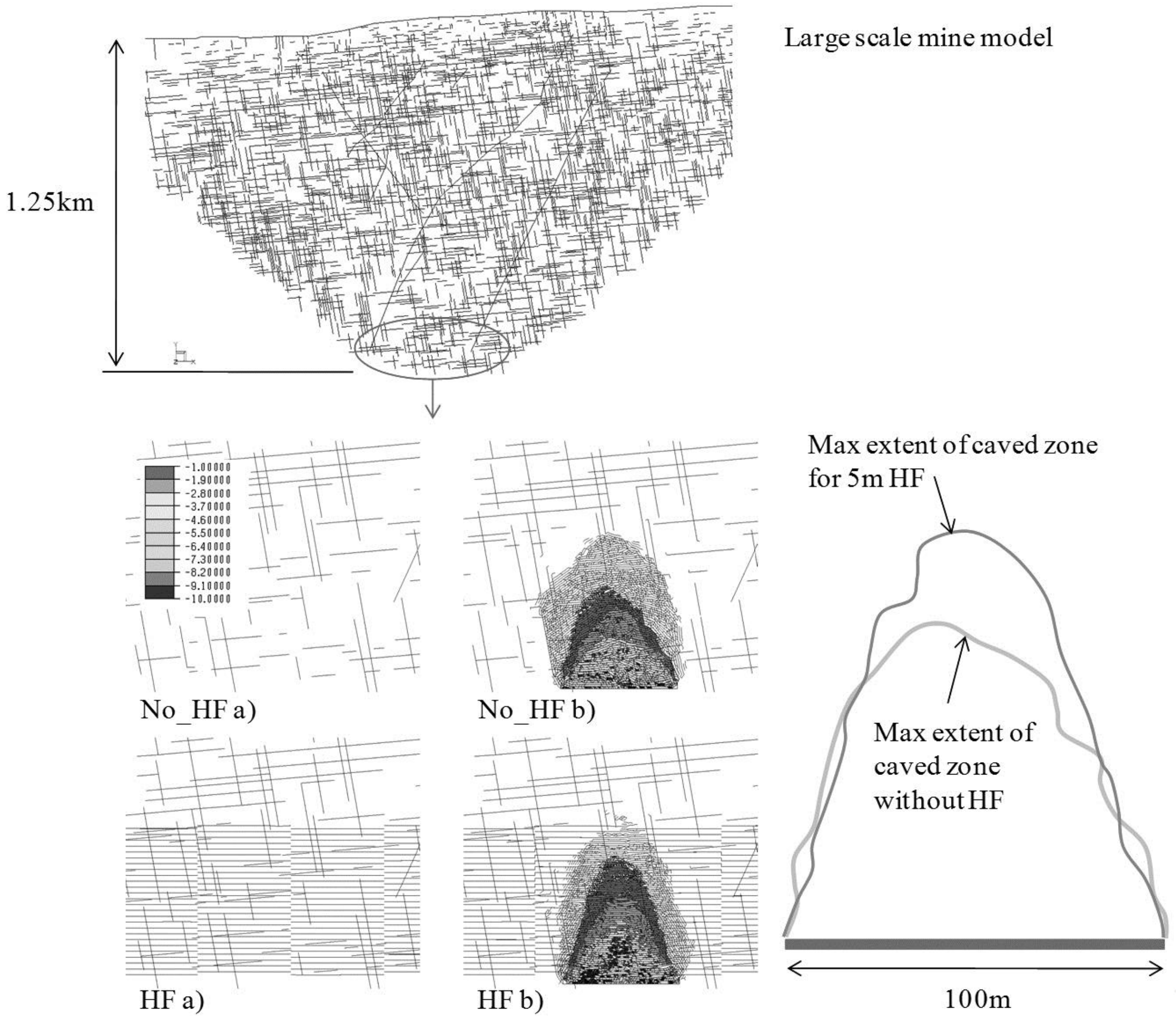

Figure 11 Simulations showing the comparison between the natural caving extent with and without HF, shaded by vertical displacement. The right hand image shows the extent of the caved zone for the two scenarios, as indicated by the 1 m vertical displacement contour

6.1 Fragmentation mapping

The volumetric fracture intensity (P32) has previously been shown to be a key parameter in identifying the degree to which the rock mass is forming potentially mobile blocks, Rogers et al. (2009). The transition from intact massive rock mass to kinematically mobile rock mass generally follows a percolation process, meaning that the transition from intact property dominated behaviour to joint dominated behaviour occurs over a relatively small change in P32 once a critical P32 threshold has been exceeded, see Figure 12.

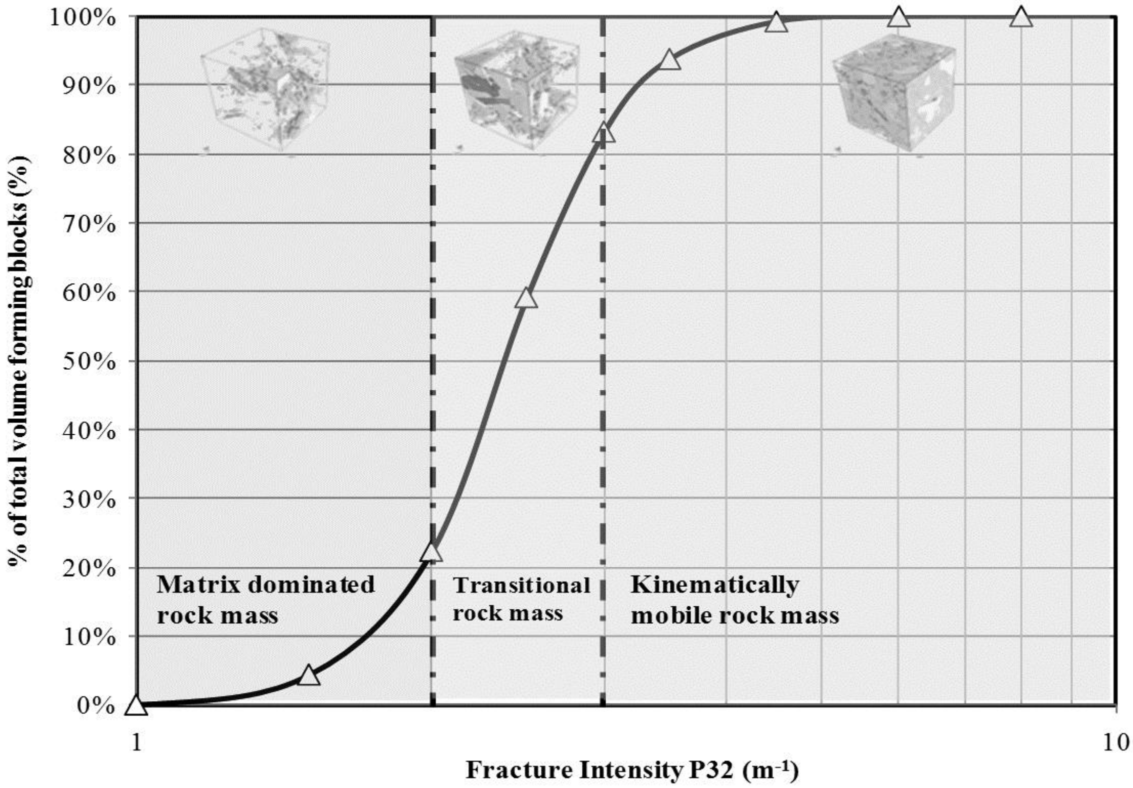

Figure 12 Graph of the percentage of total volume forming blocks plotted against fracture intensity P32. The inset models show the progression from a matrix dominated rock mass at low P32 values to a largely kinematically mobile rock mass at higher P32 values

The strength and behaviour of these rock mass types is going to be different, with one clearly dominated by the intact rock properties and the other by joint properties and small intact rock bridges. As such it is anticipated that the caving characteristics of the two rock mass types will also be different, with the matrix dominated rock mass having an increased propensity for poor cave initiation, irregular draw characteristics and hang-ups. The P32 property derived from the DFN modelling can be used to identify those parts of the cave volume where the proportion of mobile blocks is expected to be low, with this information used as a possible tool for guiding preconditioning to aid caving propagation and block mobilisation. Figure 13 show views of the P32 property for the Lift-0 and Lift-1 domains below a certain P32 threshold.

These results provide a means for identifying potentially problematic rock volumes where the fracture intensity has fallen below a critical level such that mobile block formation is limited and therefore the potential of large residual rock mass blocks exists with its poorer fragmentation properties and increased hang-up potential. In this context, HF preconditioning could be devised to specifically target areas in the model showing a relatively lower P32 distribution.

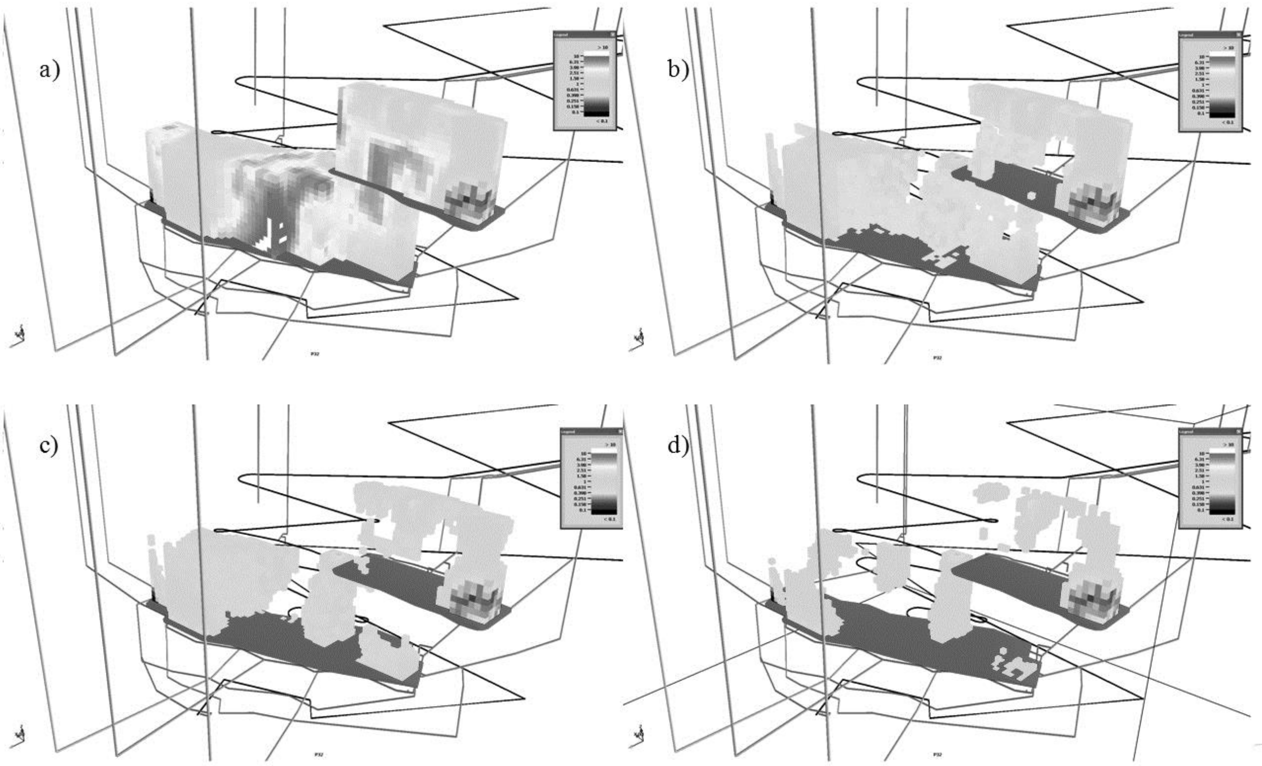

Figure 13 Distribution of P32 for the Lift-0 and Lift-1 volumes, calculated from the DFN model. Each image shows all cells below a certain maximum P32 value and progressively reveals areas of the cave with the potential for poorer fragmentation and possible hang-ups: (a) shows all cells; (b) all cells below 2.25 m^{-1}; (c) all cells below 1.75 m^{-1}; and (d) all cells below 1.25 m^{-1}

7 Discussion and conclusions

This paper has provided an initial quantitative evaluation of the likely impact of various HF preconditioning scenarios, using a combination of DFN and finite/discrete numerical modelling. The simulations of rock mass preconditioning has been shown to impact both the in situ fragmentation and the rock mass response to caving in a number of ways:

- A measurable shift to the left (reduction) to the in situ fragmentation curves as derived from the 3D DFN analysis was observed.
- The modelling results indicated a more noticeable reduction in the proportion of oversized material (block volumes >2 m^3) as a consequence of the HF preferentially effecting the larger size portion and by association, the proportion of rock mass contained within the less mobile residual blocks.
- A reduction in the amount of finer material created during primary fragmentation was observed with decreasing HF spacing as a result of the HF accommodating much of the deformation, resulting in less brittle failure occurring.
- Below a HF spacing of approximately 1.5 m, the ELFEN simulations suggest that there is no significant increase in the amount of induced fracturing that occurs and therefore this appears to represent the limit of fines production during primary fragmentation.
- The analysis suggest that with the marginal reduction in fragmentation resulting from preconditioning and a point where there is no significant primary fragmentation below a threshold HF spacing, there is clearly little benefit in the continued reduction of HF spacing.
- A general increase in the caveability of the rock mass with natural caving simulations (i.e. undercut removal but no draw) was observed, with the generation of a notably greater overall cave volume as defined by the 1 m displacement contour.

It is anticipated that further work is required to extend and validate the proposed methodology by considering different in situ DFN patterns and HF scenarios.

Acknowledgements

The authors would like to acknowledge Newcrest Mining Ltd., who kindly gave permission to publish the modelling results presented in this paper.

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