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A discrete fracture network based approach to defining in situ, primary and secondary fragmentation distributions for the Cadia East panel cave project

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Abstract

One of the most critical elements in pre-caving assessment process is determining the likely distribution of rock mass fragmentation, with the impact of poor or unexpected fragmentation upon cave operations being significant. For a number of years it has been recognised that discrete fracture network (DFN) tools could assist in the fragmentation assessment, primarily through providing a better description of the pre-caving in situ fragmentation distribution. To date the evaluation of primary and secondary fragmentation has been mostly carried out using alternative methods based on engineering principles and practical experience. More recently, synthetic testing of relatively small DFN models has been proposed to assess fragmentation mechanisms. However, it is argued that neither of these approaches can fully capture the broader heterogeneity of the rock mass, drawing on only a limited portion of the rock mass characterisation data. Recent work has demonstrated the sensitivity of rock mass fragmentation to the volumetric fracture intensity property P32 and the importance of determining the critical intensity value at which the transition from intact massive rock mass to kinematically mobile rock mass occurs.

To address these issues, the authors have developed an approach that has at its core the development of a full scale DFN model description of fracture orientation, size and intensity built up from all available geotechnical data. The model fully accounts for a spatially variable description of the fracture intensity distribution. Primary fragmentation analysis is undertaken by using a DFN based rule approach, which draws from an explicit numerical simulation of fracture mechanisms to characterise stress induced fracturing within a given rock mass. Direct modelling of secondary fragmentation related to mining-induced stress and comminution of caved material in the broken ore column poses significant challenges as large-scale discrete modelling (including fracturing) of processes requiring a centimetre-scale mesh discretisation becomes computationally prohibitive. To obviate this problem, this paper introduces a method to assess secondary fragmentation based on a probabilistic analysis by combining the DFN derived primary block volume distribution with micro-defect intensity data to derive a probability of block degradation during caving.

1 Introduction

One of the most critical elements in the pre-caving assessment process is determining the likely distribution of fragmentation at the draw points, the impact of poor or unexpected fragmentation likely to have a significant impact upon cave operations. However, the task of developing fragmentation predictions has been notoriously difficult because of the large number of inputs to define the geometry of the initial fragmentation and the complexity of the processes by which it evolves during cave development and migration. Various approaches have been attempted ranging from DFN related techniques to numerical simulation and rule based methods. However, none of these methods have been able to accurately represent the whole life cycle of the fragmentation evolution in a sufficient manner. To answer this dilemma, this paper introduces a mixed modelling approach to fragmentation that draws upon all three modelling approaches.

As a starting point, DFN models provide the best description of the in situ fragmentation (the degree to which the rock mass is naturally broken by the fracture system). However, in order to understand how the initial rock mass fabric evolves during both primary and secondary fragmentation, numerical models are required that allow the simulation of stress induced fracturing and blocks breakage. To date, it is not practical to run full cave scale rock fracturing simulations with sufficient accuracy, therefore relatively small scale models are used that allow fragmentation rules to be developed, based upon the cave specific stress history. The results can then be applied to the initial in situ fragmentation models to allow the constrained but rapid rule based stochastic simulation of caving induced fragmentation. The methodology presented in this paper attempts to capture the fragmentation evolution with as few assumptions as possible (fracture network geometry and stress history) to define blocks and the potential for blocks to break where possible.

2 The Cadia East underground project

The Cadia East underground project involves the development of the massive Cadia East deposit into Australia's first panel cave. The mine will be the deepest panel cave in the world and Australia's largest underground mine. Mining studies have identified panel caving as the mining method which will deliver the optimum technical and economic outcomes for development of this orebody. It is 100% owned by leading Australian gold producer Newcrest Mining Ltd., and 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 1 shows cross sections east–west looking to north through the Cadia East orebody (Catalan et al., 2008), with indication of the different block and location of the planned undercut levels (Lift-0 and Lift-1 respectively). This paper specifically presents modelling results describing mine plan scenarios discussed as part of the prefeasibility study (PFS).

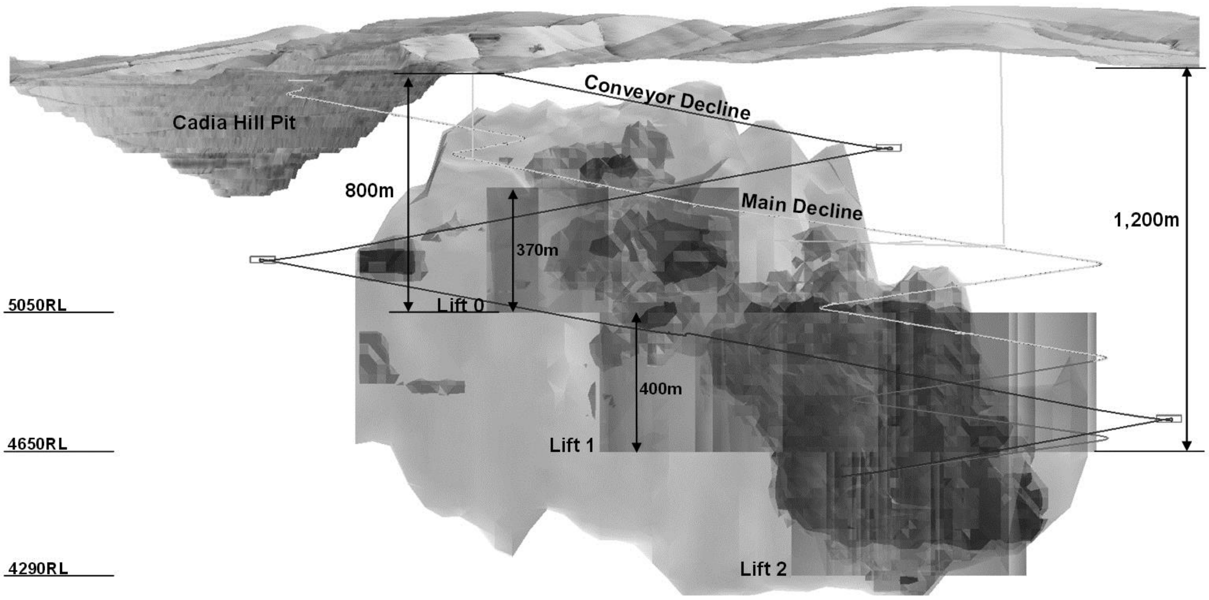


Figure 1 Section east–west looking to north through the Cadia East project of the PFS

3 The DFN approach to fracture modelling

3.1 Introduction

The DFN approach is a modelling methodology that seeks to describe the rock mass fracture system in statistical ways by building a series of discrete fracture objects based upon field observations of such fracture properties as size, orientation and intensity. Much of the early interest in the DFN approach was associated with modelling of groundwater flow through natural fracture systems (largely as part of nuclear waste isolation programmes) and for modelling fractured hydrocarbon reservoirs. The code FracMan (Golder

Associates, 2009; Dershowitz et al., 1998) is the platform used in the current analysis for DFN data synthesis.

Increasingly, the DFN approach is being used to address both fundamental and practical geomechanical problems when engineering large structures in fractured rock masses. For instance, DFN methods have been used within the caving industry as a means to define rock mass properties through their integration with numerical codes to simulate so called synthetic rock mass (SRM) properties.

DFN methods have a number of key advantages over more conventional methods in that they are better at describing local scale problems because of their ability to capture the discrete fracture properties more accurately than larger scale continuum approaches and can also capture the heterogeneity of the fracture system by explicitly describing key elements of the system. Most importantly they provide a clear and reproducible route from site investigation data to modelling because real fracture properties are being preserved through the modelling process.

In order to build a volumetrically simple DFN model, the primary fracture properties of orientation, fracture size, intensity and its local spatial variation are required to be defined as distributions to allow the stochastic generation of a large number of fracture elements that represent the fracture network. Basic DFN modelling has been well documented elsewhere (e.g. Dershowitz et al., 1998; Rogers et al., 2009). For the purposes of the work detailed within this paper, the most important parameter to understand is fracture intensity. In order solve to address the issues of multiple ambiguous definitions of fracture intensity, the DFN community developed a unified system of fracture intensity measures that provide an easy framework to move between differing scales and dimensions known as the P_{ij} system, Dershowitz and Herda (1992). The P_{ij} system seeks to define fracture intensity in terms of dimensions of the sample (e.g. borehole, trace map, volume) and dimensions of the measure (e.g. count, length, area). As an example, P10 (or fracture frequency) is a one dimensional sample and has a zero dimension measure (count).

The fracture intensity input for DFN modelling is usually defined either from borehole data (fracture logging or borehole imaging tools) as fracture frequency (P10, units m^{-1}) or from trace mapping upon surfaces such as benches or tunnel walls (P21, units m/m^2). Both of these data are directionally biased. The preferred measure of fracture intensity for a DFN model is known as P32 (fracture area/unit volume, units m^2/m^3). P32 represents a non-directional intrinsic measure of fracture intensity and has wide applications in rock engineering. Whilst it cannot be directly measured it can be inferred from the 1D and 2D data above using a simulated sampling methodology by simulating non P32 values and observing the resultant P10 or P21 on borehole or trace plane samples in the model.

3.2 Cave scale DFN model development

To date there have been few documented attempts at cave or mine scale DFN modelling. The general workflow required for the development of a data constrained large scale DFN model is discussed by Rogers et al. (2009). The most important aspect of cave scale DFN modelling is the development of an accurate 3D model of the variation of fracture intensity. The ultimate objective of DFN model generation is to create an accurate description of the P32 variation through the cave volume as this has been shown to be key to understanding variations in the in situ fragmentation and overall rock mass quality.

The primary input for fracture intensity modelling at the cave scale is borehole derived fracture frequency (P10) data. Each borehole needs to be interpreted to identify zones of the rock mass where P10 remains constant over intervals lengths of around 10–100 m, the typical modelling resolution. The most efficient way to achieve this is by using cumulative fracture intensity (CFI) plots for all geotechnical boreholes. These display depth on one axis and cumulative fracture frequency on the other. Where the gradient of the CFI curve is relatively constant, the fracture frequency (P10) over that interval is constant and can be determined. Interpretation of CFI plots from a large number of boreholes results in the creation of a data set of specified P10 values and interval lengths that provide the basis for any 3D spatial modelling and extrapolation of fracture intensity.

As mentioned above, P10 data are directionally biased with the true measure of intensity being dependent upon the orientation of the boreholes and the orientation of the fracture orientation distribution. To account for this issue, the P10 intensity values need to be converted to a non-directional intensity property known as

P32 potential, using the technique firstly introduced by Wang (2006) and described in details in Rogers et al. (2009). Once the initial bias P10 values have been converted to orientation-corrected P32 potential (P32P) values, geostatistical methods can be used to interpolate these values through the cave volume.

For the specific case of the Cadia East data set, geostatistical modelling of the P32 potential property has involved some pre-processing as the underlying data was highly irregular in sample length as a result of the interpretation method (i.e. picking of zones of constant fracture frequency rather than conventional point samples). To aid modelling and interpolation the initial data set was first regularised by converting it into standardised sample lengths of 5 m.

Using an understanding of the main geological structures of the deposit, variographic analysis of the data was undertaken using the mapped orientations. Applying the modelled variography, simulation runs were developed on a 25 m block size. A total of 1,000 equi-probable simulations were run with the average of the 1,000 simulations taken as the P32 potential for modelling. Simulation instead of conventional kriging was used as the latter, whilst providing a best estimator of the P32 potential value, lacks the geological reality of the simulation approach, Figure 2. By taking the average of a high number of simulations, the accuracy of kriging is maintained whilst also preserving the natural variability of the simulation.

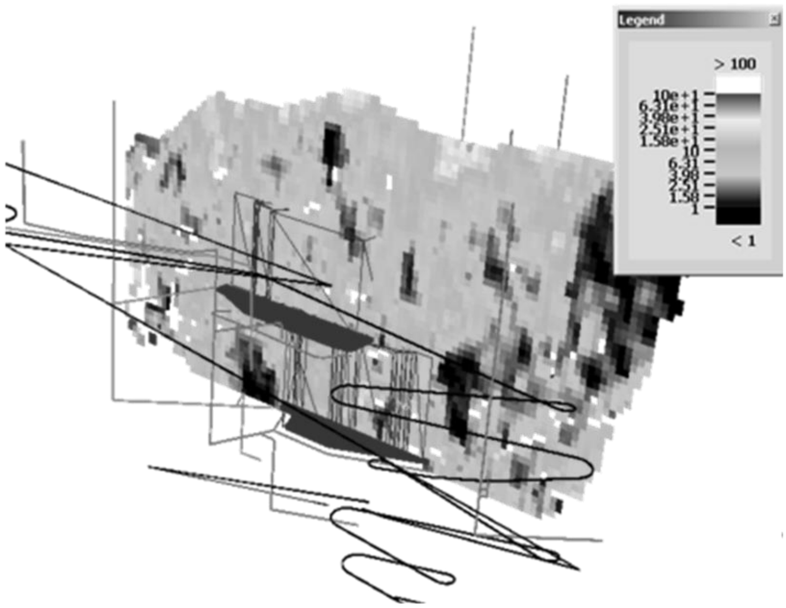


Figure 2 Section through P32 potential property generated through simulation with lighter colours indicating areas of higher fracture intensity and darker colours indicating low fracture intensity

The 3D fracture intensity P32 potential property provides the relative distribution of fracture intensity through the cave scale model. However, to condition the model to the correct absolute fracture frequency, the model needs to use a technique of P10 conditioning at the boreholes. This approach to large scale modelling allows the spatial intensity property to control the probability of a fracture occurrence in a certain part of the model, with modelling continuing until the average fracture frequency on the selected conditioning boreholes has been honoured. A summary of fracture properties used for the Cadia East cave models are shown in Table 1.

Table 1 Summary of DFN modelling parameters and justifications

Fracture Property	Distribution	Definition	Justification
Fracture orientation distribution	Bootstrapped generation	For mine scale use 450 m maximum radius and dispersion of 90.	Orientation data quite dispersed and hard to define as distinct sets. Also given that size is independent of orientation, bootstrapping allows the model to be made in a single modelling step.
Fracture size distribution	Exponential distribution	Mean = 2 m, minimum fracture radius generated = 0.5 m.	Trace mapping data from 5250 level best described with exponential distribution. Radius increased to represent non recording of larger structures in drifts and intermediate scale faults.
Spatial fracture intensity variation	Log normally distributed property	From modelled intensity property.	Distribution derived from geostatistical modelling of orientation corrected fracture frequency data.
Absolute fracture intensity		FracMan uses mean P10 intensity condition to control fracture generation.	Fracture intensity conditioned to match mean fracture frequency P10 on all borehole intervals by sector, corrected for minimum size truncation.

3.3 DFN model validation

When generating mine scale DFN models, a significant degree of model validation is required as the modelling volume, and its internal variability, it is much greater than for small scale DFN models. The main spatially varying properties that need to be validated within the large scale DFN model are overall fracture intensity and fracture orientation.

Validation of fracture intensity is achieved by taking the boreholes with their identified P10 intervals and target values and testing the DFN model to identify how many fractures intersect those P10 intervals. Figure 3(b) shows a graph of the simulated versus target number of fractures on all boreholes penetrating the DFN model showing the high level of agreement between the model and source data. The good match also confirms the validity underlying spatial model of the DFN model.

Orientation within the DFN model was conditioned using a bootstrapping technique (Rogers et al., 2006), which in the specific case of the Cadia East data set uses actual orientation data from the acoustic televiewer (ATV) to directly condition the DFN orientation, assuming a search radius of 450 m around each borehole. This approach allows capturing the broad scale variations in the overall fracture population observed in the Cadia East rock mass (e.g. a detectable clockwise rotation in orientation from east to west). By using a large enough search radius ensures that no part of the model is conditioned by a single borehole, but rather the conditioning reflects the average of several boreholes. This helps to minimise the directional bias imposed by the borehole sample itself. The actual validation of the simulated orientation data set is similar to the intensity tests, with the orientation of fractures intersected by the boreholes in the model compared against the fractures actually seen at that borehole. Figure 3(c) shows an example of the simulated versus actual fracture orientations, showing good agreement.

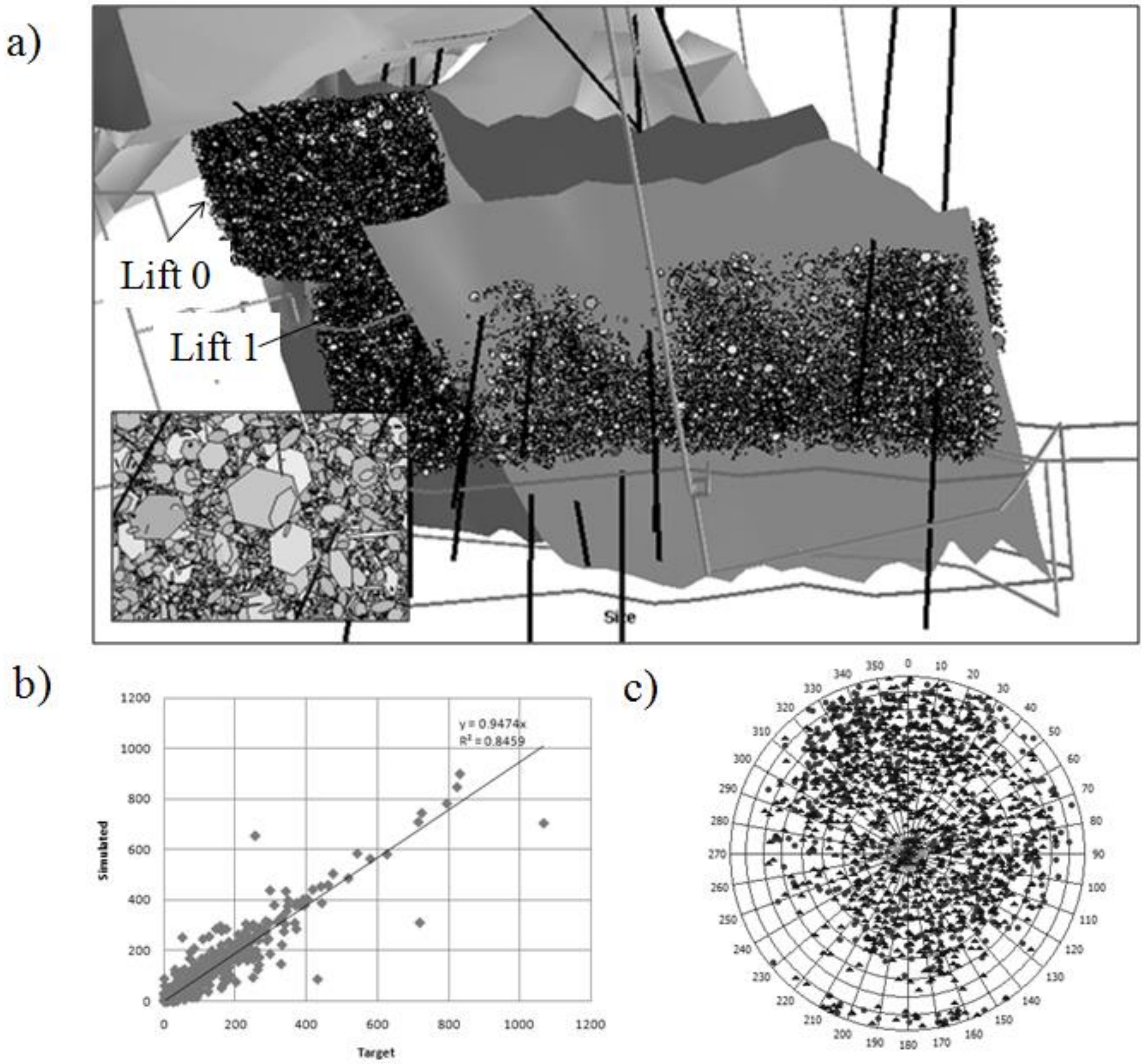


Figure 3 a) DFN model for caving scenario with 2 lifts, with fractures coloured by size, only 10% of fractures are shown. Conditioning boreholes are shown in black with major structures also added as large wire framed objects (small insert shows detail of DFN fractures); b) comparison of simulated and actual fracture count within defined intervals showing good accuracy of the DFN model; and c) an example from a single borehole showing the comparison between simulated (circles) and actual (triangles) fracture orientations from a borehole sample of the model

4 Determining cave scale in situ fragmentation

4.1 Block formation and P32 fracture intensity

The conventional approach to fracture characterisation, assuming fractures are ubiquitous and infinite generally over predicts the connectivity of a fracture system and therefore the degree to which a rock mass comprises well defined in situ blocks. As described earlier in Section 2.2, P32 is the preferred definition of fracture intensity for fracture modelling purposes. It has been shown to be a critical parameter in understanding fracture connectivity in well test analysis but has recently been shown to be a key property in determining the likelihood of block formation in fractured rock masses (Rogers et al., 2009).

For relatively low P32 values, a rock mass is generally a large volume of intact rock and fractures, with the rock mass strength dominated by the properties of the intact rock bridges. However, at higher P32 values, the rock mass increasingly becomes a kinematic assemblage of well defined potentially mobile blocks with joint properties dominating the material strength. Figure 4(a) shows a series of DFN models whose blocks have been mapped for a range of increasing P32 values showing how the volume occupied by mobile blocks increases from less than 10% of the total volume to close to 100%.

The conversion from rock-bridge dominated to kinematic rock mass happens over a relatively small change of P32. As shown in Figure 4(b), the percentage volume occupied by blocks rapidly jumps from < 10% to > 90% over a relatively small change in fracture intensity (between 2–3 m^{-1}). It may be argued that the induced stresses during caving are such that intact rock bridges will be broken and the material will be converted to a mobilised kinematic assemblage. For instance, 2D mine scale discrete models of cave development for Cadia East indicate that large residual poorly fragmented rock mass mega blocks may exist within the migrating caved material, supporting the notion that these mega blocks do not have to fragment fully (Elmo et al., 2010).

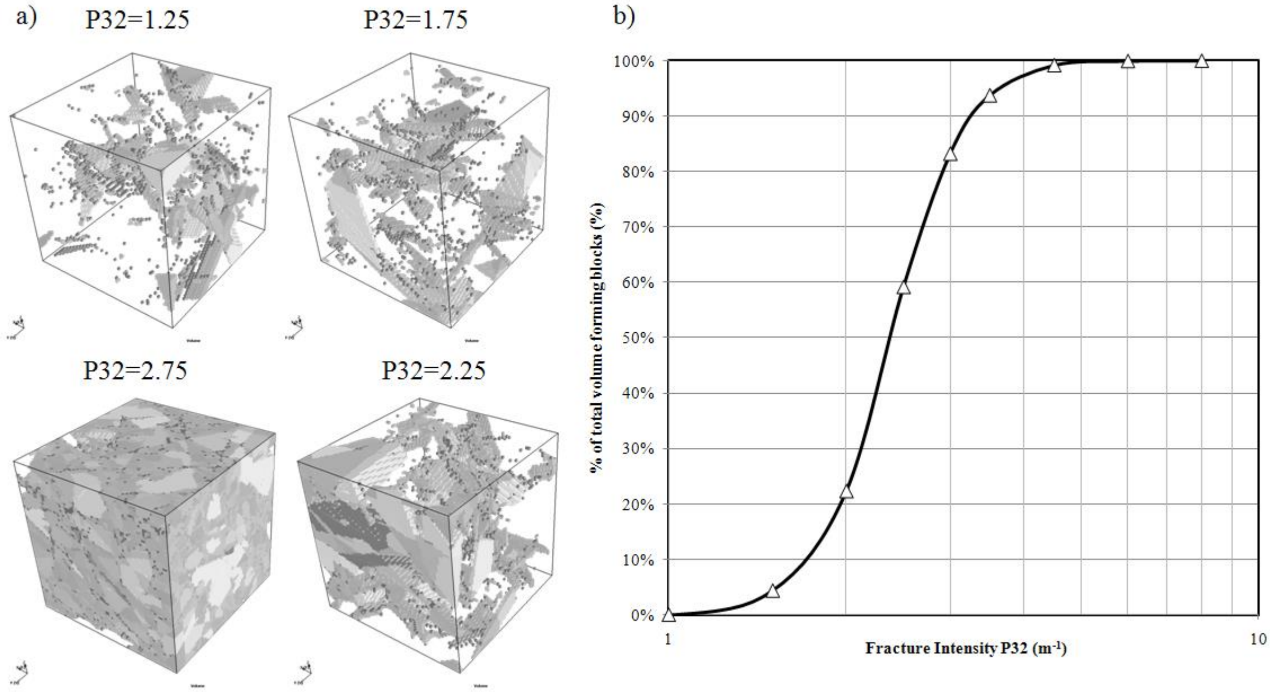


Figure 4 a) Rock blocks mapped within four DFN models of differing P32; and b) graph of the total percentage of volume occupied by blocks for a particular P32. Graph represents smoothed average of multiple iterations

4.2 Modelling methodology for cave scale fragmentation assessment

Detailed mapping of in situ blocks within a large discrete model is a computationally intense process owing to the highly complex geometrical nature of the problem. To provide a more rapid solution, the authors have developed a technique that allows the replication of the in situ fragmentation description for large models without the need to simultaneously search through a large volume.

This is achieved by initially calculating the distribution of P32 for each cave lift and domain within that lift. The P32 distribution is subsequently replicated to define its overall composition, based upon a range of smaller models of varying P32 (Figure 5). Using a 50 × 50 × 50 m volume, DFN models are built with a range of P32 values extracted for each lift and domain. For each of these various P32 models, the in situ fragmentation is then mapped within a 15 × 15 × 15 m sub-volume of the initial 50 × 50 × 50 m model to reduce edge and boundary effects, Figure 6. The process is repeated five different times for each P32 input to ensure reasonableness in the results.

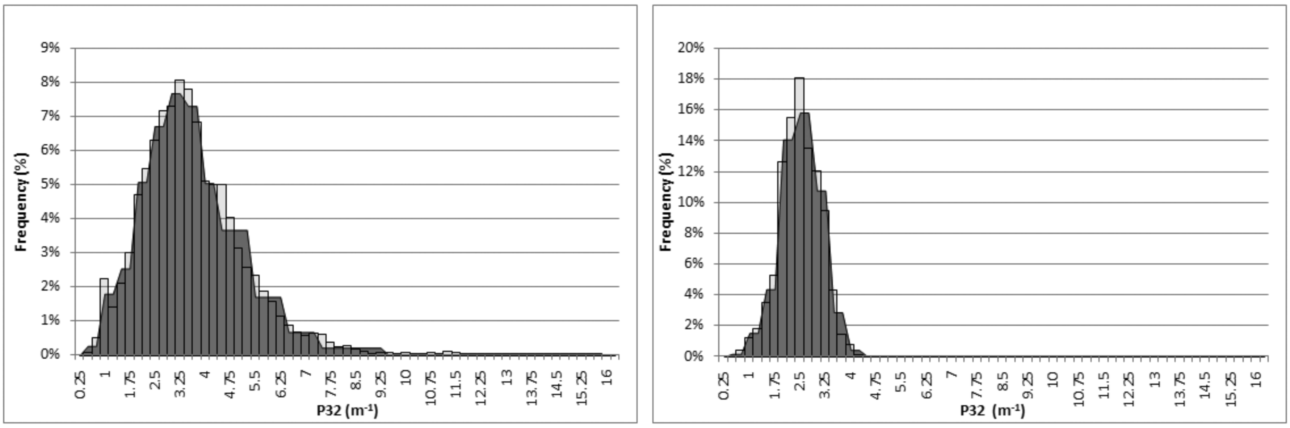


Figure 5 Examples of the distribution of derived P32 at the back, overlain with the discretised P32 distribution used reproducing the overall fragmentation of the domains

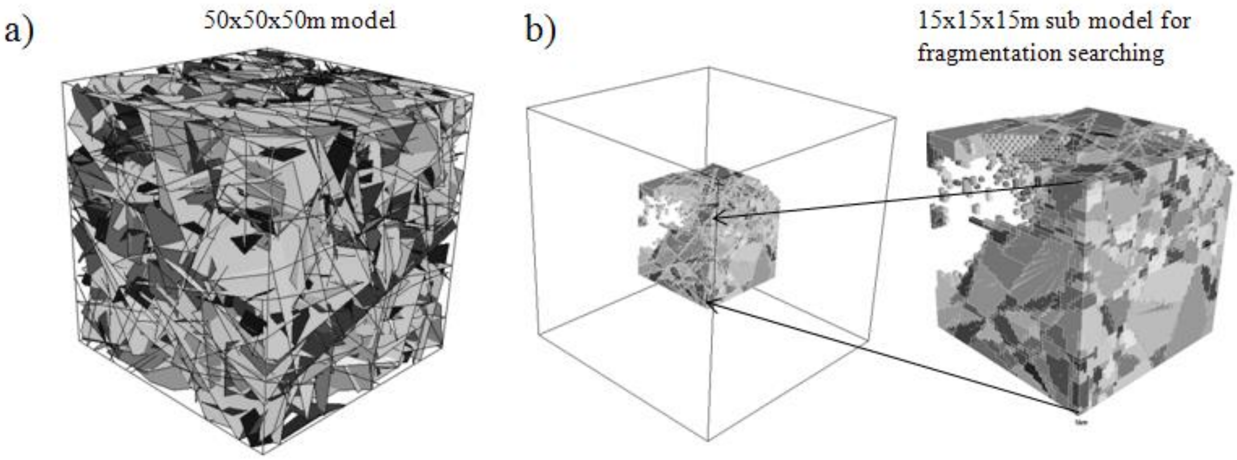


Figure 6 a) Small scale DFN models (50 m cube); and b) block searching is carried out within a sub-volume (15 m cube) to reduce edge and boundary effects. Each different shade in the right model represents a distinct in situ block

Once all the different size curves have been generated for each P32 input model, a volume weighted size curve is derived by combining the different fragmentation curves, according to the distribution of observed P32 values for that lift/domain. Figure 12 in Section 6 shows the size curves for the combination of each iteration from the multiple P32 simulations plus an average size curve. To better understand the likely range of results that might be plausibly observed, the distribution of blocks from the five simulations are bootstrapped in Crystal Ball (Oracle, 2009) to reproduce 100 possible, statistically likely, size distributions. The 10th percentile, 50th percentile and 90th percentile curves are also shown on Figure 12.

5 A rule based primary fragmentation approach

5.1 Introduction

Once the distribution of in situ fragmentation has been derived, the analysis has to focus on the determination of the increase in fragmentation as a result of stress induced fracturing during cave development. The majority of cave operations use the rule based approach of BCF (detailed in Laubscher, 1994) for the prediction of primary and secondary fragmentation. The use of advanced numerical simulations for explicit modelling of rock breakage is well established (e.g. Pierce et al., 2007; Cundall et al., 2008; Elmo and Stead, 2009) and provides an alternative approach. However, discrete analysis has been to date limited to relatively small scale rock samples and currently it is not practical to undertake large-scale numerical simulations including fracturing to determine block evolution owing to the computational requirements and restrictions on the size of the smallest element or particle size. To address this issue, a rule based approach to primary fragmentation analysis has been developed that integrates the results of induced fracture development in simulated small-scale discrete models as rules to be stochastically implemented within the code FracMan. Two-dimensional fracturing simulations are carried out using the hybrid finite/discrete code ELFEN (Rockfield Software, 2009), which employs fracture mechanism principles to better capture the transition from continuum to discontinuous state typical of rock brittle failure. The ELFEN computational methodology has been extensively tested and validated fully against controlled laboratory tests by Yu (1999), Klerck (2000) and Yan (2008).

The integrated hybrid/stochastic methodology is shown in this paper to efficiently reproduce primary fragmentation for potentially large modelling volumes.

5.2 Rule derivation through numerical simulation

The basic methodology for the rule based approach includes several modelling steps. Initially, modelling is carried out for a 20 × 20 × 20 m DFN model to establish the in situ fragmentation, using a representative P32 for a given cave lift. 2D sections from orthogonal planes through the DFN model are subsequently generated, including only fractures whose dip direction is within ±20 degrees of the trace plane orientation to account for plane-strain conditions in the hybrid finite/discrete model. The trace plane maps are then embedded into 20 × 20 m ELFEN 2D models and loaded using a representative stress-path derived from large scale modelling of cave evolution. Selected history points are identified within the large scale models and the relative stress-paths recorded to define the rock mass response as the cave propagates, Figures 7 and 8. For a detailed description of the assumed rock material and joint properties the reader is referred to Elmo et al. (2010). Selected examples of the modelling results are shown in Figure 9.

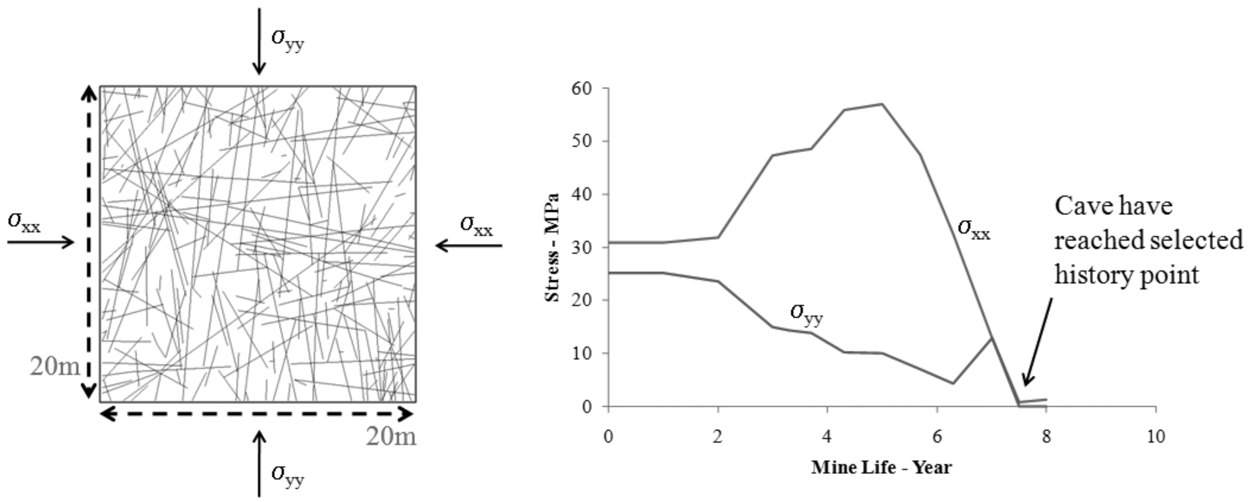
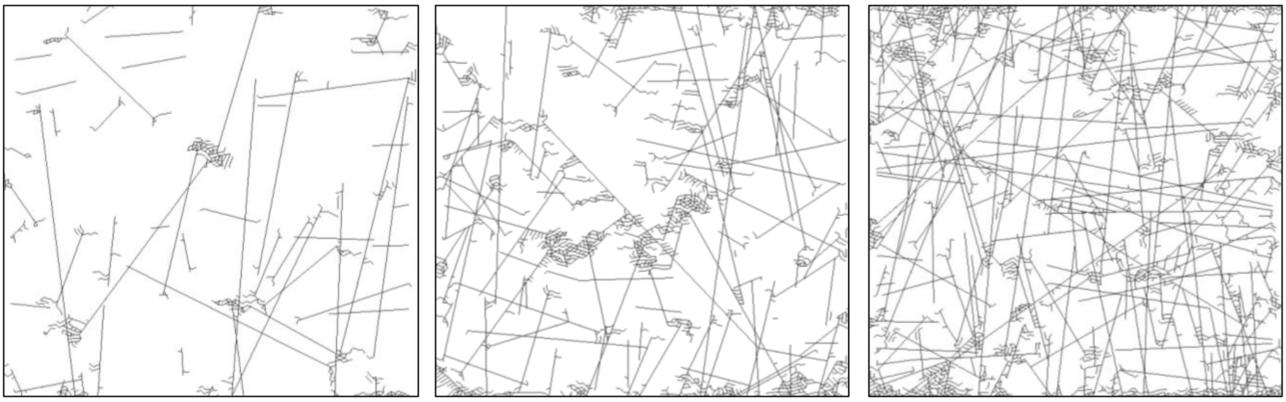


Figure 7 2D simulations of primary fragmentation: model geometry, loading conditions and example of stress path history as a function of simulated mine life for a selected history point



10th Percentile P32 50th Percentile P32 90th Percentile P32

Figure 8 Example of 2D simulations of primary fragmentation. Results for model with increasing initial fracture intensity, corresponding to the 10th, 50th and 90th percentile respectively of the observed DFN fracture intensity P32 for the target lift volume

Based upon these ELFEN simulation results it is then possible to quantify the geometry of the induced fractures in terms of fracture intensity, orientation, size and spatial variation. These observations are converted into rules for simulating primary fragmentation in FracMan as a rapid way of replicating rock mass degradation during cave evolution. Table 2 below presents examples of the primary fragmentation rules developed for a selected lift.

The generation of primary fractures can be undertaken in a number of stages where the stress history is more complex, allowing the application of a succession of induced fractures to be generated, following the evolving stress field. Figure 9 illustrates the generalised workflow for primary fragmentation assessment.

Table 2 Example primary fragmentation rules for FracMan simulation

Property	Modelling Observation	Rule Development
Orientation distribution	The majority of the fractures form sub parallel to the maximum horizontal stress and are typically within ±20 degrees of this direction.	Rule 1: Set orientation parallel to σ_1–σ_2 plane with dispersion k = 30.
Size distribution	Estimation of the size of fractures generated by ELFEN indicates that this can be sensibly described with an exponential distribution of mean 1 m.	Rule 2: Fracture radius exponential distribution with mean = 0.4 m and minimum size = 0.2 m.
Fracture intensity	The relationship between the ELFEN derived 2D induced fracture intensity (P21) and the equivalent 3D DFN input (P32) has been derived by simulated sampling.	Rule 3: Primary fragmentation P32 inversely related to P32 initial.
Spatial variation	Primary fragmentation appears to follow zones of higher in situ fracturing and so by mapping P32 variation in base model and use that to guide the induced fractures reproduces this observation.	Rule 4: Correlate intensity to in situ fragmentation intensity.

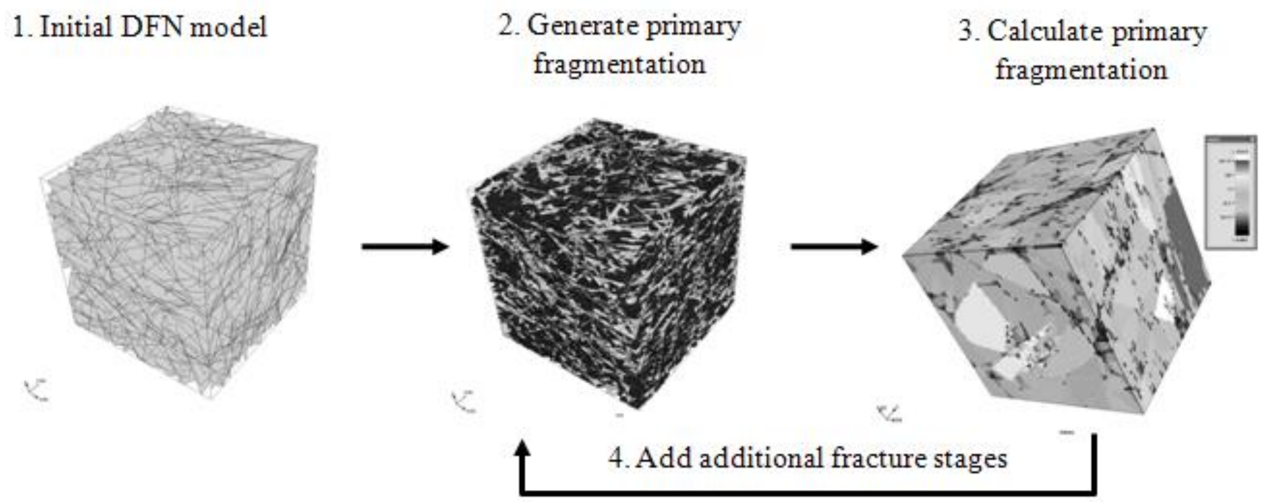


Figure 9 Illustration of the workflow to go from an initial DFN model of in situ fragmentation to primary fragmentation through the generation of stress induced fractures

6 Rule based probabilistic secondary fragmentation approach

6.1 Modelling methodology

In order to determine the secondary breakage of blocks, there is the need to assess their potential to degrade and unravel during their journey through the cave. The methodology presented in this paper assumes that the natural open joint system is primarily involved with formation of in situ blocks, which are potentially split by stress induced fracturing during cave evolution. As they move through the ore column, the remnant blocks potentially break and unravel, largely along micro-defects and/or veinlets.

Defects and veinlets are defined as close (cemented) structures mapped along rock cores, ranging in size from around half a core width to greater than the core size. For Cadia East, the veinlet frequency is in the range 3–50 m^{-1}, and these values have been converted to P32 values by conducting small block scale DFN simulations. In the current analysis, these smaller structures are assumed to represent primarily the part of the size distribution not directly simulated as open joints (i.e. < 1 m radius) within the existing in situ DFN model. An exponential distribution of mean 2 m, clipped between 0.025 m and 1 m is used to define the size of the defects and veinlets. Orientation distribution is taken as the same as that for the open joint population, and it is simulated by using the same bootstrapping data set.

The methodology presented in this paper for assessing secondary fragmentation is probabilistic, implemented within the code Crystal Ball™. The analysis reuses the small scale fragmentation characteristics of a block to be initially determined, and the process includes DFN simulations upon a 1 m^3 primary block, utilising various P32 input values for veinlets. These simulations allow the definition of a function describing block degradation (i.e. the transition from an intact block to a fully disintegrated block) as a function of veinlet P32.

To address the issue of block degradation as a consequence of the variable draw height travelled by the blocks through the cave, simple 2D analysis consisting of multiple blocks with variable face/point loading scenarios and containing a variable number of defects/veinlets are carried out in ELFEN. By measuring the reaction forces at the base of the model it is possible to calculate induced stress values, relating those to the height of an hypothetical ore column (Figures 10 and 11). These results are interpreted to define a breakage efficiency term which is subsequently used in an integrated FracMan/Crystal Ball analysis. The efficiency term ranges between 0–100% using a uniform distribution. Figure 10 shows that in all cases, the maximum fragmentation is reached at around 5 MPa (or approximately 190 m column height assuming a linear relationship between depth and stress) for all models and this function is used to guide the breakage efficiency function.

The actual secondary fragmentation workflow implemented within Crystal Ball follows a number of logical steps, as follows:

- based on the previously derived primary fragmentation distribution, randomly draw the volume of a primary block
- next randomly draw a veinlet P32 using distributions of these data obtained for each lift and domain
- based upon the drawn veinlet P32, calculate the percentage of the block that could form secondary blocks. This effectively divides the block into two parts:
  - a volume of potentially mobile blocks
  - the residual block volume (i.e. the part of the block that will remain unbroken).
- randomly draw a value from the breakage efficiency distribution which determines how much of the potentially mobile block volume is available for breakage
- based upon the drawn veinlet P32, calculate the mean block volume and divide up the potentially mobile volume into sub-blocks.

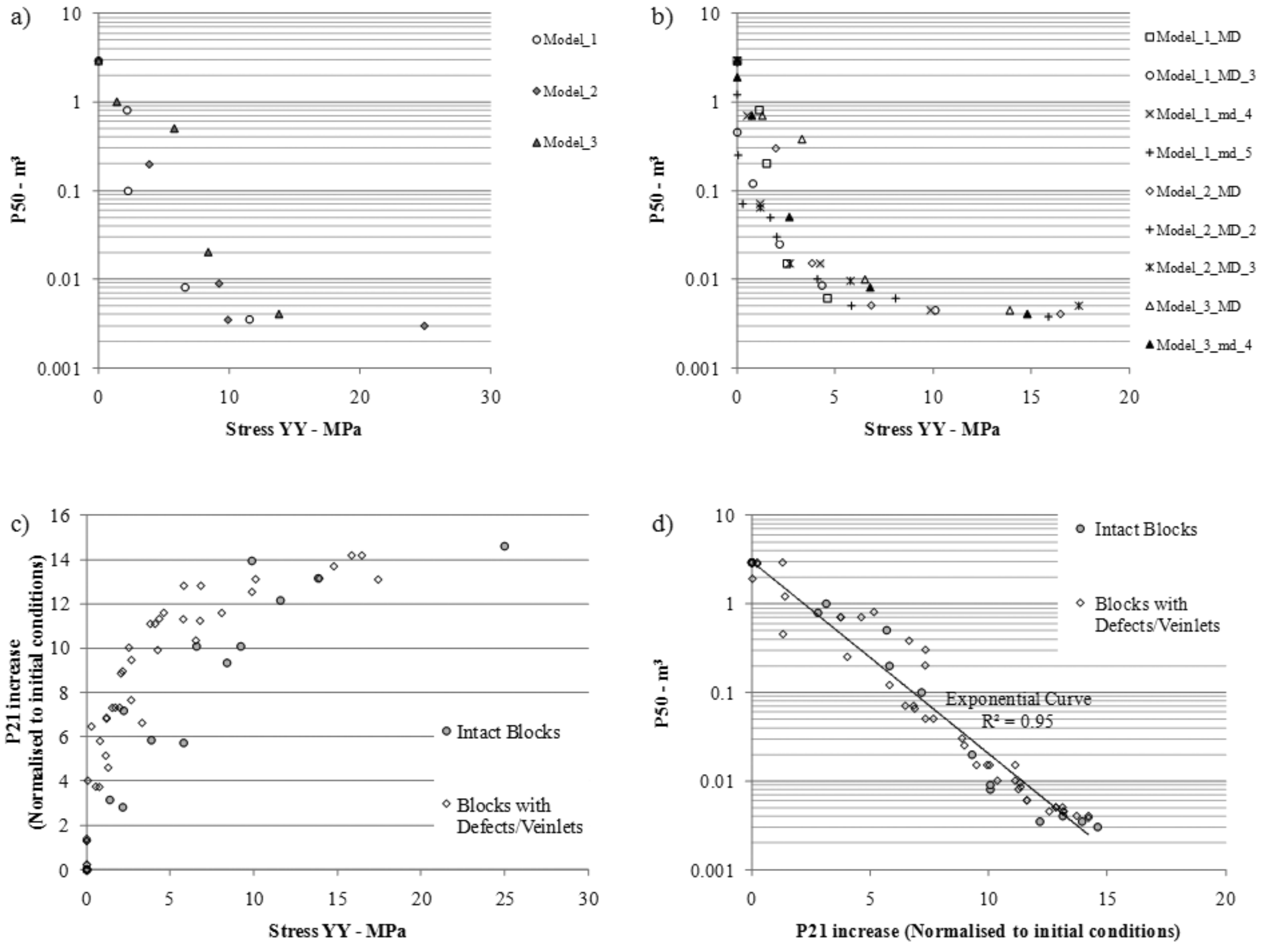


Figure 10 Results for ELFEN 2D models simulating blocks fragmenting due to different loading conditions through the cave: a) models with intact blocks; b) models with blocks containing defects/veinlets; c) progressive simulated induced fracturing as a function of increasing stress (indirectly representing the height of the ore column); and d) simulated relationship between induced fracturing and mean block volume

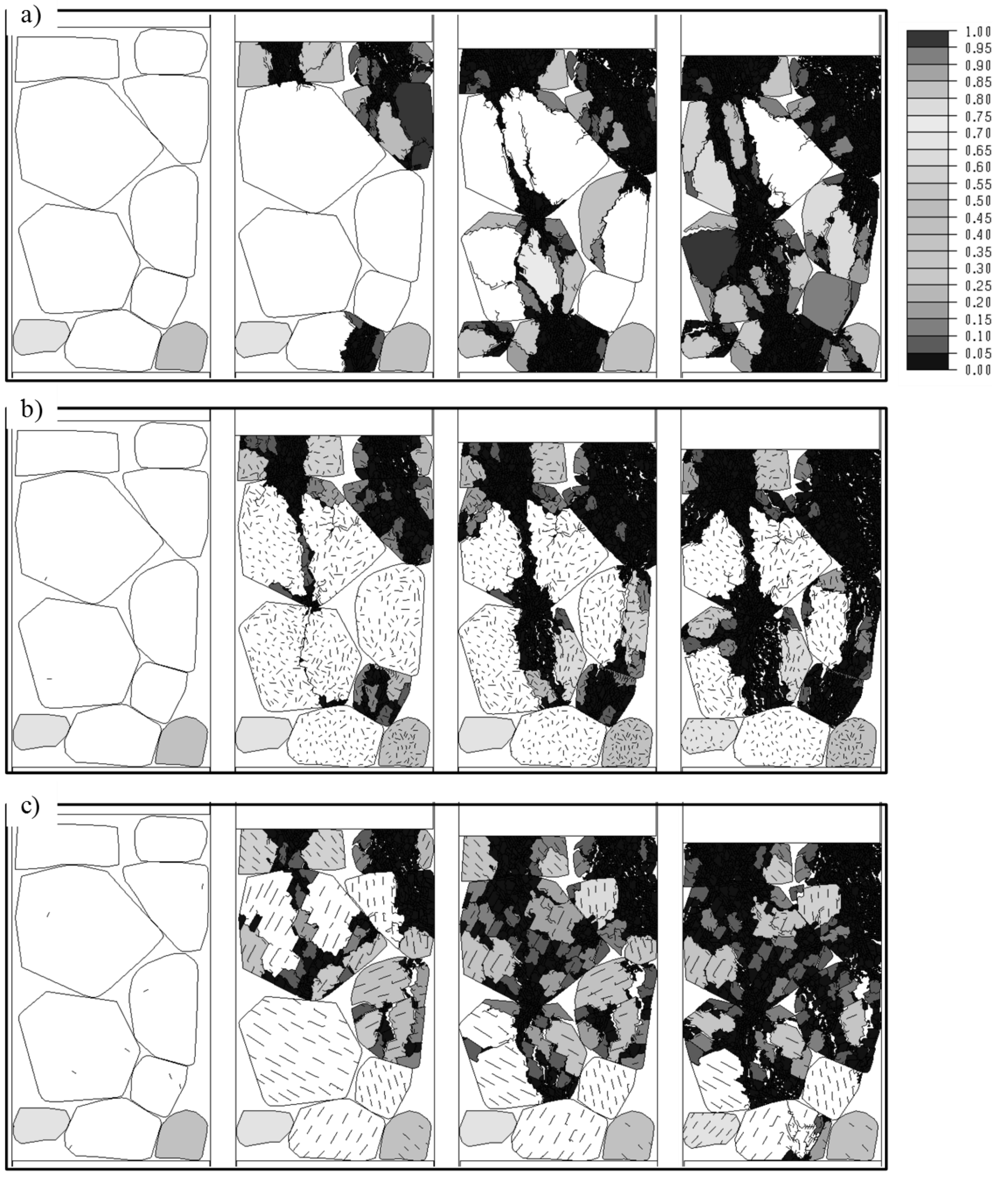


Figure 11 Example of ELFEN 2D simulations to investigate progressive block fragmentation as a consequence of blocks experiencing different loading conditions through the cave. Contours indicate block volume (m^3). White zones correspond to volume greater than 1 m^3. a) Model with intact blocks; b) model with blocks containing randomly oriented defects; and c) model with blocks containing defects with constant orientation

This methodology is repeated several thousand times for each lift and domain and the distribution of secondary blocks generated. It should be stressed that, despite the approach revolving around small scale discrete block geometries, the block mapping methodology still includes a small proportion of intact rock bridge, therefore when these secondary blocks are broken, the analysis implicitly assumes that there is a small volume of rock breakage occurring. An example set of in situ, primary and secondary fragmentation curves are shown in Figure 12.

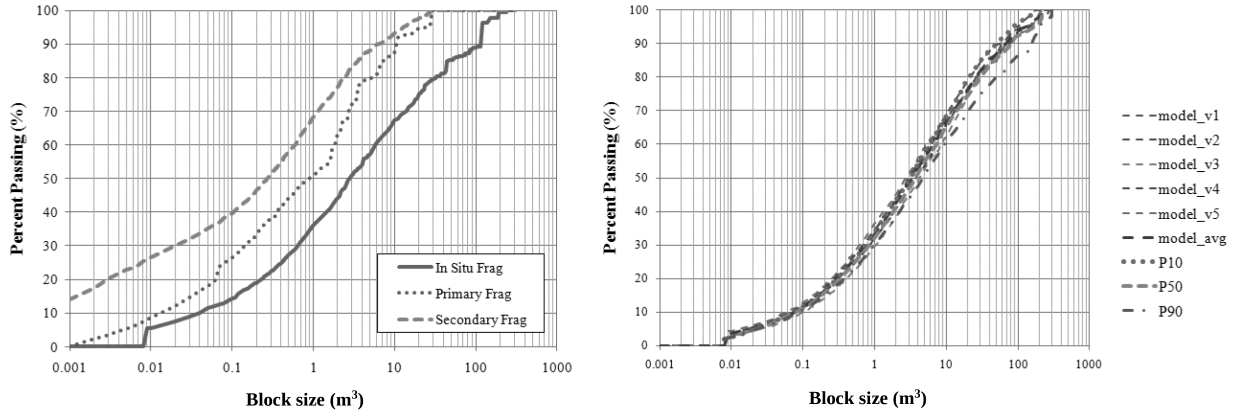


Figure 12 a) Size distribution curves for in situ fragmentation from an example domain showing the results for five different iterations plus the results of 100 simulations shown as the 10th, 50th and 90th percentile curves; b) example in situ, primary and secondary fragmentation curves for a domain derived using the DFN rule based probabilistic approach

7 Discussion and conclusion

This paper represents a well documented approach to large scale DFN modelling at the scale of the cave volume and greater. This is in contrast to most existing cave related DFN modelling that is typically carried out in a single spatial homogeneous volume at the scale of tens of metres. The ultimate objective of any DFN model generation should be the definition of a realistic description of the P32 variation through the cave volume, as this has been shown to be key to understanding variations in the in situ fragmentation and overall rock mass quality.

The proposed modelling approach was shown to provide an accurate 3D model of the variation of fracture intensity for the proposed Cadia East panel cave. This is derived from the analysis of a large data set of borehole fracture frequency measurements, broken into zones of common intensity and corrected for orientation bias. These data are then converted to a volumetric equivalent property and subsequently geostatistically modelled to provide a constrained description of P32 potential through the cave volume. With the distribution of P32 derived for the cave volume, in situ fragmentation curves can be determined for the range of intensity values observed and a weighted fragmentation distribution derived. It is anticipated that as data acquisition methods continue to improved and computer power increases, more and more mine scale DFN modelling will be undertaken as the logical starting point for any geometrical analysis such as in situ fragmentation definition.

The rule based approach to primary fragmentation provides a pragmatic solution to the large scale modelling of stress induced rock breakage during cave evolution. Whilst the ultimate goal is the ability to undertake cave scale numerical simulations for fragmentation assessment, until that is feasible the stochastic generation of primary fracturing constrained through smaller scale simulations remains a practical alternative. Ongoing research is aimed at better rule development to allow the stochastic fracturing to more accurately mimic stress induced fracturing.

Large scale detailed numerical modelling of secondary fragmentation represents a poorly constrained problem given the uncertainties associated with primary block geometry and block by block loading conditions. The authors believe that the DFN based probabilistic approach presented in this paper efficiently capture first order processes based around a better block geometry. The DFN approach can only attempt to capture the breakage of blocks as the move through the cave and cannot realistically model the grinding of blocks, therefore the inherent uncertainty with respect to fines production and their impact upon material handling and mill through put currently remains unanswered by the proposed approach.

A key learning from the secondary fragmentation ELFEN simulations was the relative insensitivity of the results to micro-defect orientation, given the completely random loading conditions encountered in a cave. Many of the current cave related logging methodologies record this property. However, more effort aimed at the characterisation of the overall geometry of these defects in terms of population size and strength, may result in a better understanding of secondary breakage.

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