Discrete Fracture Network approach to characterise rock mass fragmentation and implications for geomechanical upscaling

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Natural fragmentation is a function of the fracture length and connectivity of naturally occurring rock discontinuities. This study reviews the use of a Discrete Fracture Network (DFN) method as an effective tool to assist with fragmentation assessment, primarily by providing a better description of the natural fragmentation distribution. This approach 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. The results suggest that DFN models could effectively be used to define equivalent rock mass parameters to improve the predictability achieved by current geomechanical simulations and empirical rock mass classification schemes. As shown in this study, a mine-scale DFN model could be converted to equivalent directional rock mass properties using a rapid analytical approach, allowing the creation of a rock mass model that incorporates the influence of a local variable structure with continuous spatial variability. When coupled with more detailed numerical synthetic rock mass simulations for calibration and validation, a balanced and representative approach could be established that puts more equal emphasis on data collection, local- and large-scale characterisation, conceptualisation and geomechanical simulation.

Keywords: Discrete Fracture Network, Fragmentation, Rock mass characterisation, Geomechanical upscaling

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Introduction

The use of Discrete Fracture Network (DFN) models to define equivalent rock mass parameters based on a realistic representation of the rock fabric has the potential to improve the predictions achieved by various geomechanical simulations. Additionally, DFN models could provide a more realistic description of the *in situ* fragmentation (the degree to which the rock mass is naturally broken by the fracture system). For instance, the impact of poor or unexpected fragmentation has a significant impact upon cave operations and draw schedules. Recent advances in the field of data capture and synthesis allow 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 true discontinuous and inhomogeneous nature of the rock mass should be reflected in most modelling conceptualisation; hence, the importance of fracture length (FL) cannot be overemphasised if realistic characterisation and fracture analysis are to be undertaken (Kalenchuk *et al.*, 2006; Kim *et al.*, 2007; Elmo *et al.*, 2008). It is clear that the volume, shape and stability of rock blocks depend on the characteristics of the natural rock fracture network. In this context, a DFN approach represents an ideal numerical tool with which to synthesise realistic fracture network models from digitally and conventionally mapped data.

Although numerical simulations provide a potentially useful means of overcoming some of the limits of the empirical methods, empirical approaches such as rock mass characterisation and classification systems still represent a fundamental component for many applications in both mining and rock engineering practice. Ideally, both qualitative and quantitative data should be collected as part of the rock mass characterisation process, providing the necessary parameters for a subsequent classification analysis. 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.

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This study introduces the preliminary concepts of a DFN-based rock mass characterisation approach, which couples empirically derived mechanical properties with orientation-dependent parameters to account for rock mass anisotropy. In particular, this study focuses on introducing a link between existing classification systems and volumetric fracture intensity, with the objective of providing an improved link between mapped fracture systems and rock mass strength in comparison to the current practice of using empirical rock mass classifications alone.

In this study, note that the term fracture is used as a synonym of joint. The term fracture size or joint size is used in lieu of term persistence to define the extent of a fracture within a plane. Fracture size (or joint size) can be measured on exposed surfaces (trace length) and the collective result is named trace map. It is important to differentiate between trace lengths and trace maps (direct measure of fracture size) and fracture radius, which is used within the framework of DFN models. Fracture size does not directly correspond to fracture radius because trace lengths observed on tunnel walls or bench faces are not actually diameters, but may be cords to larger discs (assuming fractures are circular). Several authors (e.g. Zhang and Einstein, 2000) have discussed the need to determine the underlying fracture radius distribution that results in the mapped trace length distribution. For the purpose of DFN modelling, fractures are considered to be planar and can be represented by circular discs or polygons with n sides (and $n>3$). For a polygonal with n sides, the fracture radius is defined as the radius of a circle of equivalent area.

DFN approach and fragmentation modelling

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 on field observations of fracture properties such 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. 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.

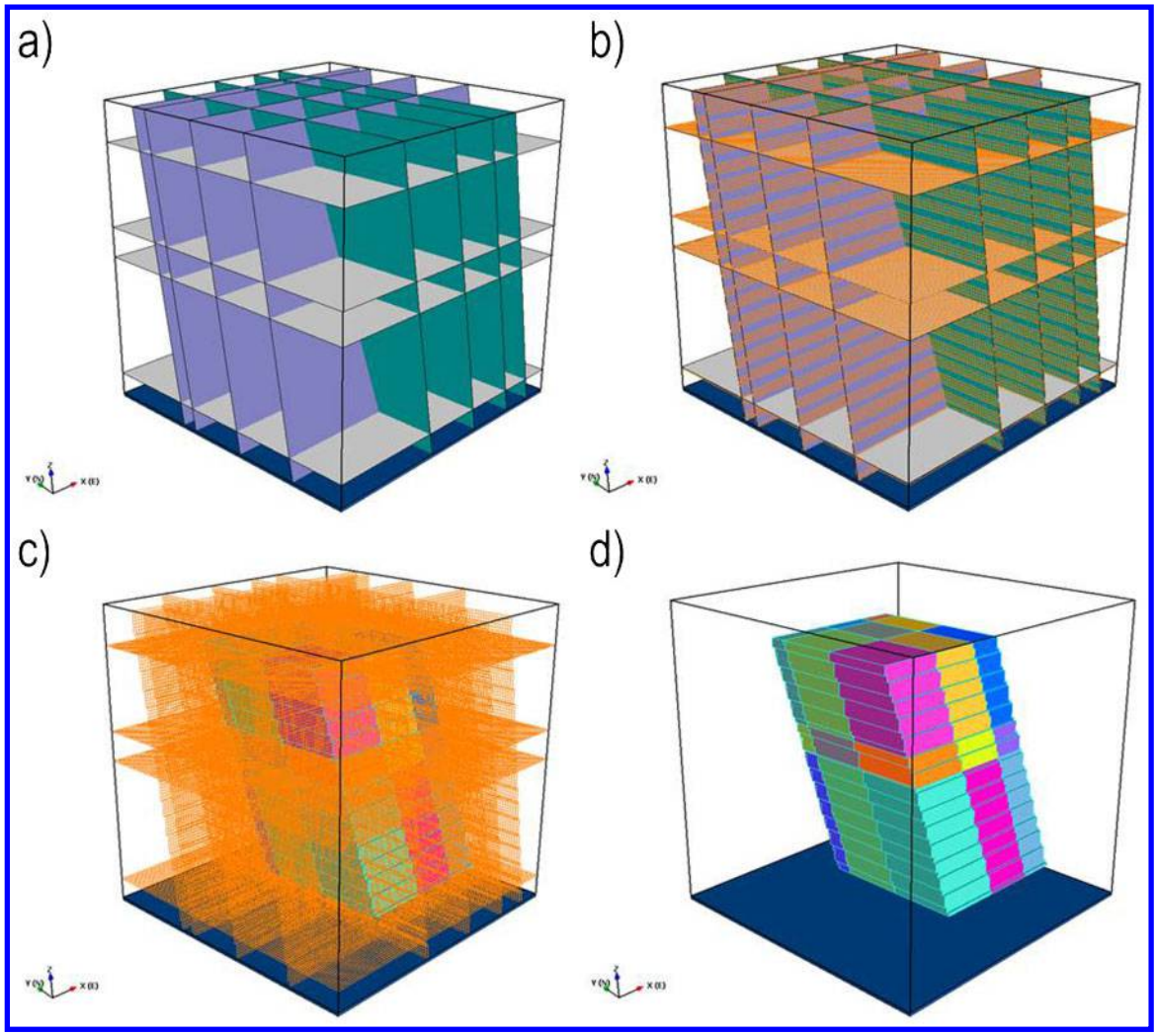
DFN methods have a number of key advantages over more conventional methods in that they are better at describing local-scale problems because of their ability to capture the discrete fracture properties more accurately than large-scale continuum approaches and can also capture the heterogeneity of the 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 (Dershowitz *et al.*, 1998; Rogers *et al.*, 2009). For the purposes of the work detailed within this study, the most important parameter to understand is fracture intensity. In order to 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 Pij system (Dershowitz and Herda, 1992). The Pij system seeks to define fracture intensity in terms of dimensions of the sample (e.g. borehole, trace map, volume) and measure (e.g. count, length, area). As an example, P_{10} (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 (P_{10}, units m^{-1}) or from trace mapping upon surfaces such as benches or tunnel walls (P_{21}, units m m^{-2}). Both these data are directionally biased. The preferred measure of fracture intensity for a DFN model is known as P_{32} (fracture area/unit volume, units m^2 m^{-3}). P_{32} represents a non-directional intrinsic measure of fracture intensity and has wide applications in rock engineering. Although it cannot be directly measured, it can be inferred from the 1D and 2D data above using a simulated sampling methodology by simulating non-P_{32} values and observing the resultant P_{10} or P_{21} on borehole or trace plane samples in the model.

The code FracMan (Golder, 2012; Dershowitz *et al.*, 1998) is the platform used in the current analysis for DFN data synthesis and fragmentation analysis. FracMan allows the 3D visualisation of blocks defined by intersecting discontinuities in the DFN model by employing an *implicit* fragmentation grid algorithm (called *Sybil Frac*) or a more conventional *explicit* block search algorithm. As shown in Fig. 1, the fragmentation algorithm works by initially overlaying a fine grid of cells onto the initial DFN model (Fig. 1*a* and *b*), then fractures are mapped onto those cells (Fig. 1*c*) and stepped blocks are assembled by joining up the connected grid cells (Fig. 1*d*). The procedure depends on the size of the grid cells and it is recommended to use a grid cell size that is approximately 25% of the average fracture spacing.

The explicit block search (referred to as Rock Wedge analysis in FracMan) is used to investigate block stability on slopes or mine and roads tunnel, allowing a truly probabilistic assessment of the kinematic stability in surface and underground rock excavations. Compared with the above implicit fragmentation grid approach, the Rock Wedge analysis allows considering realistic rock blocks defined by the intersection of the underlying DFN model with a given free surface (e.g. tunnel walls or a slope face). The process involves the generation of a trace map formed by the intersection of



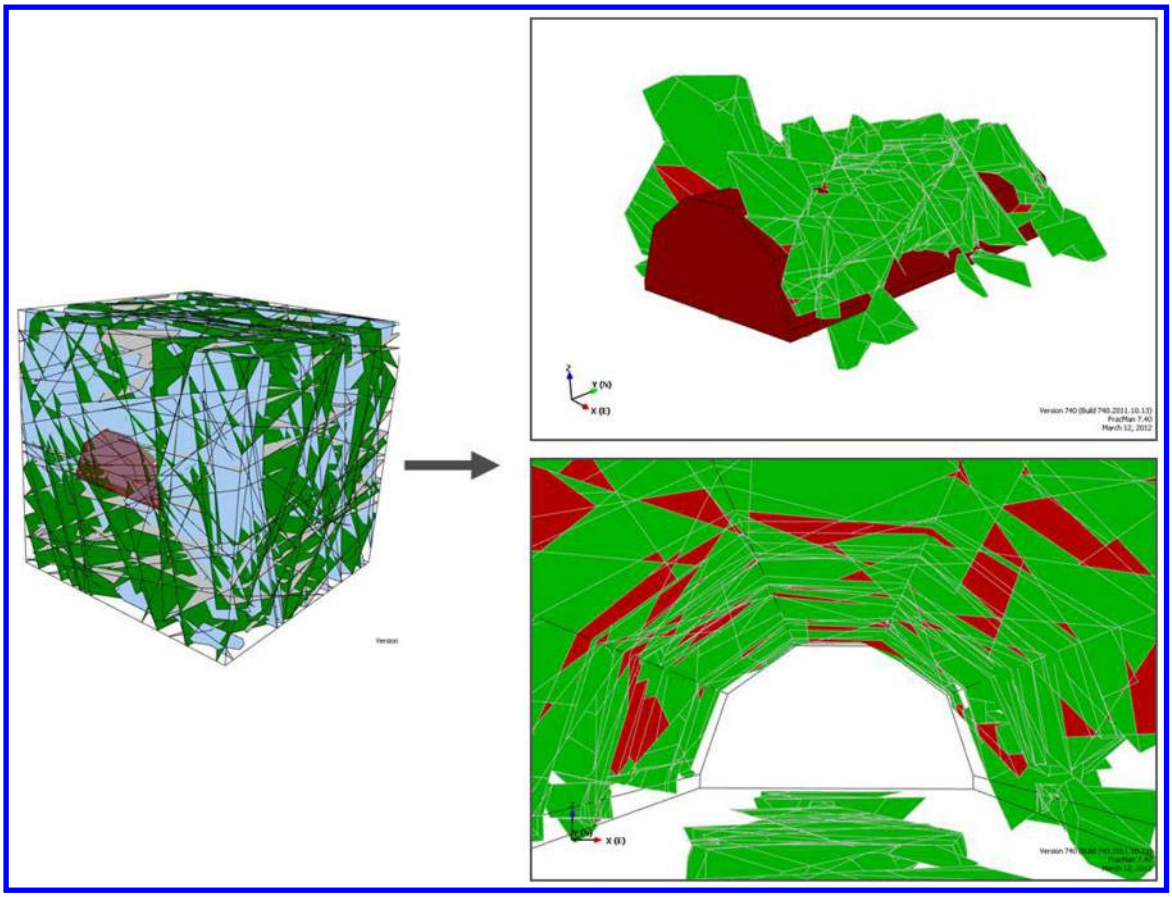
1 Example of a DFN-based cell mapping algorithm: *a* Initial DFN, *b* fractures being mapped the specified grid, *c* blocks being mapped along the grid cells and *d* Final block model

the DFN fractures with the assumed free surface. Rock blocks are constructed by identifying those fractures that form closed two-dimensional blocks in the trace map. This results in a collection of faces and connection information. All these faces are processed using an unfolding algorithm to generate the minimum volume polyhedron that connects the specified free surface. The rock block volume (Fig. 2) is computed by a process of 3D tessellation with the associated block mass being calculated using the computed volume and the assigned rock density (Dershowitz and Carvalho, 1996). The Fragmentation Grid algorithm is optimised to provide an initial estimate of the rock natural fragmentation, while the Rock Wedge algorithm provides an accurate estimate of block shape and volume, which is suited for the kinematic assessment of block stability.

Characterisation of block shapes and volume

Starzec and Tsang (2002) used the explicit algorithm to quantify the relationship between the volume of unstable blocks and surface fracture intersection density (defined as the number of intersections between fractures on the trace plane divided by the area of the trace plane) for a circular tunnel. They postulated the use of the volumetric fracture intersection density as a means of quantifying the combined effect of the fracture–parameter estimates on block-prediction estimates. However, this property cannot be obtained in the field by direct measurement, consequently there is a need to define a relationship between the volumetric fracture intersection density and specific fracture intersections parameters measurable on a given rock surface. Rogers *et al.* (2007) used FracMan for characterising the natural fragmentation of a fractured rock mass, while Elmo *et al.* (2008) used a similar approach combined with a sequential sampling technique for characterising intact rock bridges. Tollenaar (2008) used the explicit block search method to characterise the volume, shape and number formed above an excavation simulating the undercut in a block cave mine.

In this analysis, all the rock blocks in the DFN models which intersect a specified free surface (representing a hypothetical undercut level) are identified. Although the size and geometry of the excavation represents fixed variables, fracture orientation and FL are expressed within the DFN model as probability density functions; therefore, the accuracy of block predictions would depend on the reliability of the initial descriptive parameters. The models shown in this study are conceptual in nature and consist of three



2 Example of a DFN-based explicit block mapping: Fractures in the DFN model (left) are processed to generate the minimum volume polyhedron which connects to the specified free surface (tunnel for the specific case shown here). Dark-coloured blocks have a Factor of Safety (FoS) less than 1, whereas light-coloured blocks have either a FoS greater than 1 or represent tapered blocks

mutually orthogonal joint sets with a constant FL (Table 1).

Each DFN model is generated within a $10 \times 10 \times 10$ m box region. In order to reduce the risk of statistically significant differences in the results, 50 Monte Carlo realisations of each fracture network were considered in the analysis. This was based on the conclusions by Starzec and Tsang (2002), which in their study concluded that 50 Monte Carlo simulations were a sufficient number to provide a reliable estimate of total unstable block volume. The scope of this study is not to provide a review of the issues concerning the convergence of Monte Carlo simulations. However, the authors recognise that the number of Monte Carlo simulations required would depend on the parameters of the probability distribution functions.

The modelling results are in agreement with observations by Chan and Goodman (1987) and Hoerger and Young (1990), who found that for a simple fracture network with three joint sets, the block volume is influenced predominantly by fracture spacing. The analysis shows that, for a given fracture spacing, the average block volume is a function of the FL factor, which is defined as the ratio between FL and problem scale (10 m). In Fig. 3*a*, a critical FL (dashed line) can be identified below which the average block volume is extremely small such that the effective control of fracture size on mean volume can be neglected. However, this is reflected in an increased number of naturally formed rock blocks with decreasing fracture spacing. Figure 3*b* shows how the calculated mean block volume varies as a function of both the FL factor and fracture intensity P_{10}. As expected, for closely spaced fracture systems (e.g. $P_{10} \approx 4\ m^{-1}$), block volume appears to be less sensitive to FL. A preliminary (qualitative) interpretation with respect to fragmentation and massive (M) to very blocky (VB) and damaged (VB-D) transition is given in Fig. 4.

The authors believe that being able to characterise block size as a function of FL has major implications for rock mass classifications systems. Rock mass characterisation systems such as the rock mass rating (RMR) system (Bieniawski, 1989), the Q-index (Barton *et al.*, 1974) and the geological strength index (GSI; Hoek

Table 1 Parameters used for conceptual explicit block analysis

	Set 1	Set 2	Set 3
Orientation (°)	000/90	090/90	000/00
Fracture length/m	1, 2, 5 and 10	1, 2, 5 and 10	1, 2, 5 and 10
Fracture intensity P_{10}/m^{-1}	1, 2, 3 and 4	1, 2, 3 and 4	1, 2, 3 and 4

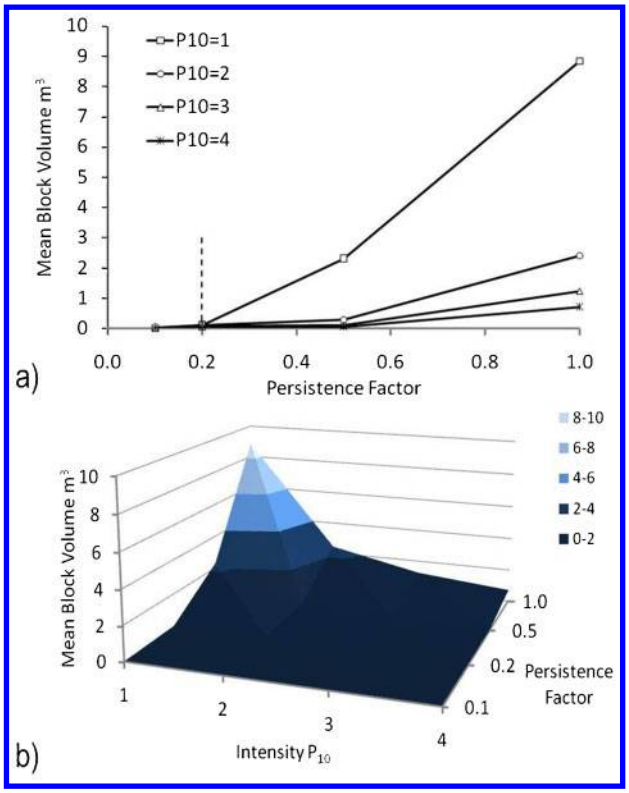
et al., 1995) are useful tools which serve the purpose of (1) identifying significant parameters influencing rock mass behaviour, (2) deriving quantitative data for engineering design and (3) providing a quantitative measure to compare geological conditions at different sites. In particular, the GSI has the advantage of being related to the Hoek–Brown failure criterion for rock masses, which is widely accepted in geotechnical and rock engineering applications. In his initial formulation, the table used to establish the GSI for a rock mass only uses qualitative descriptors (i.e. joint surface conditions and rock structure characteristics). In 2004, Cai *et al.* presented a quantitative method to assist in the use of the GSI system, by using fracture spacing as a quantitative indicator of the rock structure and the term Jc to quantify the joint surface conditions. The term Jc is similar to the factor used by Palmstrom (1995) to quantify the joint surface condition in the RMR classification system. Later, Kim *et al.* (2007) extended the approach by Cai *et al.*'s (2004) study to account for fracture size by introducing the concept of equivalent block volume. The equivalent (or apparent) block volume should be larger for rock masses with non-persistent joints and the equivalent block volume constitutes a form of blockiness index for the rock mass (the greater the apparent block volume, the more massive the rock mass).

Only blocks defined by the intersection of the underlying DFN model with a given free surface can be visualised using the Rock Wedge algorithm. This partly limits the results of the analysis shown in Fig. 3, since it does not includes blocks away from the assumed free surface. To compensate for this and with the objective of investigating the concept of equivalent block volume, a sequential sampling technique is used in conjunction with the same DFN model used to produce the results shown in Figs. 3 and 4. In the sequential sampling technique, the Rock Wedge analysis is performed repeatedly by moving the simulated free surface towards the box centre for an assumed incremental distance.

Accordingly, the sequential analysis allows to provide a qualitative characterisation of the degree of natural fragmentation as a function of both FL and fracture spacing (Fig. 5). Relatively short fractures (e.g. 2 m long) coupled with a relatively high intensity P_{10} (i.e. closely spaced fractures) would potentially yield a block assemblage characterised by very few and sparse intact rock bridges, as shown by the inset VB (Very Blocky) in Fig. 5. Because of the conceptual nature of the analysis, no attempt was made at this stage to quantify the *y*-axes (block volume). The authors recognise that there is a need to extend the analysis to consider different combinations of the assumed initial parameters used to generate the DFN models and to include results from case studies in order to constrain the *y*-axes in Fig. 5, possibly by normalising the block volume to the problem scale, thus using an overall blockiness index. In this context, the work by Palleske *et al.* (2013) could provide further constrain to the proposed block characterisation, by including the effects of limited data set on model generation.

Development of a DFN-based rock mass characterisation approach

The analysis described in the previous section has shown that it is possible to provide a preliminary characterisation of the rock mass to account for both length and



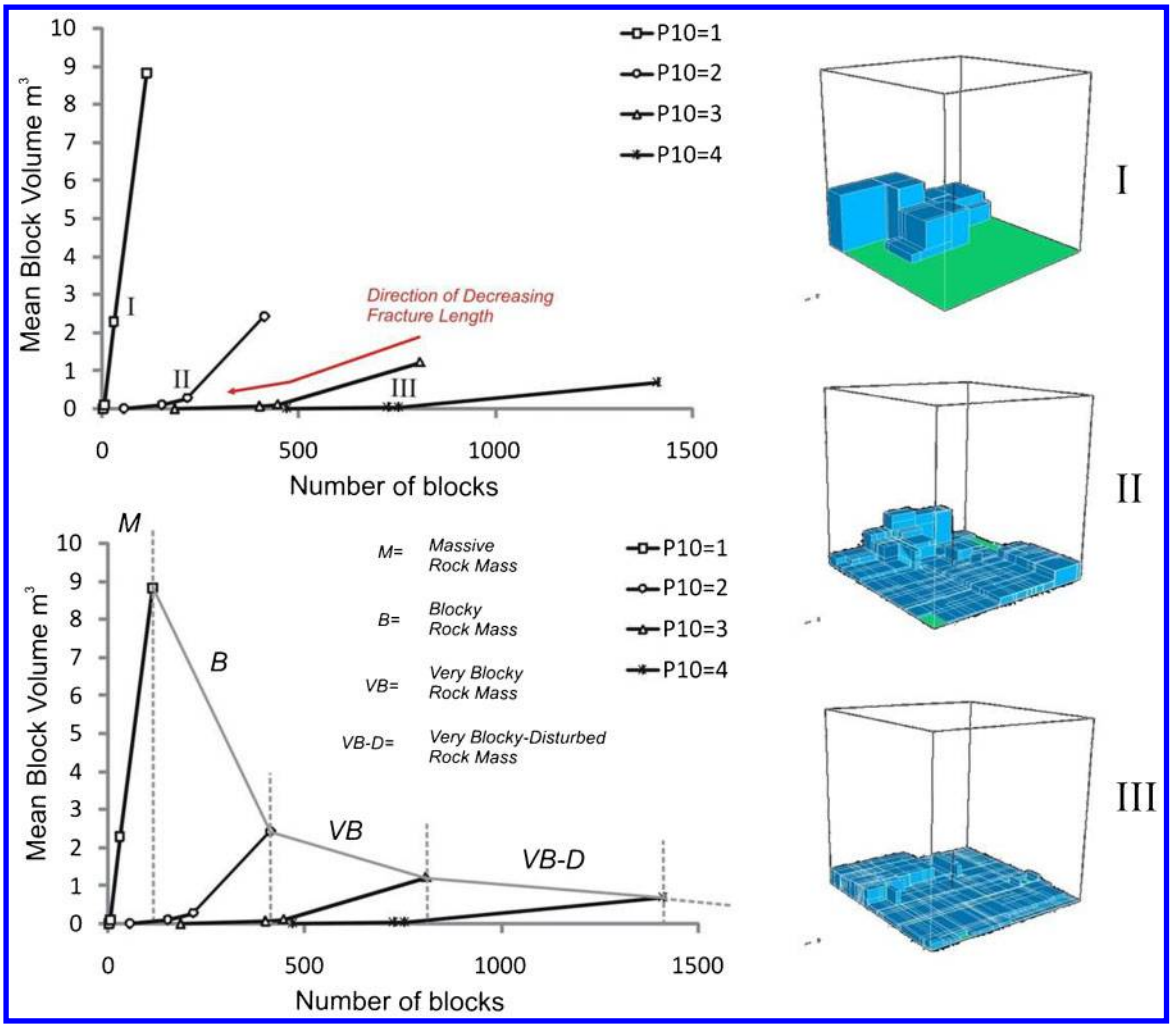
3 ***a*** **Mean block volume as a function of the persistence factor, defined as the ratio between FL and problem scale (10 m) and** ***b*** **mean block volume as a function of both persistence factor and fracture intensity P_{10}**

spacing of the fractures. Using the Fragmentation Grid function in FracMan, an attempt was made to further develop the approach and test whether inputs to classification schemes could be expressed as functions of specific DFN parameters.

The analysis considered a DFN model generated using the parameters listed in Table 2. The number of joint sets is defined using the Jn parameter convention (Barton *et al.*, 1974) and each set is defined using a function which randomly generates numbers within the range [0, 360] for dip direction and [0, 90] for dip. The dip and dip direction of the random joints are also defined using a similar function (Fig. 6*a*). Each DFN model is generated within a $80 \times 80 \times 80$ m box region and three simulated boreholes are used to estimate the Rock Quality Design (RQD, Deer, 1963) of the rock mass (Fig. 6*b*). The fragmentation analysis is carried out using the implicit cell algorithm within region with dimensions $10 \times 10 \times 20$ m.

RQD provides a measure of rock mass quality from drill core and is used as an input into geomechanical classification schemes, e.g. RMR (Bieniawski, 1989) and the Q system (Barton *et al.*, 1974). Recently, Hoek *et al.* (2013) introduced a quantification of the GSI classification system based on RQD and Joint Conditions parameters established using the RMR system. The results (Fig. 7*a*) show that there is an apparent correlation between RQD and the DFN volumetric intensity P_{32} and the modelled correlation is independent of orientation (i.e. number of joint sets).

Studies by Priest and Hudson (1976) show that RQD can be defined as the integral of the spacing distribution



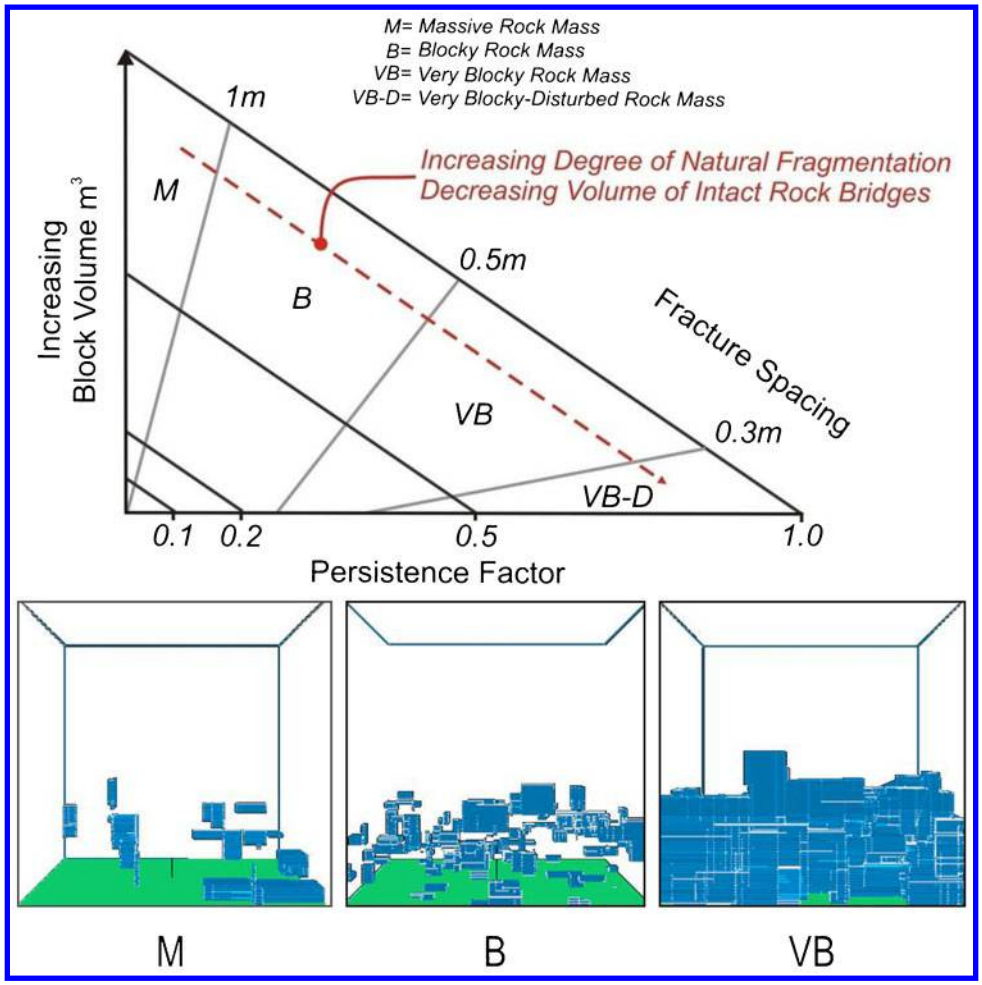
4 ***a*** **Relationship between mean rock block volume and number of blocks rocks for a given fracture spacing,** ***b*** **Preliminary qualitative interpretation with respect to fragmentation and massive (M) to very blocky (VB) and damaged (VB-D) transition. Insets I, II and III show blocks formed above the simulated undercut (10 × 10 m model size)**

$$\mathrm{RQD} = 100e^{-0{\cdot}1\lambda}(0{\cdot}1\lambda + 1) \quad (1)$$

where λ is the mean fracture frequency. They proposed a linear relation that could be used as an approximation of RQD for λ in the range of 6–16 fractures m^{-1} (Fig. 8). In this context, the linear correlation between RQD and volumetric intensity P_{32} shown in Fig. 7 would be valid assuming that the calculated RQD is in the range of 40–90. Further analysis would be required to extend and verify the proposed relationship between P_{32} and RQD. Despite the preliminary nature of the analysis, the results show that it is also possible (Fig. 7*b*) to define a relationship between RQD and the degree of natural fragmentation of the assumed rock mass, expressed as normalised volume index (i.e. ratio of total number of blocks being formed to volume of problem domain). Note that the current analysis does not make any assumption on the conditions of the joints being modelled. However, assuming that all joints in the system have the same roughness/alterations characteristics (e.g. JCon=40 according to RMR 1989) and using the quantified table introduced by Hoek *et al.* (2013), it is possible to correlate RQD to GSI for varying fracture intensity P_{10} (Fig. 9). As expected, closely spaced fracture networks consisting of three and four sets would have relatively lower values of GSI. Similarly, the influence of joint spacing on the estimated range of GSI would increase with increasing joint set number. As shown here, DFN models could therefore provide an alternative modelling route for the estimation of rock mass properties for continuum modelling, taking into account the spatial variability of fracture intensity and joint roughness/alteration conditions.

Cave-scale DFN model development

This section introduces some of the issues associated with building a mine-scale DFN model for which the primary fracture properties of intensity, spatial variation, orientation and size are needed to be defined across a much wider and potentially complex volume. 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 a large-scale DFN model 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 P_{32} variation through the cave volume, as fracture intensity has been shown to be key



5 Reinterpretation of the results shown in Figs. 3 and 4 using a sequential sampling technique in the DFN model to a qualitative characterisation of the degree of natural fragmentation as a function of both persistence factor and fracture spacing (10 × 10 m model size)

to understand variations in the *in situ* fragmentation and overall rock mass quality.

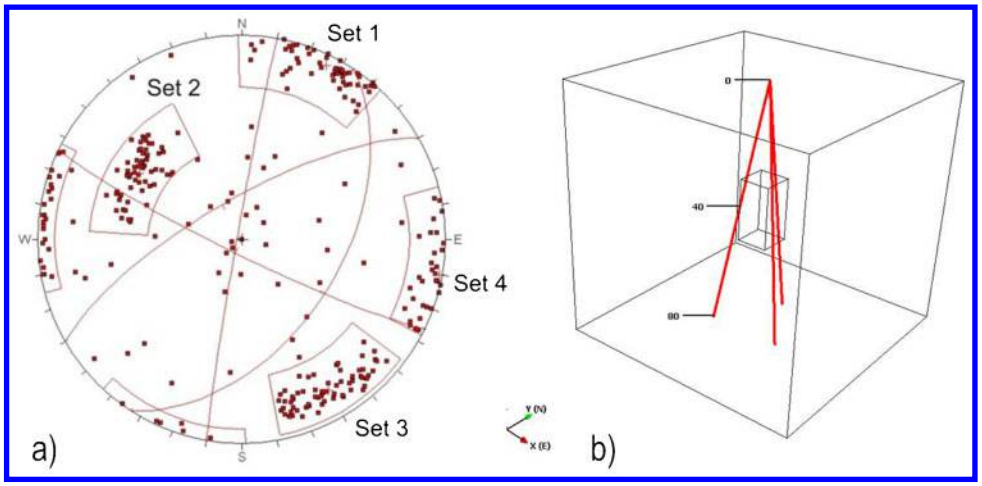
The primary input for fracture intensity modelling at the cave scale is borehole-derived fracture frequency (P_{10}) data. Each borehole needs to be interpreted to identify zones of the rock mass, where P_{10} remains constant over intervals lengths of around 10–100 m, the typical modelling resolution. 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 (P_{10}) 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 P_{10} values and interval lengths that provide the basis for any 3D spatial modelling and extrapolation of fracture intensity.

P_{10} data are directionally biased with the true measure of intensity being dependent on the orientation of the boreholes and the orientation of the fracture orientation distribution. To account for this issue, the P_{10} intensity values need to be converted to a non-directional intensity property known as P_{32} potential, using the technique first introduced by Wang (2006) and described in details by Rogers *et al.* (2009). Once the initial bias P_{10} values have been converted to orientation-corrected P_{32} potential (P_{32P}) values, geostatistical methods can be used to interpolate these values through the mine volume.

The 3D fracture intensity P_{32} potential property provides the relative distribution of fracture intensity through the mine-scale model. However, to condition the model to the correct absolute fracture frequency, the model needs to use a technique of P_{10} 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. Figure 10 shows an example

Table 2 Parameters used for conceptual explicit block analysis

Orientation (°)	Set 1	Set 2	Set 3	Set 4
	203/82	119/49	327/74	277/86
Fracture length	Negative Exponential with a mean of 5 m			
Fracture intensity P_{10}/m^{-1}	1, 2, 4 and 8			

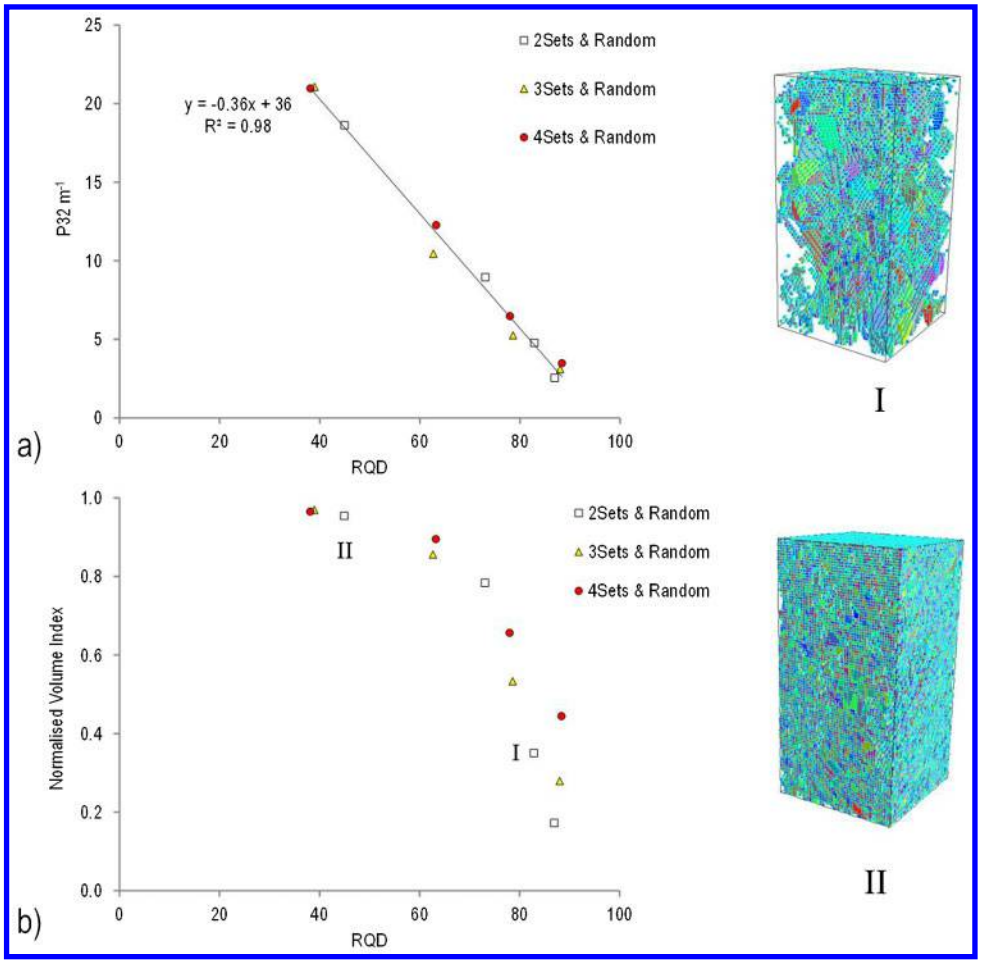


6 ***a*** **Stereoplot showing the four main joint sets and random joints;** ***b*** **Boreholes used to calculate the RQD value for simulated rock mass**

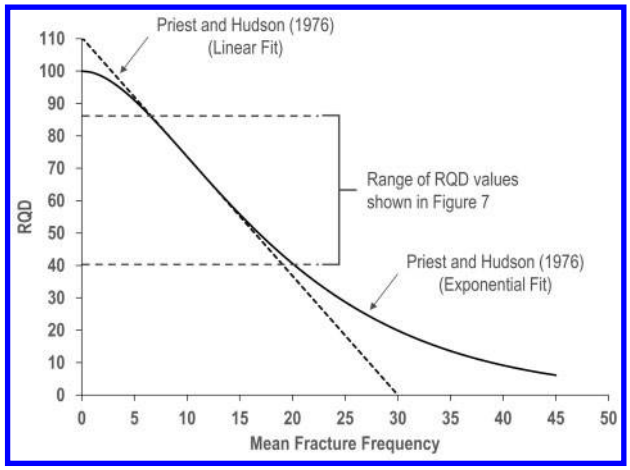
of a mine-scale DFN model in both plane views and also as a simulated structural map generated from the intersection of the pit shell with the DFN model.

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 P_{10} intervals and target values and testing the DFN model to identify how many fractures intersect those P_{10} intervals. Using data from an undisclosed mine location, Fig. 11 shows a graph of the simulated versus target number of fractures on all boreholes penetrating the



7 ***a*** **Correlation between RQD and volumetric intensity P_{32};** ***b*** **relationship between RQD and the degree of natural fragmentation of the assumed rock mass, expressed as normalised volume index (i.e. ratio of total number of blocks being formed to volume of problem domain)**



8 Comparison of the analytical relationship between RQD and mean fracture frequency proposed by Priest and Hudson (1976) and the preliminary result shown in Fig. 7

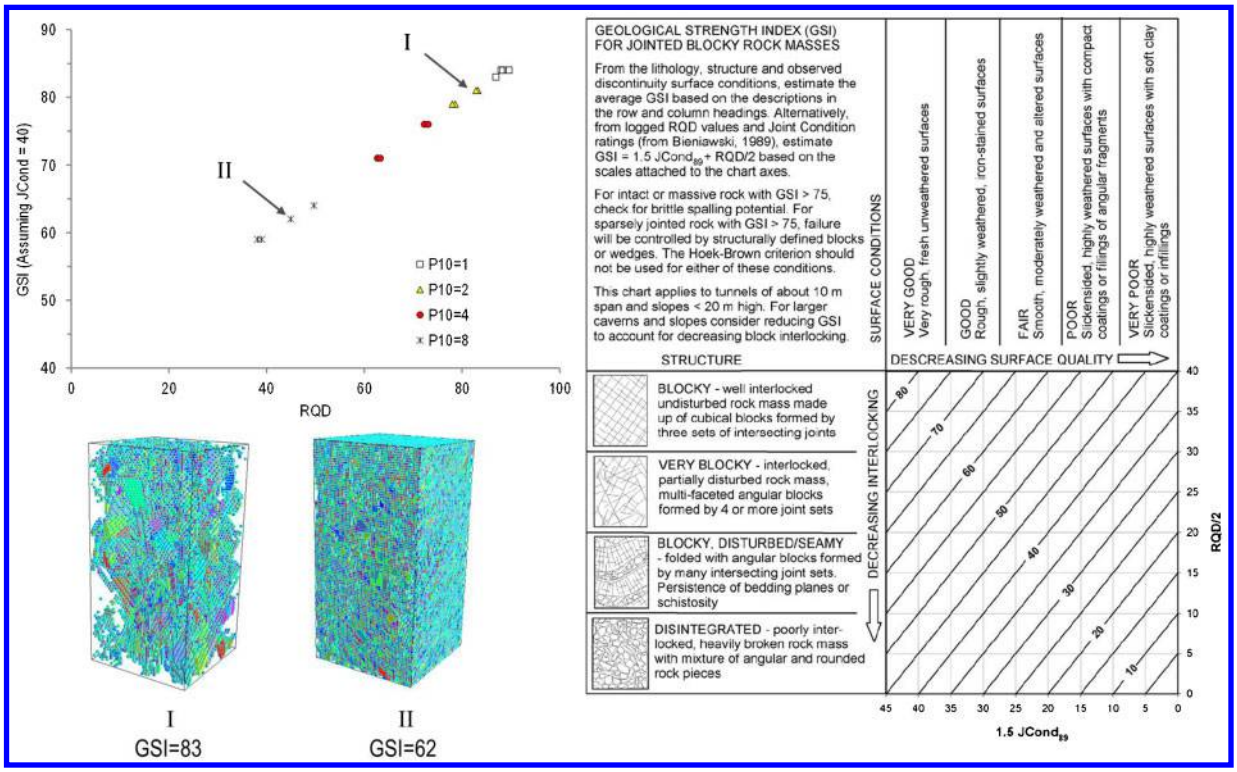
DFN model showing the high level of agreement between the model and source data. The good match also confirms the validity underlying spatial model of the DFN model. Orientation within the DFN model was conditioned using a bootstrapping technique (Rogers *et al.*, 2006). This approach allows capturing the broad-scale variations in the overall fracture population that may be observed in the rock mass. 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.

Determining natural fragmentation for large-scale DFN models

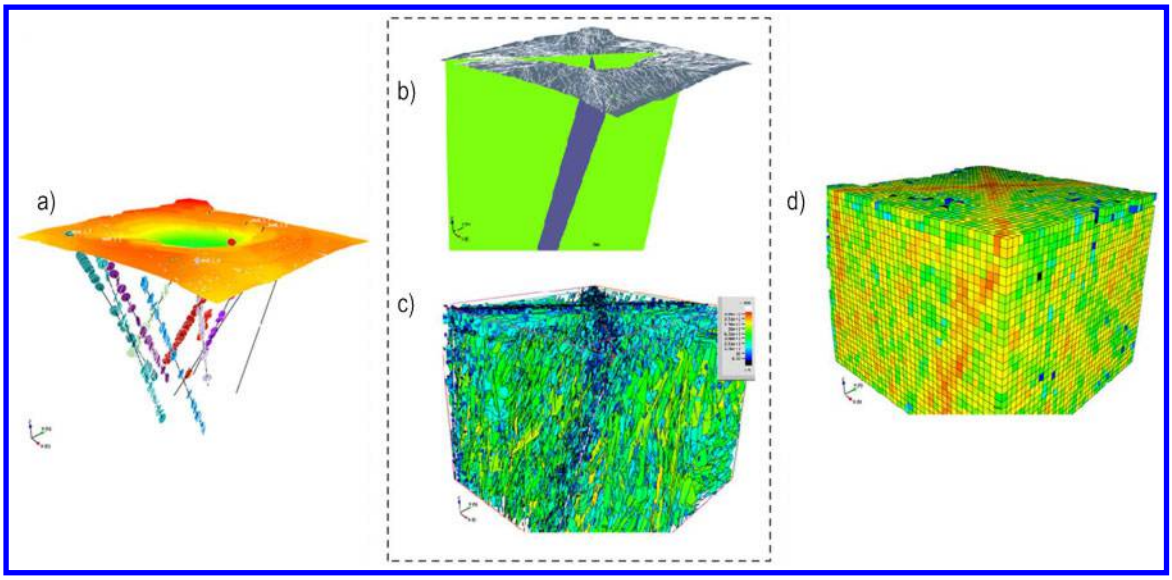
Block formation and P_{32} fracture intensity

The conventional approach to fracture characterisation, assuming that fractures are ubiquitous and infinite, generally overpredicts the connectivity of a fracture system and therefore the degree to which a rock mass comprises well-defined *in situ* blocks. P_{32} 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).

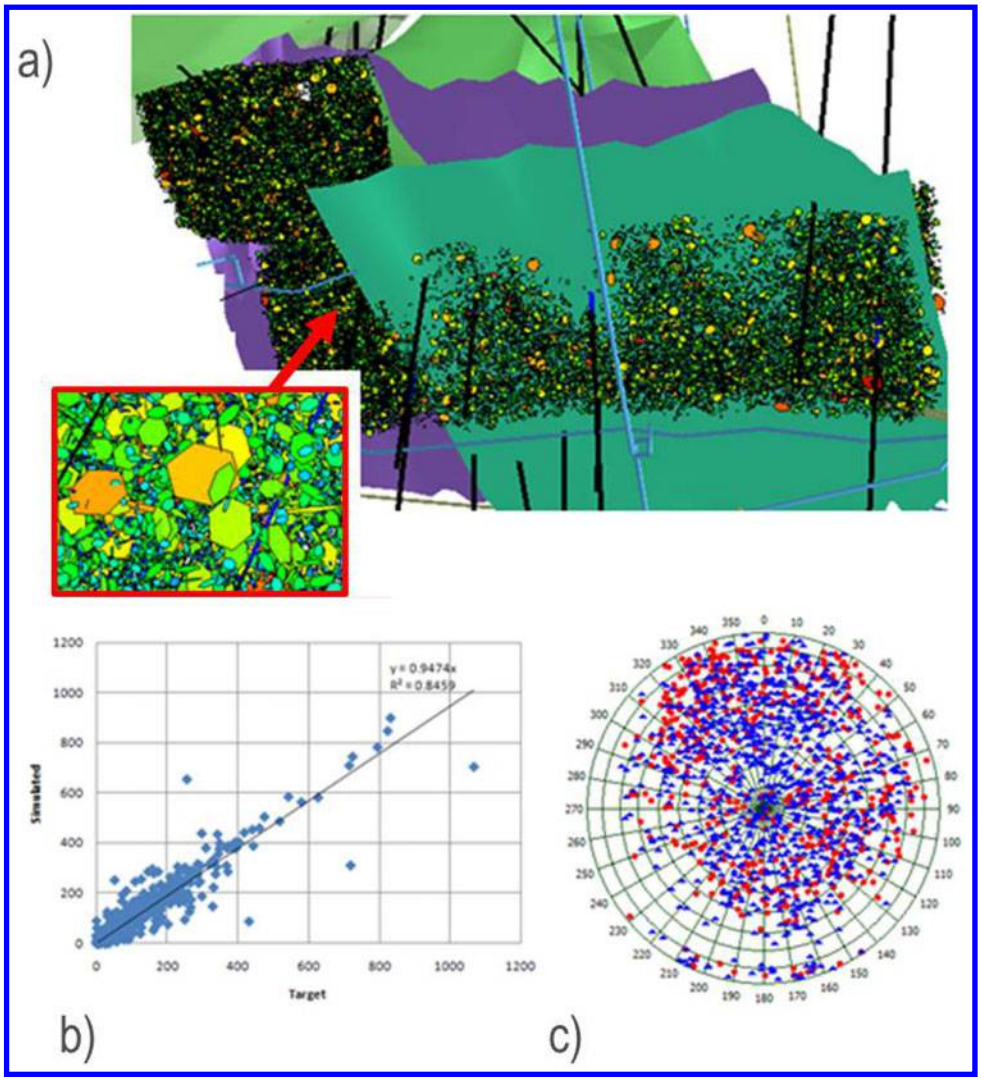
For relatively low P_{32} values, a rock mass is generally a large volume of intact rock and fractures, with the rock mass strength dominated by the properties of the intact rock bridges. However, at higher P_{32} values, the rock mass increasingly becomes a kinematic assemblage of well-defined potentially mobile blocks with joint properties dominating the material strength. Figure 12 shows a series of DFN models whose blocks have been mapped for a range of increasing P_{32} 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 P_{32}. The percentage volume occupied by blocks rapidly jumps from <10% to >90% over a relatively small change in fracture intensity (P_{32}≈2–3 m^{-1}). It may be argued that the induced stresses during caving are such that intact



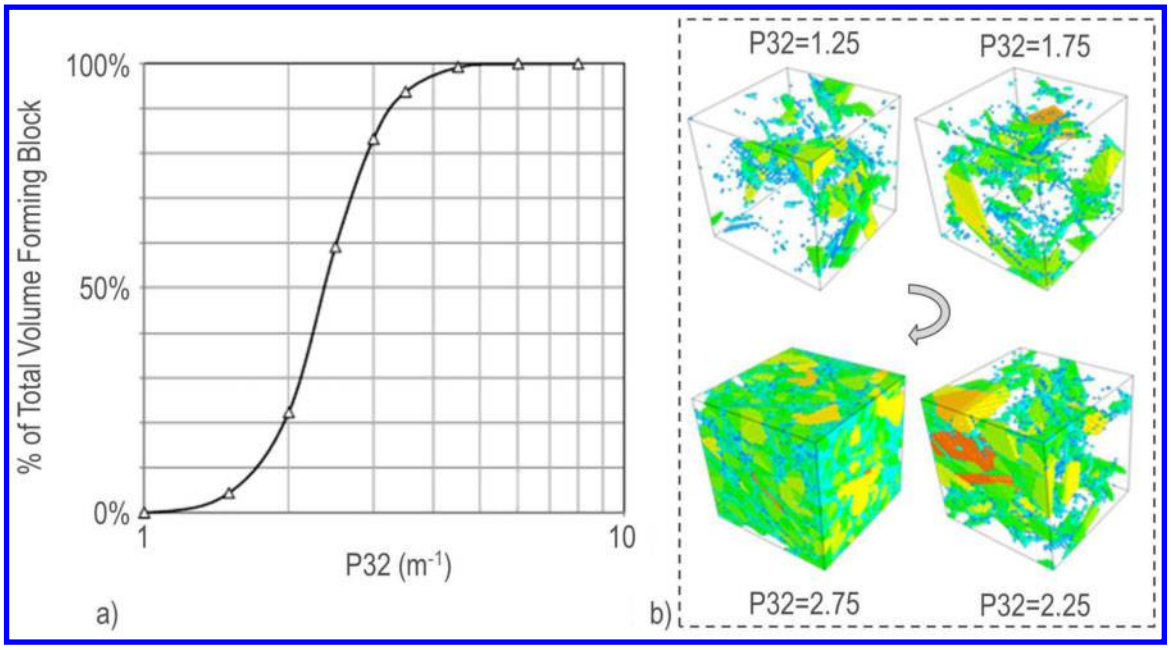
9 Correlation between RQD to GSI for varying fracture intensity P_{10}, for the specific DFN model under consideration: Note: all joints are assumed to have the same roughness/alterations characteristics ($JCond_{89}$=40) using the quantified GSI table proposed by Hoek *et al.* (2013)



10 **Example of the major elements of a mine-scale DFN model: *a* Pit shell and a number of the boreholes used for bootstrapping the fracture orientations from *b* and *c* DFN model containing both stochastically generated and deterministically placed major structures and *d* computation of the resultant model P_{32} property with dark colours representing highest P_{32}**



11 ***a* Large-scale DFN model (≈1 km size) showing conditioning boreholes (black lines) and major structures, while small inset shows detail of DFN fractures; *b* comparison of simulated and actual fracture intensity count; *c* is an example from a single borehole showing the comparison between simulated (circles) and actual (triangles) fracture orientations**



12 ***a*** **Relationship between total percentage of volume occupied by blocks and** P_{32}**;** ***b*** **rock blocks mapped within four DFN models with varying** P_{32}

rock bridges will be broken and the material will be converted to a mobilised kinematic assemblage.

Modelling methodology for mine-scale fragmentation assessment

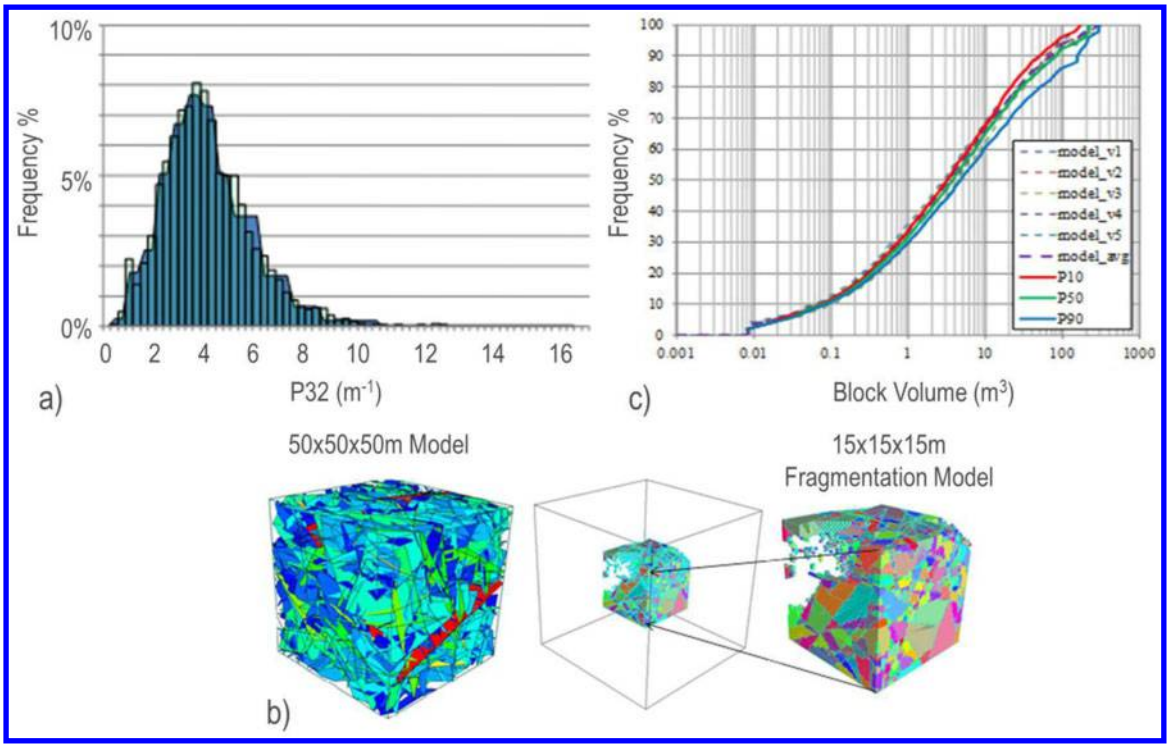
Detailed mapping of *in situ* blocks within a large discrete model is a computationally intense process owing to the highly complex geometrical nature of the problem. To provide a more rapid solution, the authors have developed a technique that allows replicating the *in situ* fragmentation description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

This is achieved by initially calculating the distribution of P_{32} for each cave lift and domain within that lift. The P_{32} distribution is subsequently replicated to define its overall composition, based on a range of smaller models of varying P_{32} (Fig. 13*a*). Using a $50 \times 50 \times 50$ m volume, DFN models are built with a range of P_{32} values extracted for each lift and domain. For each of these various P_{32} models, the *in situ* fragmentation is then mapped within a $15 \times 15 \times 15$ m sub-volume of the initial $50 \times 50 \times 50$ m model to reduce edge and boundary effects, Fig. 13*b*. The process is repeated five different times for each P_{32} input to ensure reasonableness in the results. Once all the different size curves have been generated for each P_{32} input model, a volume-weighted size curve is derived by combining the different fragmentation curves, according to the distribution of observed P_{32} values for the specific problem domain, Fig. 13*c*.

Upscaling the DFN model to continuum properties

The use of DFN models to define equivalent rock mass parameters based on a realistic representation of the rock fabric has the potential to improve the predictability achieved by various geomechanical simulations. An increasingly employed methodology is to explicitly include a small-scale representative DFN model within an intact rock matrix that can be used as a numerical laboratory test to allow a quantitative assessment of rock mass strength and anisotropy (Elmo *et al.*, 2005; Pierce *et al.*, 2007; Beck *et al.*, 2008). These SRM approaches provide a significant opportunity to improve upon the more traditional method of deriving rock mass properties from empirical rock mass classification schemes. However, while our ability to undertake small-scale realistic rock mass simulations has significantly advanced, this has been achieved at the expense of ignoring the variability of the rock mass structure. If the rock mass of interest is spatially homogenous, without variation in intensity, orientation, size and fracture properties, then upscaling with a limited number of small models would be acceptable. However, in the majority of rock masses (e.g. large-scale open pits), geological and structural homogeneity is not the norm and therefore small-scale SRM upscaling may be failing to adequately describe the rock mass variability.

Having generated a detailed mine-scale spatially variable DFN model that accurately reflects the broad variation in fracture geometry and properties, there is a need to convert the discrete model into equivalent properties (upscaling) for use in numerical simulations. Based on the conclusions drawn in Sections 2 and 3, the objective would be the incorporation of the best possible rock mass description within numerical models. The key rock mass parameters that need to be derived for input into a continuous numerical simulation are rock mass strength and stiffness, anisotropy and post-failure properties (for applications of post-failure material such as caving). The conventional approach to numerical modelling is for the analysis of geotechnical data to provide rock mass classification values (e.g. GSI) as the description of rock mass strength and stiffness. In the case the rock mass being highly anisotropic, ubiquitous joints or similar may be added to the model. As described earlier, the SRM approach is somewhat different in that it combines the intact rock properties with a structural description from a DFN realisation in order to determine the rock mass behaviour through a



13 ***a*** **Example of the distribution of derived P_{32} in light blue, overlain with the discretised P_{32} distribution used for reproducing the overall fragmentation;** ***b*** **small-scale DFN models and block searching region for fragmentation analysis;** ***c*** **example of size distribution curves for** ***in situ*** **fragmentation showing the results for five different iterations plus the results of 100 simulations shown as tenth, fiftieth and ninetieth percentile curves**

discrete numerical simulation. This behaviour can then be applied constitutively in continuum simulations through the application of the derived rock mass properties. Again, in the case the rock mass being highly anisotropic, ubiquitous joints or similar may be added to the model to provide the necessary anisotropy.

A simple form of upscaling would be to utilise the DFN model and associated joint properties to derive a spatially varying description of GSI as the primary input into numerical modelling, using the results shown in Section 3. It is anticipated that this would be a relatively straight forward process and ensures that the mapped areas of high and low fracture intensity are accurately captured within the numerical model rather than being ignored as outliers to the average properties, conventionally used to define a particular geological domain. In order to add anisotropic properties to the model, a stiffness tensor could be calculated for every grid cell using the approach of Will *et al.* (13), who suggested that the compliance Δs_{ijkl} of a system resulting from the presence of fractures could be expressed as

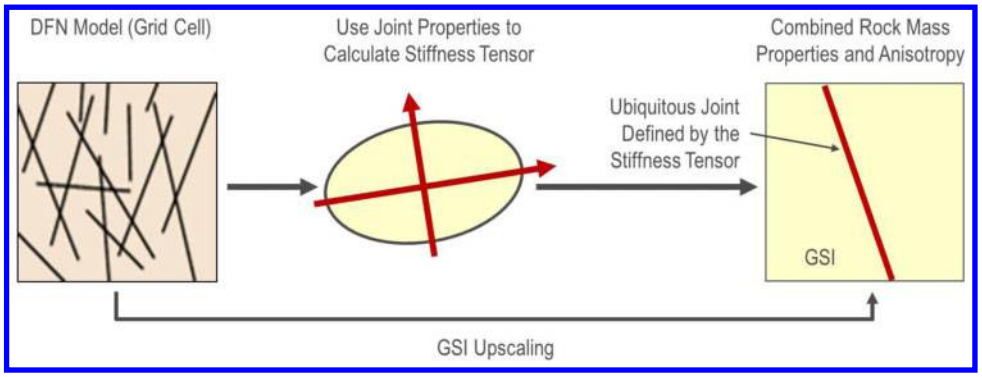
$$\Delta s_{ijkl} = \frac{1}{4}\left(\delta_{ik}\alpha_{jl} + \delta_{il}\alpha_{jk} + \delta_{jk}\alpha_{il} + \delta_{jl}\alpha_{ik}\right) + \beta_{ijkl} \tag{2}$$

$$\alpha_{ij} = \frac{1}{V}\sum_{r} B'^{(r)}_{T} n_i^{(r)} n_j^{(r)} A_s^{(r)} \tag{3}$$

$$\beta_{ijkl} = \frac{1}{V}\sum_{r} B'^{(r)}_{N} n_i^{(r)} n_j^{(r)} n_k^{(r)} n_l^{(r)} A_s^{(r)} \tag{4}$$

where B_T is the fracture normal compliance, B_N is the fracture shear compliance, A_S is the fracture surface area and n is the unit normal vector.

This approach would allow using the DFN model to provide equivalent directional property within the



14 Proposed methodology for deriving a DFN-based upscaled rock mass property description for numerical geomechanical analysis, including GSI-based properties and deformability tensor in the form of a ubiquitous joint

simulation. Experiments are continuing to test the use of a ubiquitous joint generated in the plane of the intermediate and minor stiffness direction in order to add anisotropy to each specific grid cell, according to the schematic shown in Fig. 14. In addition, each grid cell would have an associated GSI rating based on the methodology discussed in Section 3.

Discussion and conclusion

DFN modelling has been demonstrated to represent a valid method for studying the continuity of rock blocks and associated rock bridges. The approach relies on quantifiable field rock mass descriptors (fracture orientation, length and intensity) and it provides genuinely realistic geometric models of fracture networks. The analysis has shown that FL represents a critical parameter in the characterisation of a DFN model. For a given FL and fracture intensity, the massive to blocky character of a hypothetical rock mass was quantitatively and qualitatively expressed as a function of mean block volume and number of fully formed blocks. Using a sequential sampling technique, it was demonstrated that the proposed DFN-Rock Block approach also constitutes a powerful tool for characterising and assessing the natural fragmentation of a rock mass, which is of major interest in block cave mining. It is recognised that the block volume characterisation described in this study only provides a preliminary correlation among the degree of fragmentation and fracture spacing and persistence. Ongoing work is currently looking at extending and validating the proposed methodology by considering different combinations of fracture orientation, length and spacing and termination modes. The influence of limited sampling of spacing and length data in particular would need to be examined to quantify the impact this limited data would have on large-scale projects. This study has also demonstrated the potential of using DFN models to define equivalent rock mass parameters, recognising the importance to represent the spatial variability of the rock mass structure and properties. In particular, the authors believe that the real potential of DFN modelling to rock mass property determination has not yet been fully exploited. The authors have demonstrated that geostatistical modelling of fracture intensity (P_{32}) along with the assignment of appropriate anisotropic properties to individual model elements rather than to crude geotechnical domains offers a marked increase in the resolution of the modelled rock mass description. At the heart of the approach is a well-constructed DFN model comprising deterministic major structures and stochastically modelled smaller and intermediate structures, providing a useful description of the structural fabric variations at the mine scale.

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