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The Discrete Fracture Network-Block Caving Fragmentation hybrid method: A new tool to assess fragmentation of block caving mining projects

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Abstract

The forecast of the size distribution of the fragmented rock, in the form as it will report at the drawpoints, is one of the relevant aspects to be studied for block caving projects and mines. Layout design and anticipation of secondary reduction necessities are key factors to which the fragmentation assessment is linked. In addition to the challenge of correctly characterising the input geotechnical parameters for the fragmentation assessment, the fractions of interest are located at the extremes (tails) of the size distribution, where the coarser and finer block sizes occur. At the 'tails' of the size distribution, data is scarcer, and statistics are more affected by random variations. Thus, the average and central tendencies of the distribution are of not much practical use. From the tools available for fragmentation assessment, the software Block Caving Fragmentation (BCF) (Esterhuizen 2005) has remained as one of the most used methods to estimate size distribution for block caving projects and mines.

In this paper, the new DFN-BCF hybrid approach is described. In this updated method of fragmentation assessment, the primary block generator built into BCF software, has been replaced with a discrete fracture network (DFN) model of the rock mass, making use of the full geometry of the relevant discontinuities that will drive the fragmentation process. Thus, the DFN model is used to obtain in situ and primary fragmentation, while secondary fragmentation is calculated by splitting these blocks applying the BCF algorithm. Several DFN realisations are produced, to cover the range of likely fracture intensities. The final product of the assessment is a weighted fragmentation curve, representing the whole rock mass to be caved, and its corresponding range of variation. It must be acknowledged that volumetric size distribution curves are not intuitive. To aid with the understanding of the results, a novel graphical output has been added to the assessment, consisting of a scaled graphical representation of the actual size distribution at the drawpoints using 3D spheres as a proxy of rock blocks volumes. In addition to the DFN-BCF method description and application, the issues related to the sampling of size distributions at drawpoints are briefly discussed. To date, the DFN-BCF hybrid approach has been calibrated and applied to two world-class block caving projects.

Keywords: *block caving, fragmentation, discrete fracture network*

1 Introduction

Since its release, the Block Caving Fragmentation (BCF) software (Esterhuizen 2005) has remained a widely used tool to estimate fragmentation in a variety of block caving projects and mines. The program is based on analytical and empirical rules, most of them created by D Laubscher, describing the processes and factors that play a role in fragmentation.

The software consists of three modules:

- The first module calculates primary fragmentation, which is the estimation of the granulometry of the rock as it detaches from the cave back. The geometry of the relevant bounding block fractures and creation of new fractures driven by induced stresses are the main factors in the primary fragmentation process. In the BCF software the block size in the primary fragmentation process is constrained by the spacing of fractures. Fractures lengths play no role in the estimation of block size in the BCF software. Stress fractures spacing is determined on empirical estimates based on the ratio 'rock block strength/induced stress'.
- A second module estimates secondary fragmentation, which is the result of the reduction of size as the block moves down the draw column. The calculation of secondary fragmentation takes into consideration the aspect ratio of the block, the block strength, the cave pressure, and stresses induced by arching in the draw column and the height of draw.
- A third module estimates the frequency of hang ups that may occur in draw bells based on the secondary fragmentation curve.

Although several methods have been developed for the assessment of fragmentation, BCF has remained as one of the preferred tools among mining practitioners and consultants, probably due to its operational simplicity and computational efficiency. However, there is space to improve some of the limitations of the assessment (Jakubec 2014). In this manner, discrete fracture network (DFN) modelling offers the opportunity of incorporating most of the geometrical characteristics of the relevant fractures, producing a realistic representation of the fractured rock mass (Elmo et al. 2014). The use of DFN modelling has been increasingly applied for fragmentation assessment (Brzovic et al. 2014; Rogers et al. 2015). Thus, a DFN model has been introduced in the BCF routine, leading to the updated version that has been named the DFN-BCF hybrid approach.

In the DFN-BCF hybrid approach, the block generator routine used by BCF in the primary fragmentation module has been replaced by a DFN model of the rock mass, making use of the full geometry of the fractures. In this manner, the full network of relevant discontinuities is used in the estimation, allowing for a better representation of the variability of the block volume distribution. It must be highlighted here that the identification and adequate data of the 'relevant discontinuities' is the very base of fragmentation assessment, and no technique can compensate for insufficient geological knowledge.

The fragmentation process in a block caving operation is a complex phenomenon, no precise forecast should be expected from any of the available methods. From the simplest estimation method based on rock quality designation to the most sophisticated numerical modelling, all that can be warranted is an approximated answer 'in the ballpark'. Thus, the selection of the estimation method is not a matter of how sophisticated the method is but what is the precision of the answer in comparison to the resources invested to obtain the estimate. In the experience of the authors, if the question is translated into financial resources, the investment of resources can be one order of magnitude higher for an advanced method based on state-of-the-art numerical modelling.

1.1 Importance of fragmentation forecast

Fragmentation forecast is a key aspect of the design of the extraction level layout. In the extraction level of the block caving method, drawpoints are spaced regularly. Size and spacing of drawpoints, as well as ore-handling facilities (grizzly and orepass), must be designed to suit the fragmented caved material. The spacing of drawpoints should be such that interaction occurs between draw columns, avoiding the creation of a zone of stalled material, and overstressing pillars in the extraction level. Thus, the spacing of drawpoints depends on the width of the extraction ellipsoid, which is a function of the fragmentation distribution, being wider for coarser fragmentation (Laubscher 1994). In addition, the expected proportion of oversize is taken into consideration for planning of secondary reduction method and associated costs, procurement of equipment such as stationary rock breakers, and secondary blasting necessities.

In summary, fragmentation forecast is relevant for the following aspects of design and operational parameters (Laubscher et al. 2017):

- Drawpoint size and spacing.
- Dilution entry into the draw column.
- Draw control.
- Drawpoint productivity.
- Secondary blasting/breaking costs.
- Secondary blasting damage.

2 The DFN-BCF hybrid method

As indicated previously, the DFN-BCF method incorporates the DFN modelling technique in the fragmentation estimation process. Thus, in this integrated approach, the block generator that BCF uses to estimate primary fragmentation has been replaced by a DFN model of the rock mass. On the other hand, minor changes have been introduced in the secondary fragmentation module and hang-up estimation module.

A DFN model correspond to a 3D representation of fractures. It is stochastic in nature and aimed to reproduce the fabric of the fractured rock mass, honouring the statistic distribution of its geometrical parameters (frequency, length and orientation).

The approach allows separately modelling the different categories of structures that will bound the in situ blocks and that consequently will control the primary and secondary fragmentation. Thus, separated DFN models can be built for second order faults and joints. In cases where mining conditions require it, simulated stress fractures are added to the DFN model to finally estimate the primary fragmentation curve (Figure 1). The DFN modelling and block volume calculation are performed in the software Fracman (Golder Associates 2021).

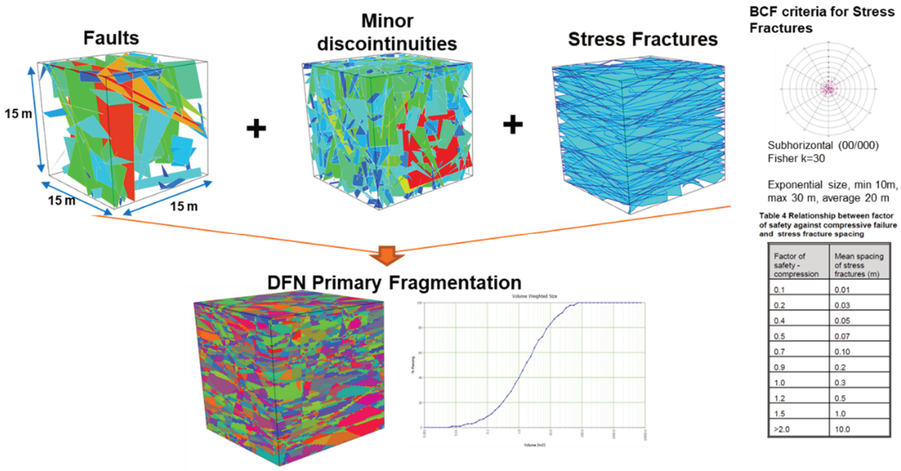


Figure 1 **DFN modelling process for primary fragmentation estimation. Geometrical properties for the DFN of stress fractures are based on BCF criteria**

To obtain the block size distribution of secondary blocks, the primary blocks are submitted to the BCF algorithm. To split a block, the BCF algorithm evaluates the probability of breakage of each block by cycles. A cycle is the vertical distance that the block travels until it reaches the drawpoint. The algorithm uses the rock block strength, as defined by Laubscher & Jakubec (2001) MRMR, to calculate the height of the cycle, while a probability of splitting is calculated based on the block aspect ratio (Esterhuizen 2005). The effect of cushioning and arching on splitting is considered in the algorithm as well. Fines generated due to corners rounding are calculated at the beginning of the process. Additional fines are generated when a block splits and are added accordingly to the fragmentation product. Defects are considered in the process for the estimation of the rock block strength (RBS). Given that the RBS defines the height of the cycle, and subsequently the number of times that the probability of splitting of a block will be assessed, the highly defected (or weak) rock will yield a finer fragmentation than a rock with scarce defects.

2.1 Discrete Fracture Network modelling for fragmentation estimation

In this work, the term DFN refers to a stochastic representation of fractures in the 3D space. It is applied to intermediate or minor discontinuities for which a deterministic modelling is not practical or possible. For a given rock mass, a DFN model of the relevant block bounding discontinuities allows the calculation of the in situ block volumes and their distribution. In the cases where induced stresses are acting in the cave back, the modelling of the induced new fractures allows the calculation of the primary block volume distribution.

The basic component for the building of a DFN model is fracture lengths, fracture intensity and fractures orientation. This data can be sourced from scanlines, drillcore logging, tunnel, or bench mapping. Pre-processing of this input data is necessary to correct truncations of size, correct directional bias and calculate volumetric intensity (Figure 2). Once a DFN model is assembled it can be sampled with simulated drillholes and traceplanes. Then the geometric characteristics of the model are compared with the input distributions of size, orientation, and frequency. Equivalence of input data and DFN output must be verified in this stage.

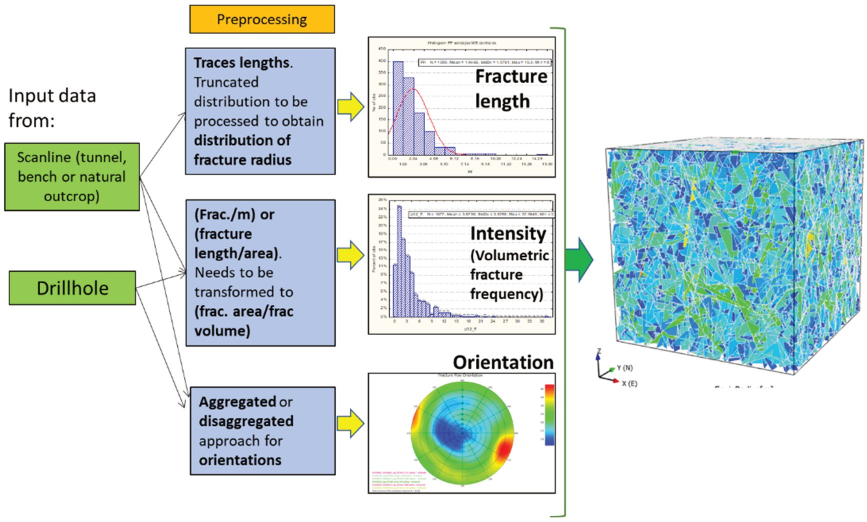


Figure 2 Source of data, input variables and pre-processing to generate a DFN model

More realistic representations of the rock mass can be produced when fracture termination is available, although, in the experience of the authors, such information is rather scarce for minor discontinuities and is not always available for second order faults. Given its stochastic nature, the aim of the DFN is not to reproduce the input data fracture by fracture, but to generate a fracture network that 'honours' the input data, fitting reasonably well to it. It is also worthwhile to point out that a data quality is always preferably than data abundance. In this manner, every DFN realisation should yield orientation and fractures length distribution similar to the raw data, together with the intended target fracture intensity.

It can be stated that the degree of fragmentation of a rock mass is highly dependent on fracture connectivity, i.e. the degree at which the fractures cross each other. Thus, for a given fracture frequency, the fragmentation will be finer when the structural orientations are split in various sets, and these are spread (far apart) in the stereonet.

In terms of availability of input data, orientations are readily available. Fracture frequency is also generally available, although it is not uncommon to find QA/QC problems in it (in which occasions drillhole photographs are quite valuable). In contrast, fracture length data is often scarcer.

The following sections describe the key aspects of the input data for DFN modelling for fragmentation assessment.

2.1.1 Fracture frequency

In any given rock mass, the fracture intensity is not homogenous, as there is a range of fracture intensities that are spatially distributed inside the rock mass volume. The variability of the fragmentation across the block to be caved is determined by this spatial variation of the degree of fracturing. Thus, density of data and geological and structural domaining are of prime importance. The best way to characterise the fragmentation of the whole volume to be caved would be constraining the DFN model to the spatial variations of the fracture intensity. The application of geostatistical techniques allows for such model to be constructed, however, the calculation of block volumes, at scale of a block caving mine, is computationally not feasible. Alternatively, several DFN models in the range of fracture intensities can be built (Rogers et al. 2015). Then, a fragmentation curve is calculated for each DFN model. The combination of all these fragmentation curves, weighted by the frequency of its respective intensity, yields the fragmentation curve representative of the whole rock mass that is assessed (Figure 3). The *Pxy* system is used for DFN fracture intensity notation, where ‘x’ is the dimension of the support and ‘y’ is the dimension of the fracture measurement. Intensity of discontinuities, namely linear frequencies from drillhole (P10) or traces of fractures from a map (P21), must be transformed to volumetric intensity (P32, ‘m^2 of fracture/m^3 of rock’) to be used in a DFN model. Depending on the source of the intensity data, forward modelling, or analytical equations (Wang 2006; Chilès et al. 2008) can be applied to this aim. While fracture frequency data is highly dependent of the direction of sampling, P32 is theoretically unbiased. However, when forward modelling is used to obtain P32, orientation of holes must be considered.

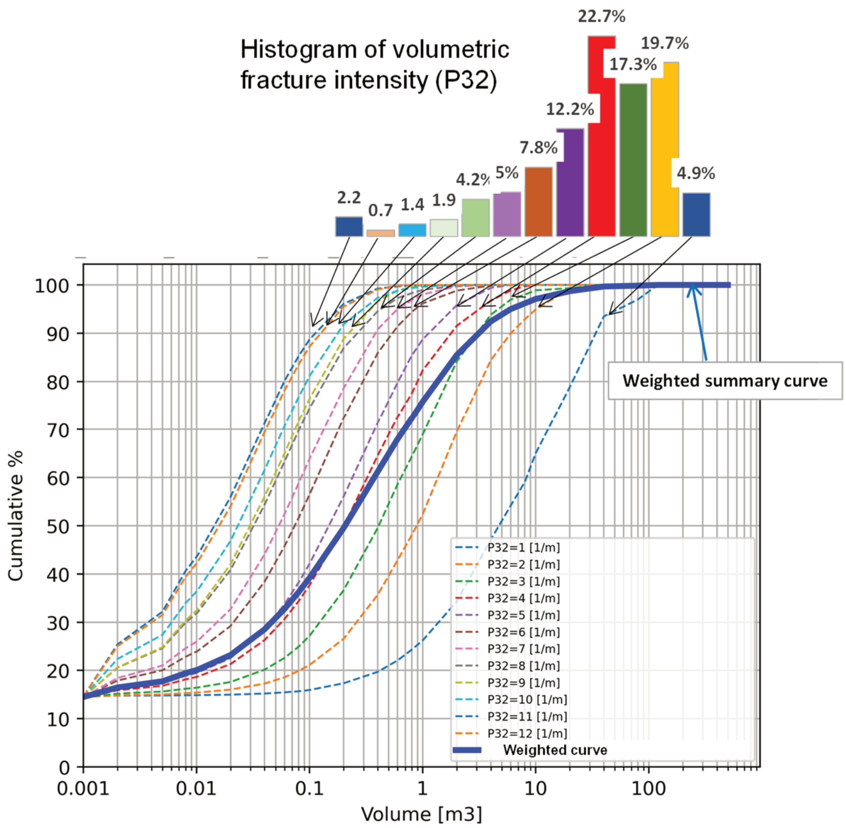
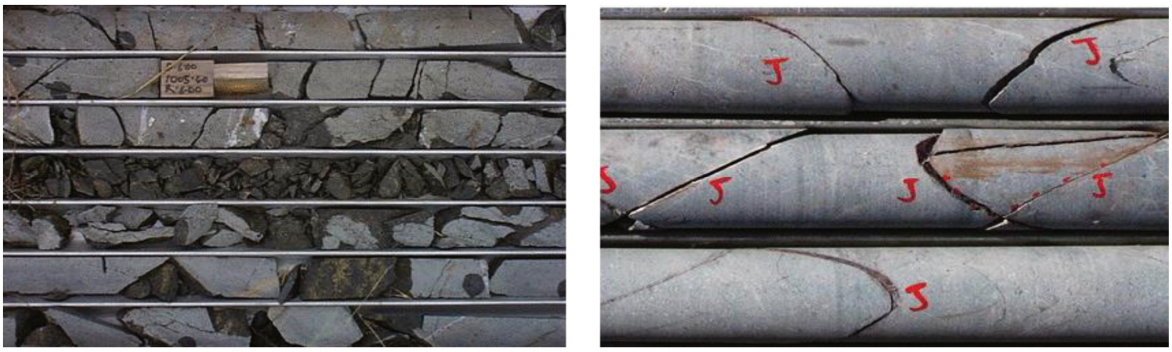


Figure 3 Relationship of intensity histogram and secondary fragmentation curve. Each one of the dotted lines represent a fracture intensity in the rock mass

In the experience of the authors, fracture frequencies from tunnel mapping are normally higher than those logged on drillcore, mainly due to blasting damage. On the other hand, logged fracture frequencies can show inconsistencies and errors. Proper QA/QC is certainly always necessary and photo logging of selected holes has proven to be a ‘healthy’ practice before undertaking further analysis.

A common practice is to assign a high number of fractures to rubblised zones in the drillcore, when these sections are deemed associated to faults or weak rock. This practice is certainly justified to represent the weaker fault zones in the geotechnical classification system in use. However, given the sensitivity of the fragmentation to the distribution of fracture frequencies, it should be avoided in the context of block caving fragmentation estimation. In the DFN-BCF hybrid approach, the rubblised zones are considered in the estimation of fines (Figure 4).



(a) (b)

Figure 4 Example of fines generating fault (a) and open joints (b) in the drillcore (Jakubec 2014)

2.1.2 Orientation of discontinuities

The scatter associated to a structural set is of prime importance to generate realistic block volumes distribution and the use of single average orientation generates coarser fragmentation (Young et al. 1995). Frequently, when structural patterns are defined, there is an important number of discontinuities occurring in the outside of the ‘set window’ in the stereonet; neglecting these random structures can produce coarse fragmentation curves that do not depict the actual blockiness of the rock mass (Jakubec 2014). In summary, the ‘background’ of randomly distributed structures in the stereonet must be included in the assessment. There are two approaches to consider the orientations in a DFN model: aggregate and disaggregate. In the disaggregated approach, the structural sets are modelled individually, with each pattern being characterised with its corresponding orientation and size distribution. In this approach the random structures must be introduced as a random set, taking care of not introducing extra fractures by the over imposition on top of the structural sets with well-defined orientation. In the aggregate approach, the sets are not individually modelled, but generated by a procedure of sampling with replacement, called in statistics bootstrap sampling. This process has the ability of yield the exact relative density of both, structural sets and random background, without the necessity of introducing a random set (Figure 5). In the geological setting of an orebody, despite the occurrence of preferential orientations or sets, scatter of discontinuities orientations seems to be the rule, for which a DFN model generated with bootstrapped discontinuities is preferred.

In addition of the random discontinuities, the number of structural sets can dramatically affect the fragmentation. The size and number of blocks is given by the degree of which the fractures cross each other, therefore at higher number of structural sets the fragmentation becomes finer.

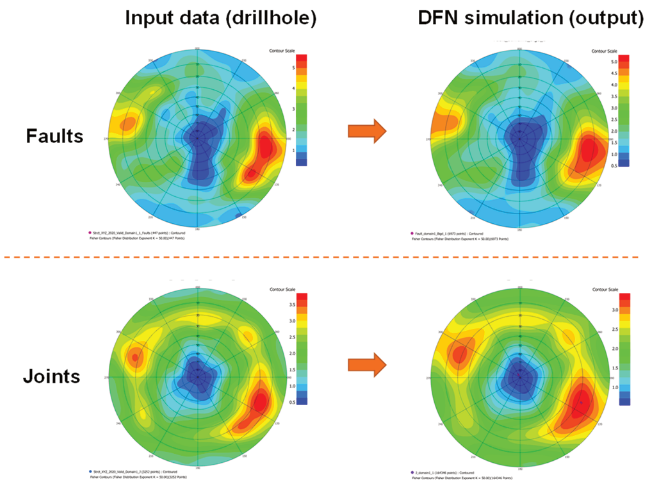


Figure 5 Comparison of orientations of input data from drillhole (left) with orientations from their respective DFN models generated using bootstrap sampling (right)

2.1.3 Fracture length

From the three components necessary to build a DFN model, fracture length data is frequently the scarcer one. It is a parameter that is not required for any classification system, therefore frequently overlooked. Fracture length sourced from limited window mapping or scanline mapping, undertaken specifically for modelling purposes, can be quite valuable, even if the data is not abundant. Alternatively, photogrammetric mapping methods offer a great opportunity to capture fracture data, including fracture lengths. Fracture length can determine the massive or blocky nature of a rock mass (Elmo 2014), due to connectivity of the network of fractures is directly related to discontinuities length. Therefore, is a critical parameter for fragmentation assessment based on the DFN modelling technique. Independently of the type of exposure that is mapped, discontinuity length data always correspond to a truncated distribution. Analytical methods (Zhang et al. 2002) and forward modelling (La Pointe et al. 1993) are some of the available tools to correct lengths truncation.

2.1.4 DFN model verification

The DFN model must be validated against the input data (Figure 6). Stereonets of the raw data versus the DFN must look similar and show the same structural sets and background of random discontinuities. Lengths are compared in terms of their distribution, sampling the DFN model using scanlines or traceplanes depending on the source of the data. Fracture frequency can also be checked using simulated drillholes of similar orientation of the real ones.

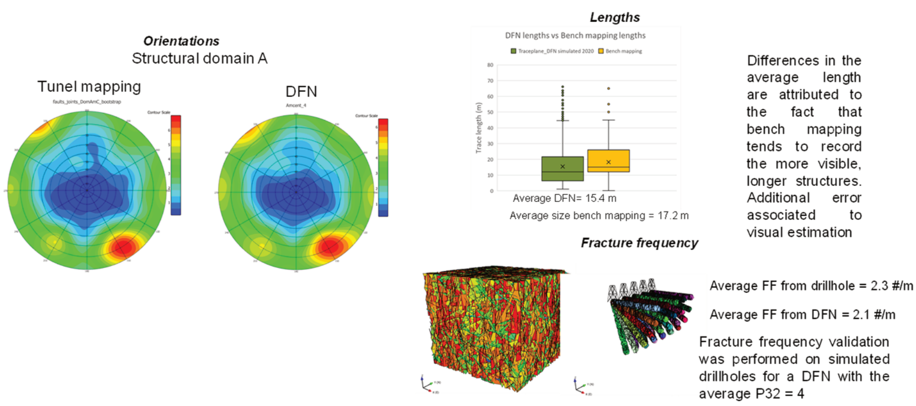


Figure 6 Verification of a DFN model generated for fragmentation assessment. In this case the orientation data came from tunnel mapping, fracture lengths from bench mapping and fracture frequency was sourced from drillhole

2.1.5 *Preconditioning*

Preconditioning of the rock mass refers to the creation of new fractures aimed to increase the blockiness of the rock mass, improving fragmentation, caveability and/or drive the caving process. New fractures are created by means of hydraulic fracturing (HF) or confined blasting (CB). These 'induced' fractures can certainly be modelled in a DFN and included in fragmentation assessment. The challenge is not the inclusion of the HF and/or CB fractures in a DFN based assessment but rather to source data on their geometrical parameters (i.e. orientation, frequency, and length). However, the introduction of theoretical preconditioning fractures in the DFN model can aid to understand the potential effects of HF and CB. At the state-of-the-art, simple rules based on field observations from several sources and numerical modelling (Donze et al. 1997, among others) are applied to model HF and CB fractures in a DFN model. A well documented case study, that combines field observations of CB and HF and DFN modelling in El Teniente block caving mine can be found in Brzovic et al. (2015). Finally, it must be acknowledged that there is no consensus in the mining community regarding the efficiency of the preconditioning. More work and case studies (and sharing) are still necessary to gain better understanding of it. For instance, questions such as the relationship of the HF with the development (or prevention) of stress fractures in the cave back remain unanswered.

2.2 Fines

There is no formal definition of fines for block caving fragmentation purposes. However, blocks of 10 cm diameter (i.e. a cube of 0.001 m^3) and smaller can be considered a reasonably threshold. For the DFN-BCF hybrid method this size corresponds to the smaller block volume that can be estimated. Fines are out of reach of the state-of-the-art fragmentation assessment tools; however, they can be estimated based on their geological knowledge of its source. Estimation of fines based on the volume of weak rock such as damage zones associated to faults, and pockets of rock with high degree of alteration, among others, are valuable for fines estimation. Furthermore, the simple addition of the proportion of rubblised core (Figure 7) to the fragmentation curve can considerably improve the fines estimation (Van As 2021). In the experience of the authors, these considerations are certainly necessary, but not always sufficient to estimate fines, as it is not uncommon to underestimate them. A proportion of 30–40% of the size distribution below 0.001 m^3 is not a rare case. The estimation of fines is not only important due to its cushioning effect during secondary fragmentation but is potentially valuable for plant processing purposes.

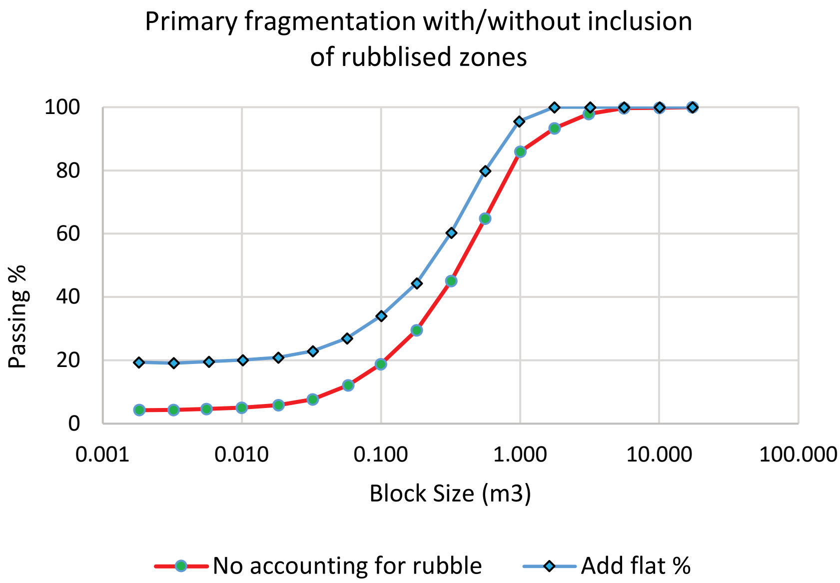


Figure 7 Effect of adding rubbled zones in the estimation of fines (modified from Van As 2021)

2.3 Results of the DFN-BCF fragmentation assessment

As indicated previously, it is certainly possible to build a DFN model that fully addresses the known spatial variability of the fracture intensity in the block to be caved. However, the calculation of block volumes for such a mining scale model is not feasible. Alternatively, in the DFN-BCF hybrid approach, to obtain the fragmentation curve, several DFN models covering the full distribution of volumetric fracture intensity in the cave are built. A minimum of three DFN realisations are created for each volumetric fracture intensity bin in a cube of 10–15 m of length. These realisations are combined with the stress fracture to obtain the primary blocks. The primary blocks are then submitted to the BCF secondary fragmentation algorithm for the chosen height of draw (HOD), obtaining a secondary fragmentation curve for each fracture intensity. The representative secondary fragmentation curve for the HOD in evaluation is obtained by combining each fragmentation curve weighted by frequency of its corresponding volumetric fracture intensity (Figure 8).

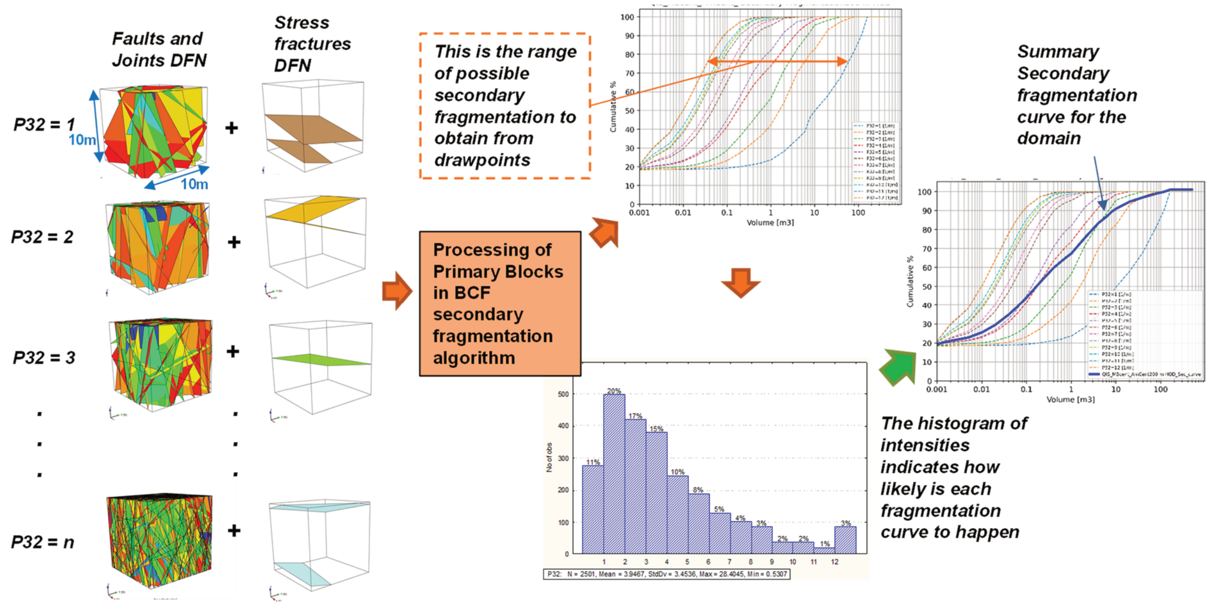


Figure 8 Workflow for the calculation of the secondary fragmentation curve applying the DFN-BCF hybrid approach

To date, the DFN-BCF hybrid approach has been applied to two world-class mining caving projects, with the opportunity of calibrating and compare estimates with real data in one of them. Observations at new drawpoints at early stage of drawing (but >20 m of HOD) have showed good agreement between the block volumes estimates and the real fragmentation for strong and moderately strong rock.

2.3.1 Graphic representation of the secondary fragmentation curve

It must be acknowledged that a fragmentation curve is not an intuitive representation of the fragmented rock. The S-curve serves well to assess the passing percentage for any given block size. However, for instance is difficult to visualise how a drawpoint with 10% oversize is different from a 15% oversize. Volumes are misleading as well, for instance, considering idealised cubes, the length of a 2 m^3 block is only 25 cm bigger than 1 m^3 block. In addition, the distribution volumes can look quite different between single observations of drawpoints. To overcome these 'cognitive' difficulties, a simple, scaled, graphic representation of fragmentation at a drawpoint has been developed as a complement of DFN-BCF fragmentation estimates. In this graphic output the blocks are depicted as spheres that match volume distribution represented in the fragmentation curve (Figure 9).

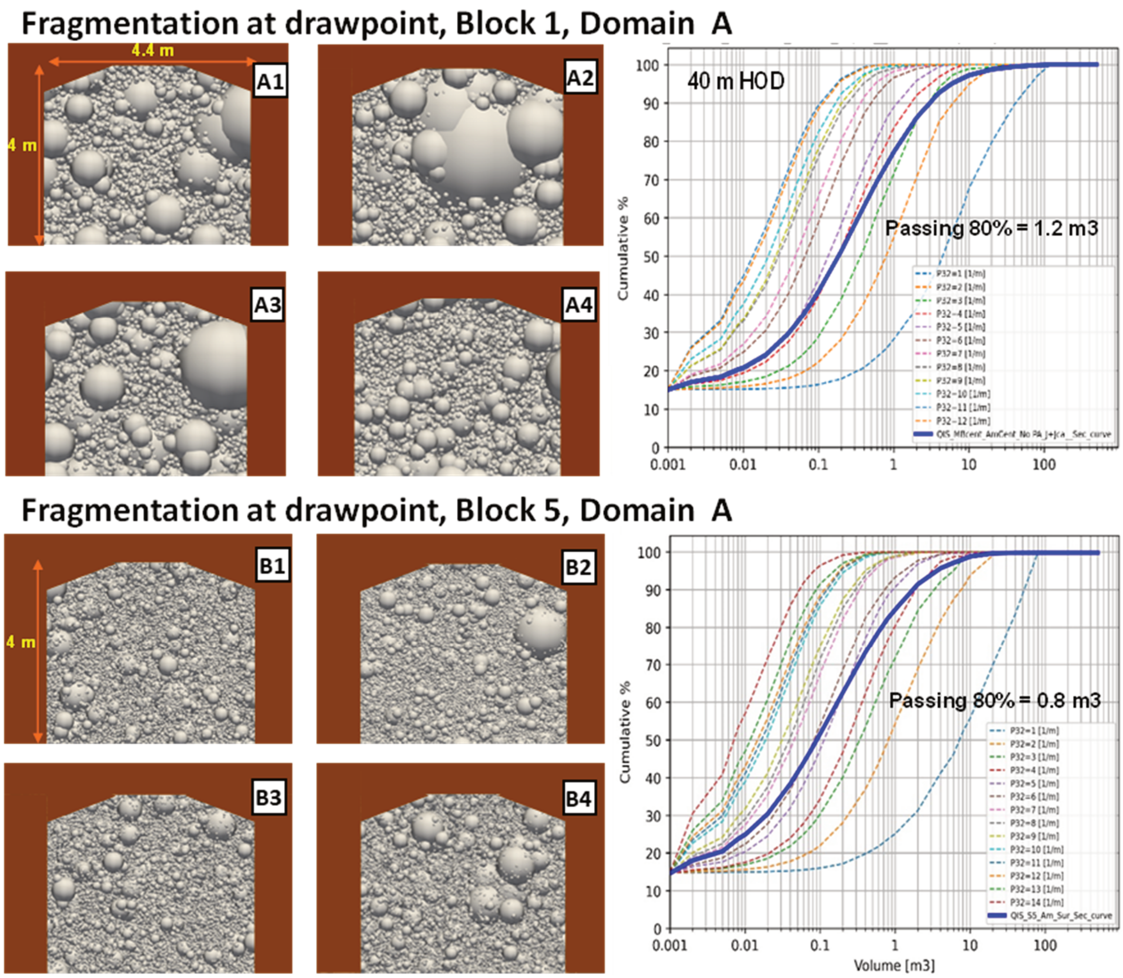


Figure 9 Graphic representations of fragmentation at drawpoints for a real case performed applying the DFN-BCF hybrid approach. The upper and lower cases correspond to different caves in the same mine (A1-A4 corresponds to the upper fragmentation curve, B1-B4 corresponds to the lower fragmentation curve). The difference in the granulometry is controlled by the fracture frequency and local variations of strength

3 Error of measurement of fragmentation from drawpoint

A very brief discussion on the error of fragmentation measurements in the drawpoints of block caving mines is offered in this section, as it is in opinion of the authors an issue commonly overlooked.

There are various methods that can be applied to measure the distribution of volumes in an operational drawpoint. In general, the method of measurement is based on digital capture of the fragmented rock at the drawpoint, normally associated with image analysis, or based on operators' judgement, where a trained technician visually estimates the fragmentation or quantity of oversize. Putting aside constraints related to accessibility of drawpoints, segregation of material, limitations of the methods and other issues, the measurement of the drawpoint fragmentation distribution carries an error. This error is related to the heterogeneity of the block volumes produced when the rock mass caves and is unavoidable. Is what is called in sampling theory an 'intrinsic error'. Every measurement at a drawpoint should be considered a very limited snapshot of the whole mass that is caving and is under no circumstance representative. The measurement error is directly proportional to the maximum block size in the distribution and inversely proportional to the size of the sample, i.e. this error is bigger for coarser fragmentation and the more drawpoint measurements available, the better. It also means that the error related to the fragmentation measurements decrease while the hod increases. At higher hod, the rock size becomes finer, more homogeneous, less dependent of the rock mass characteristics and more related to the physical interaction between blocks in the draw column.

The validity of drawpoints measurement data must be assessed before being used. A simple way to corroborate or discard such measurements is evaluate how sensible or realistic they are in comparison to the operational parameters. For instance, when comparing measured oversize versus hung up or secondary blasting, if the measurements say there is a 30% of oversize, but the productivity and secondary blasting does not say the same, chances are that the number of measurements is not enough to capture the actual size distribution, or the measurements are simply biased.

To test the existence of the intrinsic error, the authors performed a computational experiment. A sampling simulation of extraction points was carried out for a fragmentation distribution with a passing 80% <=1 m^3. The simulation assumed perfect sampling, as all blocks had the same probability of reporting to the drawpoint in each measurement, and all blocks located between 0.5–1 m from the surface of the muck pile in the drawpoint were visible. The error for 10 simulations, with 140 measurements each (i.e. snapshots), was in the range of 1–45%.

4 Conclusion

The DFN-BCF hybrid approach corresponds to the updating of the BCF fragmentation assessment approach created by Esterhuizen (2005). In this updated approach, the block generator of BCF software has been replaced by a DFN model, which provides a stochastic representation of intermediate and minor structures (Joints and/or Faults) which implicit modelling is not possible or practical. The DFN model addresses the full geometry of the relevant fractures that will bound blocks during the fragmentation process in a block caving operation. The basic data to generate a DFN model are the distribution of fracture frequency, orientations of discontinuities and discontinuities length. These parameters can be sourced from core logging, scanline, bench mapping or tunnel mapping. Photogrammetric techniques also offer a good opportunity to capture data for DFN generation.

Pre-processing of the input data is necessary to remove directional bias and truncations. Several DFN realisations are generated, covering the whole distribution of binned volumetric fracture frequencies. These realisations are combined with stress fractures, which generation is based on empirical rules related to induced stresses and the rock strength. Primary blocks are processed applying the BCF algorithm for secondary fragmentation. The secondary fragmentation curve is obtained combining the primary curves for each volumetric intensity weighted by the frequency of their bin in the histogram. Graphic representations of the fragmentation curve have been developed together with the DFN-BCF hybrid approach. Finally, a brief discussion on 'intrinsic error' of drawpoint fragmentation measurement is offered. Errors between 1–45% were obtained from simulated drawpoints sampling.

To date, the DFN-BCF hybrid approach has been applied successfully to two world-class block caving projects and has been partially verified against initial fragmentation results at one of these operations.

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