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Practical fragmentation estimates using a new block cave fragmentation tool

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Abstract

Realistic fragmentation estimates are a critical input for block cave mine design, yet they remain a great challenge for mining practitioners. The block cave fragmentation (BCF) software has been utilised in cave mining design since the 1990s. Although realistic input parameters are key to obtain realistic results in any methodology, fragmentation predictions using BCF or any available tools are challenging especially in predicting the smaller rock fragments and fines (<5 cm). This is largely due to a scarcity of field data from operating caves required to calibrate prediction logic. Consequently, the proportion of fines is often underestimated, despite the introduction of sophisticated approaches such as explicit modelling using discrete fracture networks (DFN) and numerical codes. The authors discuss the reasons for the poor correlation between predictions and operational reality across all 3 fragmentation stages: in situ, primary, and secondary. This paper reviews initial experiences with the newly released BCF version 4 (V4), which attempts to address these shortcomings by improved simulation of the crushing/grinding/block splitting processes in a draw column. Significantly, the updated BCF has been calibrated against fragmentation data collected from mines with diverse rock mass characteristics at varying depths, including jointed, weak, and veined ground. The paper also outlines a refined workflow, tested against real-world cases, that incorporates DFN and three-dimensional fracture-mechanics-based hybrid codes (3D-FDEM).

Keywords: *block caving, fragmentation, fines predication, DFN, 3D-FDEM*

1 Introduction

Fragmentation is a fundamental driver of the technical and economic viability of any block or panel caving operation. Unlike most mining methods where fragmentation is controlled through engineered blasting, caving relies on gravity and caving-induced stresses to break the rock mass. Consequently, the resulting fragment size distribution dictates nearly many aspects of cave mining design, including drawpoint spacing, the dimensions of the extraction level, primary crusher specification, and the selection of material handling equipment (Laubscher 1994; Brown 2003). Poor or unexpectedly coarse fragmentation can lead to a high frequency of ‘hang-ups’, requiring secondary breakage that increases operational costs and poses safety risks. Conversely, excessive fines can lead to early dilution entry or potential inrush hazards. Because these risks are established at the onset of the cave, the ability to forecast fragmentation during the feasibility and planning stages is critical (Laubscher 1993, 1994; Castro et al. 2012).

Historically, the block cave mining method was selected for weaker rock masses where regular caving and acceptable fragmentation would occur with limited requirement for secondary breaking. During the 1990s, the trend for block cave operations to move into stronger rock masses at increasing depth (e.g. some of the porphyry deposits; see Section 3) raised concerns that fragmentation would be coarse, which may result in

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excessive hang-ups at the drawpoints and require significant secondary blasting of oversize blocks (Brown 2003; Ngidi & Pretorius 2010). Experience in weak rock masses would not be applicable to caving in strong rocks and a method to estimating likely fragmentation in the stronger rock masses was needed. Furthermore, during the early stages of project development, engineers are often faced with significant geological uncertainty and must evaluate a wide range of ‘what-if’ scenarios. This creates a specific need for a tool that can rapidly assess fragmentation across numerous variables (e.g. varying stress paths, draw heights, and fracture intensities) without prohibitive computational cost.

To address these forementioned needs, the block cave fragmentation (BCF) software (Esterhuizen et al. 1996; Esterhuizen 1998) was developed with the emphasis on fragmentation in strong rock masses, hang-up potential and secondary breaking requirements, providing a rule-based, rapid assessment framework. The contribution of Dr Dennis Laubscher, who provided leadership and formulated many of the original concepts included in the software, is acknowledged. In the early 2000s, BCF became an industry standard for assessing cave fragmentation (Brown 2003). Over the past 2 decades, it was found that BCF provided reasonable estimates of the coarser fragment sizes reporting at a drawpoint, but the smaller fragments and fines were underestimated (Brown 2003; Nadolski et al. 2018).

Recently, a team of mining engineers and geologists at SRK Consulting – involved in both feasibility and operational caving projects – collaborated to update and improve the BCF software. New developments in rock mass characterisation and understanding of cave fragmentation processes were incorporated in the update to improve the alignment of predictions with observed fragmentation. This collaboration also explored the capabilities of leveraging the discrete fracture network (DFN) technique combined with GPU-based hybrid finite element-discrete element method (FDEM) modelling to predict stress-assisted fracturing and primary fragmentation. This paper provides a summary of the improvements made to BCF-V4 and presents examples of the results achieved.

2 Modifications to the block cave fragmentation software

The overall analysis approach in BCF-V4 remains the same as in the previous versions. BCF remains an empirical tool, based largely on field measurements and observations made at producing block cave operations by experienced engineers and geologists. Where appropriate, established rock mechanics principles, results of laboratory testing, and physical model testing are used to develop algorithms for representing the mechanics of cave fragmentation. The strength of this approach lies in the fact that real-world observations form the basis for the BCF-produced results. However, given the uncertainties and variability of the factors affecting fragmentation, the BCF predictions should be considered an estimate. Taking advantage of the rapid calculation of results by BCF, users can run hundreds of simulations to develop an understanding of how variability and uncertainty may impact the fragmentation.

To further investigate rock block strength and stress-induced fracturing of rock blocks, numerical modelling using discontinuous codes, particularly the 3D FDEM codes, was conducted (Xu et al. 2025, 2026). FDEM is well suited for cave modelling because it follows rigorous fracture mechanics to capture the transition of rock mass status from semi-discontinuous (in situ) to fully discontinuous during the primary fragmentation process. Although calibrating numerical modelling parameters at varying field scales remains difficult – a challenge partially shared with continuum-based codes during the project study phase – the rapid improvement of GPU capabilities in the AI era allows for 3D FDEM modelling and calibration at the rock mass scale. These models provided useful insight for quantifying fragment size distributions in BCF-V4. This progress provides a pathway to upscaling modelling parameters to the field scale.

Improvements were made to the various processes that affect fragmentation, from the in situ rock mass state to the point where fragments report at a drawpoint. The processes are summarised in Figure 1 and may be described as follows:

- Natural fragmentation of the rock mass by jointing, veins and structural weaknesses such as shear or breccia/gauged zones
- Fracturing that may be caused by stress in the cave back
- Gravity separation of blocks from the surrounding rock mass
- Fracturing from impact of the separated blocks if they fall through an airgap
- Block splitting in the draw column related to the block aspect ratio
- Rounding of blocks through attrition in the draw column
- Stress fracturing from point loading in temporary arches formed in the draw column.

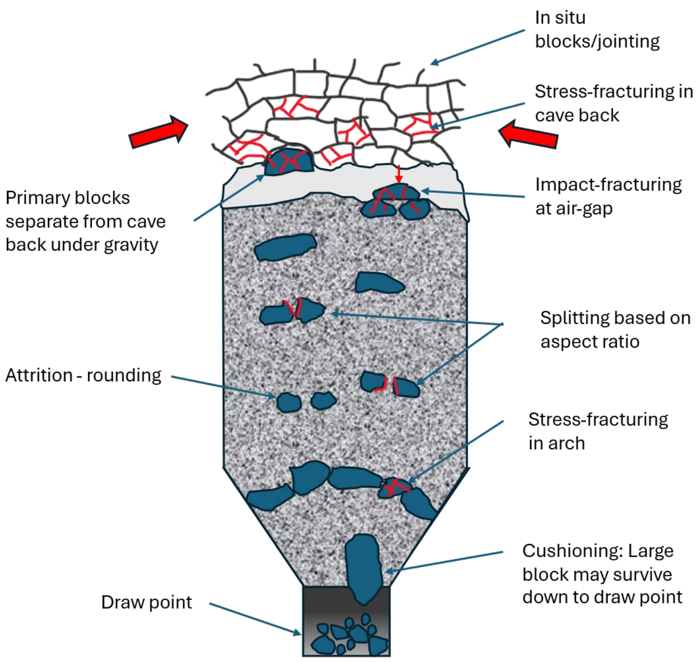


Figure 1 Illustration of the various primary and secondary fragmentation mechanisms considered by block cave fragmentation

Calibration of BCF-V4 against real-world cases was conducted by comparing results to published case histories (Brunton et al. 2016; Srikant 2005; Fuenzalida et al. 2024; Gomez et al. 2017) as well as case histories from the SRK project archives. During the calibration phase, the parameters affecting the different fragmentation mechanisms were adjusted to provide a final set of parameters that provided a reasonable match between simulated fragmentation curves and the observed curves. The critical parameters considered for matching were the maximum block size, percent oversize blocks, the 50% passing size, and the fines percentage. The empirical nature of this process implies that BCF should be used with caution in cases that lie outside the range of geotechnical conditions considered in the calibration process.

2.1 Modifications of in situ rock mass characterisation

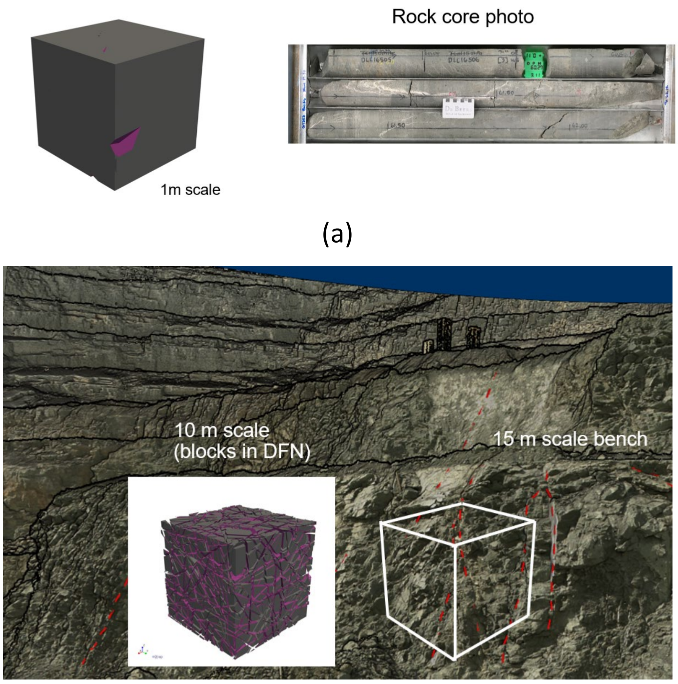
2.1.1 Estimate of rock block strength

A switch was made from using the Hoek–Brown failure criterion to estimate rock mass strength to the Laubscher & Jakubec approach (2001) in which rock block strength (RBS) is the basis for rock mass strength estimation. The results of the synthetic rock mass modelling combined with improved understanding and quantification of the impact of veins, as described by Jakubec (2013) and Hormazabal & Russo (2023), were applied in the estimation of vein and micro-vein impacts on rock strength and fragmentation. The impact of veins on the generation of fines under compressive stress, the formation of aggregated blocks, and the maximum block size calculation are now considered.

2.1.2 Discrete fracture network import for discontinuity and veinlet characterisation

Although studies have shown that BCF and DFN methods provide similar in situ fragmentation results when using the same inputs (Jakubec et al. 2012), some users may prefer to use DFN generated blocks as an alternative to BCF generated blocks. A module is available in BCF-V4 that allows DFN generated blocks to be imported into BCF. For a well-calibrated DFN model, incorporating DFN capabilities into fragmentation estimates can honour the site-specific spatial and size distribution of discontinuities. This includes random oriented joints, which the authors' experiences suggest are often important yet overlooked (Jakubec 2014).

It is also important not to overstate the power of DFN applications. Like many geotechnical assessments, DFN is limited by data quality aside from the time-consuming nature of its construction process. Nevertheless, DFN remains an informative tool even when data is sparse, provided it is applied intuitively with professional expertise. For instance, characterising kimberlites for cave mining geotechnical design is notoriously difficult. The seemingly massive in situ rock mass quality can degrade rapidly under physical disturbance such as caving or chemical disturbance like weathering. The degradation occurs primarily due to serpentinization-related defects and veins that are not visible in fresh drillcore or exposed surfaces. In a recent caving project, referring to Figure 2, field observations of defects and veins exposed in weathered pit walls after blasting provided an opportunity to calibrate a bench-scale DFN model against the observed defects and query the block volumes in the DFN model to develop a fragmentation curve. By incorporating both the observed discontinuities and veins, the DFN model yielded fragmentation estimates that matched historical field observations. Refer to case study 3 in Section 3.3 in which BCF was used to assess the impact of weathering on potential fragmentation for this project.



(a)

(b)

Figure 2 Calibration of discrete fracture network model against core photo and pit wall mapping (courtesy of Debswana). (a) Calibration of in situ visible fabric (joints) from core sampling; (b) Calibration of in situ hidden defects (veinlets) from pit wall exposure after blasting disturbance

2.2 Modifications to primary fragmentation estimates

Primary fragmentation is the block size distribution when rock blocks separate from the rock mass at the caving boundary. Primary fragmentation is affected by the in situ size distribution of blocks and particles that make up the rock mass prior to mining. The stress in the cave back may further modify the primary fragmentation by fracturing rock blocks or rock bridges and causing shearing along joint or vein surfaces. At the caving boundary gravity causes separation of the individual rock fragments from the rock mass.

2.2.1 In situ fine materials

In BCF-V4 fine materials are simply treated as the volume of particles that are less than 5 cm in size, aligning with industry practices, without attempting to classify them into smaller sizes. Fragments larger than 5 cm are individually accounted for in BCF and are reported in the fragmentation size distribution. The in situ rock mass typically contains fine materials which exist prior to mining. These fine materials may include broken particles in brecciated zones, finely ground particles in shear zones, intrusion related particles such as small-scale veinlets or block defining veins. In BCF-V4, these pre-existing fine materials are defined by specifying the percentage of broken or rubble-core or otherwise observed fault-shear and brecciated zones.

2.2.2 Stress fragmentation in the cave back

Fragmentation of in situ blocks subject to cave back stress is now based on the concept of single-block fragmentation. Observations of fragments in drawpoints, the results of laboratory tests, and numerical simulations show that when an intact rock block fails under compression, broken particles can be produced that have a wide range of sizes, ranging from less than 1 mm to a large fraction of the original rock block (Li & Elmo 2025; Pierce et al. 2010). In BCF-V4, the variability of the RBS is considered and the blocks that are over-stressed are assumed to break up into a range of fragments with the maximum fragment volume stochastically assigned, ranging from 25—50% of the original block volume. A percentage of the volume is assumed to be fines, depending on the ratio of cave back stress to block strength. The remaining volume is stochastically distributed into fragments with volumes that lie between the maximum fragment size and the fines limit (5 cm block size). This approach better represents the breakup of a rock block that fails in a compressive stress environment. The resulting fragmentation is more representative of actual compressive stress failure when compared to the simple introduction of parallel stress fractures used in earlier versions of BCF.

Figure 3 shows an example of primary fragmentation block size distributions for a rock mass subject to low and moderately high cave back stress.

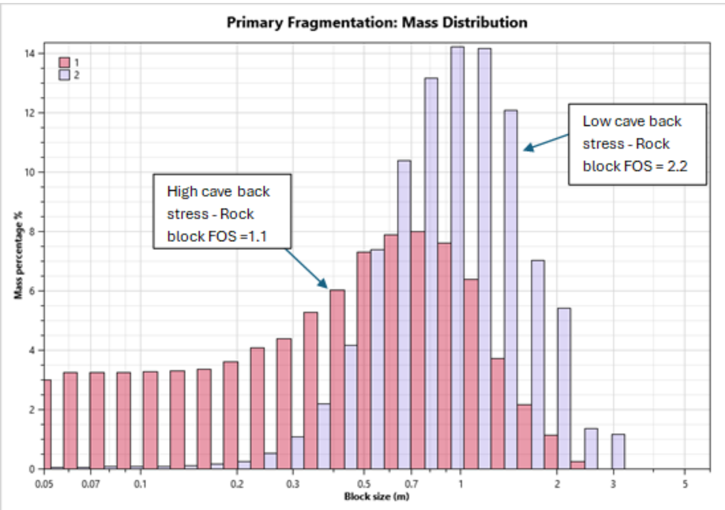


Figure 3 The block cave fragmentation estimated impact of stress fracturing in the cave back for low- and high-stress conditions that reduce the Factor of Safety (FOS) of the rock blocks in the cave back from 2.2 to 1.1

For the lower stress case the Factor of Safety (FOS) of rock blocks in the cave back is 2.2, which does not cause any stress fracturing. In the higher stress case with FOS = 1.1, more than 50% of the blocks in the cave back fail and the size distribution of the fragments becomes spread out through the smaller size categories with about 30% of the fragments being classified as fines (<5 cm).

2.2.3 Applying discrete fracture network and 3D-finite discrete element method models as alternative for primary fragmentation modelling

The authors have conceived and tested a workflow for projects that incorporates both DFN and 3D-FDEM techniques to provide alternative estimates of primary fragmentation as the input for subsequent BCF-V4 analysis. This approach serves as an alternative for the BCF-V4 primary fragmentation algorithm module, following the steps outlined below and illustrated in Figure 4:

- Step 1: construct and calibrate an in situ rock mass DFN model of the geotechnical domain at a scale comparable to several draw column widths.
- Step 2: construct and calibrate a 3D FDEM model integrating the aforementioned DFN model, loading the model up to the expected stress levels at cave back.
- Step 3: use insights from fracture growth measured via the 3D FDEM modelling to construct a new DFN representing the products of primary fragmentation. The resulting block size distribution of this new DFN model then serves as the input for BCF-V4 secondary fragmentation estimates.

While many DFN codes and software packages exist, few offer the capability to perform rapid DFN construction and calibration alongside block formation and identification. Specifically, the ability to identify hundreds or thousands of blocks within minutes is rare. For our current workflow, mXrap's developing DFN module from ACG and its block identification package were utilised.

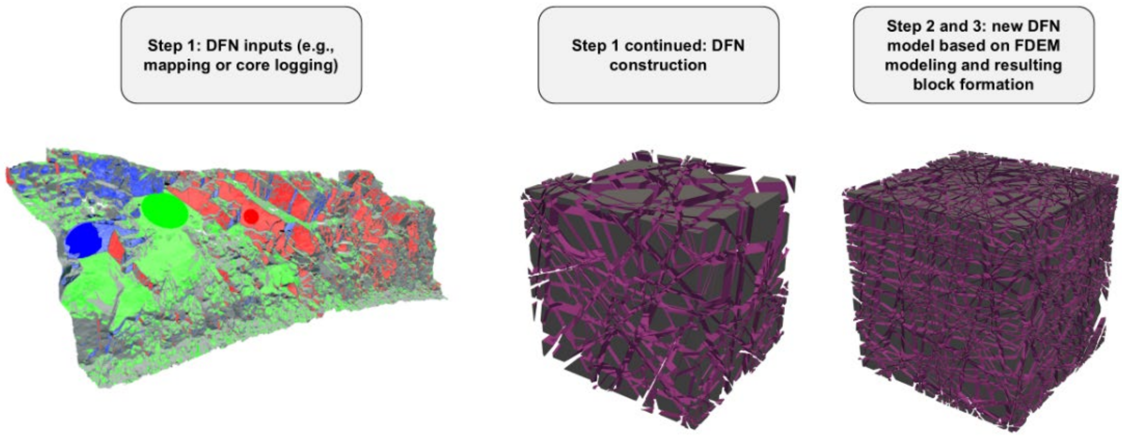


Figure 4 Applying discrete fracture network (DFN) and finite discrete element method (FDEM) as inputs for BCF-V4

2.3 Modifications to secondary fragmentation estimates

The fragmentation of rock blocks in the draw column is generally known as secondary fragmentation. Fragmentation may also occur if caved blocks free-fall through an airgap that may exist between the cave back and the top of the previously caved rock blocks. Airgap related fragmentation is categorised under secondary fragmentation.

2.3.1 Fines from block attrition

As rock blocks travel down the draw column, they move at different velocities and may tumble when they are at the border of a movement zone. The resulting attrition between rock blocks is assumed to produce fragments smaller than 5 cm and directly contributes to the fines volume. In BCF-V4, fines generation due to attrition is calculated using the RBS, which is affected by potential weathering and the presence of veins withing the block. Each time a block splits in the draw column, new ‘unrounded’ corners are created which will further contribute to fines generation.

2.3.2 Block fragmentation from splitting and crushing

Block splitting due to point loading or bending when the block aspect ratio is large is the most common fragmentation mechanism considered by BCF. Splitting is also recognised as the primary mode of failure in granular materials (Mesri & Vardhanabhuti 2009; Pierce et al. 2010). The occurrence of splitting is treated as a probabilistic event that depends on several factors, including the aspect ratio of the block, the RBS, amount of fines in the draw column, and the cave pressure. The presence of fines acts as a cushion against point loading of a block and will lower the probability that a block will split.

In BCF-V4, each of the parameters affecting splitting are evaluated at vertical intervals as a rock block travels down the draw column. When a block splits, the fragmentation products are tracked as they travel further down the draw column. The products may again split as the cave pressure increases or the RBS decreases due to weathering. The procedure described earlier for cave back stress related failure is applied to determine the largest split fragment and the intermediate fragments larger than 5 cm. Fragments smaller than 5 cm are treated as fines.

The split fragmentation parameters differ from the cave back stress fragmentation parameters to account for the fact that block splitting under bending will produce larger fragments and less fines than crushing under multiaxial compression.

The probability for block crushing in the elevated stress conditions associated with arching in the draw column is evaluated using the same compressive failure procedure as that used for cave back stress fragmentation. Arching related failure is affected by the cave pressure in the draw column and the block strength, including the potential impact of weathering.

Figure 5 presents an example of the various fragmentation processes that BCF-V4 applies to the primary fragments as the height-of-draw (HOD) increases. This set of results is for relatively strong rock mass with a RBS of 70 MPa. The results show that initial fracturing in the cave back and block splitting in the draw column are the main processes of block fragmentation, while about 35% of the fragmented material is produced by block attrition when the HOD is 300 m. As the HOD increases, the attrition mechanism consumes a portion of the fragments that failed in the cave back and split in the draw column. When the HOD is 300 m approximately 8% of the primary fragments arrive at the drawpoint unaffected by the splitting and crushing activity in the draw column.

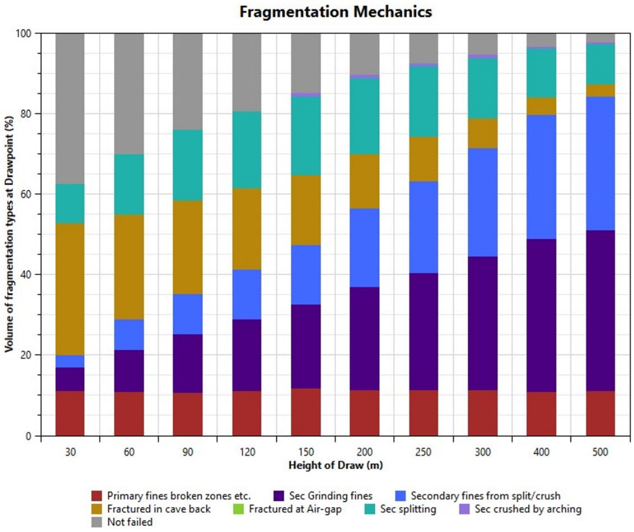


Figure 5 Illustration of the various failure mechanisms in block cave fragmentation that contribute to fragmentation at the drawpoint as the height-of-draw is increased

2.3.3 The impact of weathering

In weaker rock masses where the ore being mined is sensitive to moisture, such as kimberlites, the exposure of rock blocks to moisture in the draw column will result in a reduction of the RBS. BCF-V4 allows the user to enter a weathering resistance parameter that will reduce the RBS in stages as a block travels down the draw column. The draw rate and HOD are used to calculate an exposure time, which is then used to modify the RBS. The weathering resistance is entered as a rating based on the mining rock mass rating (Laubscher & Jakubec 2001).

2.3.4 Airgap fragmentation (experimental)

In recent years, cave operators have attempted to limit the airgap between the top of the draw column and the cave back to limit the potential air-blast effects when a large area of the cave back collapses. Although the objective currently is to eliminate an airgap, it is insightful to consider how an airgap may have affected fragmentation outcomes in the past, and how the potential impact of a small airgap of a few metres may affect the fragmentation.

In BCF-V4, the effect of an airgap on fragmentation is provided as an experimental option since no observational data are available to verify the BCF results. The kinetic energy of a falling block is used as the driving source for impact fragmentation. Since the falling block will land on a relatively loose pile of previously caved rocks, it is assumed that there is a 50% loss of kinetic energy by dissipation of the energy into the cave rocks. The resistance of the falling block to impact-damage is calculated using the cross-sectional area of the block and the RBS. The result is that large blocks will fail more readily than smaller blocks given equal fall height, as observed. The energy per square metre of block cross-sectional area is used to estimate whether a block will fragment when it falls. The critical energy density for fragmentation is based on the observation that 2 m blocks of moderate strength are likely to fail if they are lifted through 1 m by a loader and dropped onto the drawpoint floor. This energy density is then used as a benchmark to estimate failure of blocks with varying volumes and airgap heights.

Impact fragmentation is a high-energy event that will produce larger fragments with less fines than quasi-static compressive crushing (Vergara et al. 2024). The resulting fragments from impact failure are calculated using a modified form of the fragmentation algorithm described earlier, resulting in larger maximum fragment sizes and lesser fines production.

2.3.5 Analysis with limited geotechnical data

In situations where detailed geotechnical data – such as joint set orientations and spacings – are not available, preliminary fragmentation analysis can be conducted using rock mass classification data and joint frequency data collected from borehole core. This type of analysis would be valuable in the feasibility stages of a cave mining project. Borehole core can be used to provide samples for rock strength testing and can be used to classify the rock mass into domains, using the Laubscher & Jakubec (2001) classification approach. BCF-V4 has an option to use the fracture frequency measured in borehole core as a basis for block formation by assuming randomly oriented joints. Knowing the rock strength, rock classification and fracture frequency, BCF-V4 can calculate in situ block size distribution. For primary fragmentation, knowledge of the expected cave back stress is needed. Depending on the level of confidence in the inputs, numerous fragmentation analyses can be conducted to estimate the likely range of fragmentation outcomes given the limited data.

2.3.6 Veins-only analysis

In some cases, with strong vein infill materials there is an absence of ‘open’ joints. Long runs of unbroken core are produced, and it is obvious that assuming the veins are standard block forming joints would be inaccurate. In such cases BCF-V4 can be used in a ‘veins-only’ mode in which the veins are treated as random joints with elevated cohesive strength. For these analyses, the cohesion and friction properties derived from laboratory testing, can be used to describe the shear strength of the veins (Hormazabal & Russo, 2023). A first estimate of likely fragmentation can then be determined.

2.3.7 Visualisation

Viewing fragmentation curves is useful for comparing the outcome of alternative sets of inputs. However, the curves are not a visual representation of fragmented blocks as they would appear in a drawpoint. BCF-V4 has the capability to create plots of fragmented blocks in a drawpoint using the fragmentation results. Looking at a single drawpoint is highly unlikely to be representative of the average fragmentation of the rock mass. BCF-V4 allows the user to visualise the fragmentation by plotting numerous realisations of fragmented blocks drawn from the secondary fragmentation distribution. Examples of drawpoint visualisations are included in following case studies.

3 Case study examples

Four case studies are presented in which the updated BCF-V4 was applied to re-analyse cave fragmentation cases using data available from SRK Consulting archives. The geotechnical data were mostly collected during feasibility studies and provided inputs to the BCF analyses. The BCF results were compared to subsequent measurements of fragmentation made during actual caving operations. The case studies demonstrate the capabilities of BCF-V4 in wide-ranging rock mass settings from deep, high-stress, massive or jointed rocks to shallow, massive or jointed, low strength rocks.

3.1 Case study 1: moderate strength rock mass at a depth of less than 1,000 m

The BCF-V4 calculated fragmentation at a typical porphyry deposit with the undercut level situated less than 800 m below the ground surface and is presented. Inputs for the analysis were based on data available during the feasibility stage of the project. The uniaxial compressive strength of the rock ranges between 60 to 90 MPa and several joint sets were identified which contained various degrees of infilling materials and the typical in situ rock mass rating (IRMR) are ranging between 50 to 55. For the BCF analysis relatively strong joint ratings were assigned to the joint sets. The joint frequency was in the range of 3 to 4 factures per metre. Most of the joints appear to be weakly cemented veins that break during drilling. The vein strength will be controlled by the type of mineral infill as highlighted by Hormazabal & Russo (2023). In this case study, during the feasibility stage, the infill materials of veins were accounted for as strong infill. The cave back stress was sufficient to cause limited crushing of the rock blocks in the cave back.

The actual secondary fragmentation reporting at the drawpoints was visually logged by mine staff over a period of four years. Fragment sizes were logged based on their linear size. Fragments less than 5 cm in length were classified as ‘fines’. Fragments greater than 1.8 m were classified as oversize. Intermediate block sizes at 50 cm and 1 m length were also logged. Figure 6 shows the observed fragmentation at four stages of production as the HOD increased from approximately 60 m to 300 m. The average observed fragmentation at approximately 128 active drawpoints is shown as coloured dots in the figure. The observed fragmentation values do not correspond to exact HOD values, because they are date based and the HOD varied between drawpoints at a specific date. The figure also shows the BCF-estimated fragmentation curves for 100, 200 and 300 m HOD. Figure 7 shows a plot generated by BCF-V4 to provide a visual representation of the fragmentation at 100, 200 and 300 m HOD. The plot is created by sampling block sizes from the BCF-produced cumulative fragmentation curve. These plots are useful for creating an impression of how the rock fragments will appear in a drawpoint.

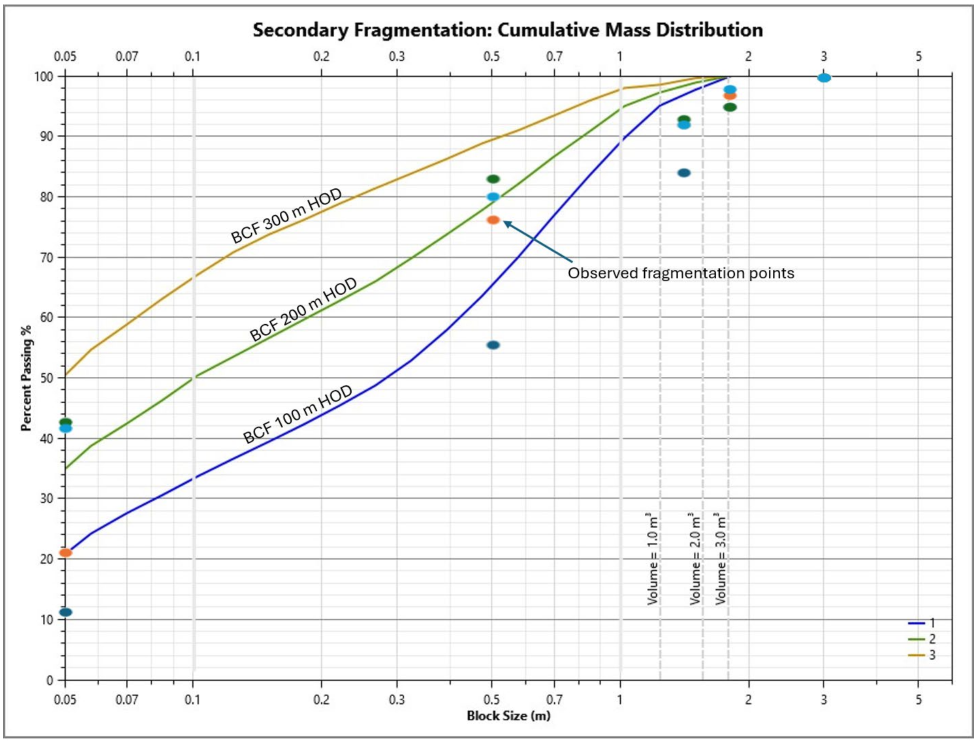


Figure 6 **Observed and block cave fragmentation calculated fragmentation curves for a moderate strength rock mass. Height-of-draw is 100, 200 and 300 m**

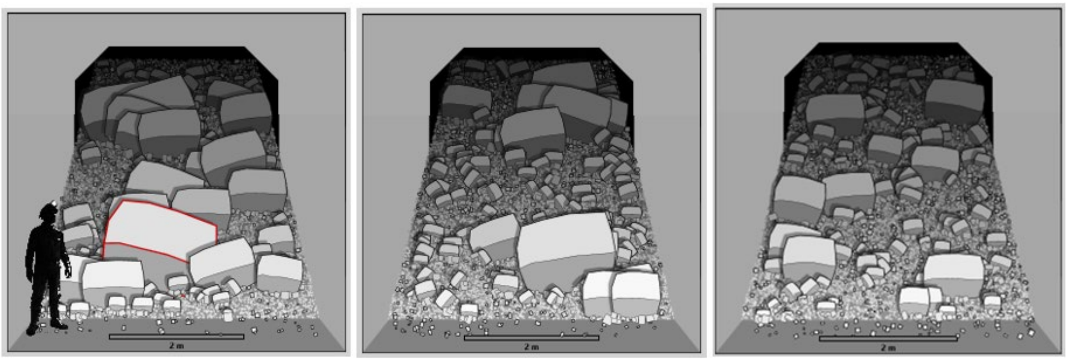


Figure 7 **Drawpoint views generated by block cave fragmentation for case study 1 at 100, 200 and 300 m height-of-draw (HOD). Red outline indicates an oversize block**

3.2 Case study 2: strong rock mass at a depth of greater than 1,000 m

The second case study considers another porphyry deposit with stronger rocks and less jointing features (hence massive) occurring at a depth greater than 1,000 m. The average uniaxial compressive strength of the rocks was ranging from 120 up to 160 MPa, with an open veins frequency around 2–3 per metre, with rock mass rating ranging from 55 to 65. The contribution of weaker cemented veins present in the orebody and their impact on fragmentation were included separately in the BCF analysis. In this case, the cave back stress was greater than the calculated average RBS, which induced failure in the cave back.

Fragmentation was measured by the mine personnel at regular intervals. Block sizes between 10 cm and 3 m were recorded. Figure 8 shows the average fragmentation results when the HOD varied between 50 and 80 m. The BCF-V4 results, using the available geotechnical data, are indicated in the figure for comparison. Three visualisations of the fragmentation as it would appear in a drawpoint are shown in Figure 9.

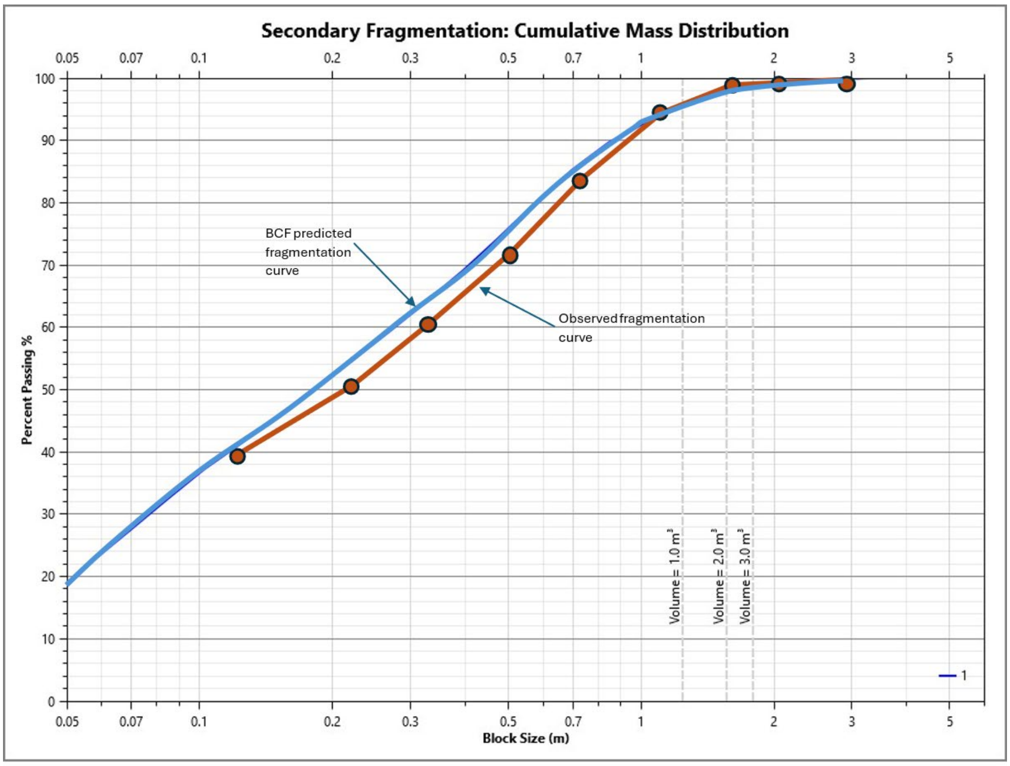


Figure 8 **Observed and BCF-V4 calculated secondary fragmentation curve for a strong rock mass in high ground stress. Height-of-draw is between 50 and 80 m**

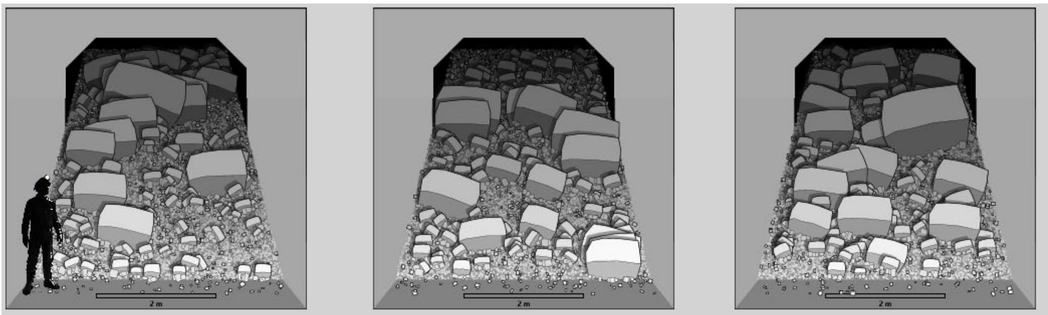


Figure 9 **Drawpoint views generated by BCF-V4 showing fragmentation in drawpoints at a height-of-draw (HOD) of 65 m for case study 2. Each image represents one realisation of the likely fragmentation at 65 m HOD**

3.3 Case study 3: low strength, massive, weathering rock mass

The third case study shows the application of BCF to provide initial estimates for a weathering rock mass in a situation where the rock mass has very few defined rock joints but randomly oriented healed-veins are pervasive throughout the rock mass. These conditions are typical of low strength kimberlites (refer to Section 2.1.2).

At the time of the study, only open pit exposure was available for the analysis. Observation of the pit bench performance indicated clearly that the rock mass degrades from solid-intact blocks to rubble when exposed to air and moisture over a period of more than 2 years. The impact of weathering cannot therefore be ignored when assessing fragmentation potential in a proposed block cave. Using the available geotechnical data and assessing the weathering potential, it was possible to conduct a 'veins-only' analysis using BCF-V4 and accounting for the expected rock strength degradation with time spent in the draw column. In this case, the cave back stress was judged to be much less than the initial, fresh rock strength in the cave back.

Block formation would be defined by gravity separation or shearing along the veins. The vein frequency was around 4 per meter and vein infill hardness was 3 on the Moh scale.

Three analyses were conducted using BCF-V4 with the weathering resistance varying from high resistance (rating = 5) to moderate resistance (rating = 3). Figure 10 presents the results, indicating the likely range of fragmentation curves that may be expected when the HOD is 100 m. Further analyses can be conducted to investigate the effect of the rate of draw, which affects the time of exposure of the rocks in the draw column. Figure 11 shows three realisations of likely fragmentation at the HOD of 100 m generated by BCF.

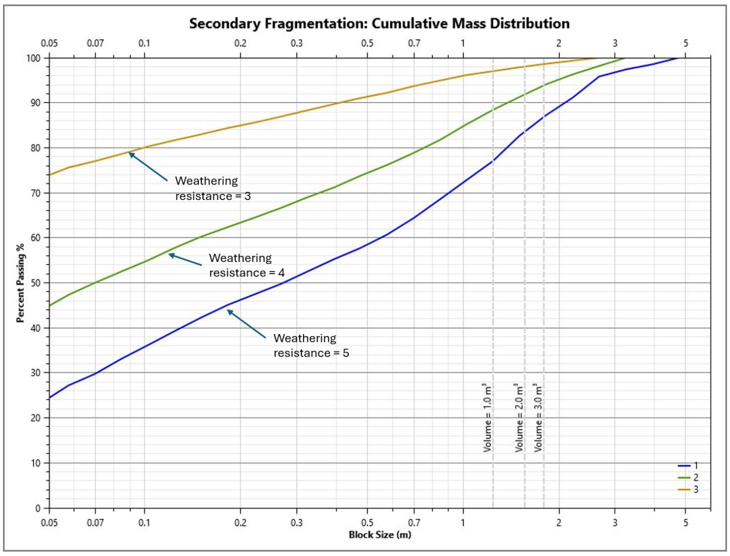


Figure 10 Weak, massive rock mass fragmentation at 100 m height-of-draw for various levels of weathering resistance

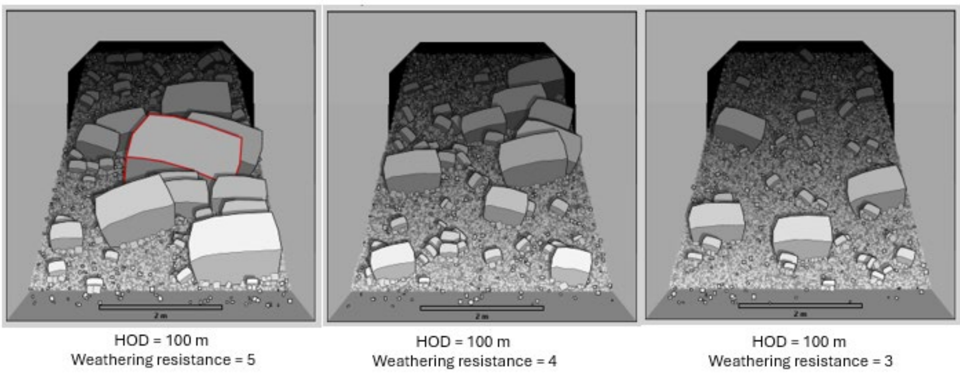


Figure 11 Drawpoint views generated by block cave fragmentation showing the effect of weathering on drawpoint fragmentation in a weak, weathering rock mass at a height-of-draw (HOD) of 100 m. The red outline indicates an oversize block

3.4 Case study 4: strong rock mass at shallow depth

Historically, block caving was conducted in weak rock masses at relatively shallow depth. The fourth case study demonstrates the capabilities of BCF-V4 to provide reasonable estimates of the fragmentation at a unique caving operation where a strong, poorly jointed rock mass, at shallow depth is being caved. The undercut level is less than 200 m below the ground surface, and the maximum HOD is 120 m. There are 3 to 4 joint sets present with a volumetric joint count of around 2.0. The rock mass is competent with the average uniaxial compressive strength of rock samples being 90 MPa. The mining rock mass rating (MRMR) falls between 55 and 60. Caving of this rock mass is characterised by numerous oversize blocks requiring dedicated secondary blasting operations. The volume of oversize blocks falls between 30 and 40% of the tonnage mined.

With the limited data available an analysis using the 'random joints only' option in BCF-V4 was attempted. Three cases were created to represent the likely variation of the rock mass strength and fracture frequencies around the quoted 'average' parameters. Figure 12 shows the BCF-V4 results obtained for the HOD ranging from 30 to 120 m. The Figure 13 also shows the range of oversize fragments observed at the mine.

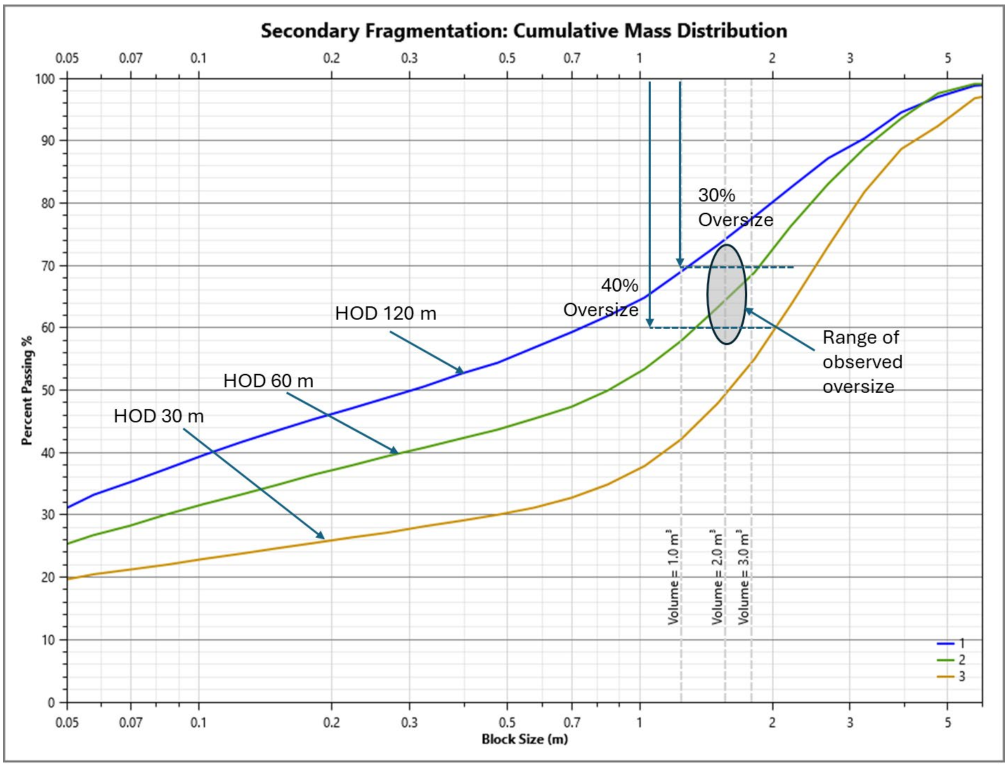


Figure 12 Observed oversize and block cave fragmentation predicted range of likely fragmentation at a shallow depth, competent rock mass caving operation

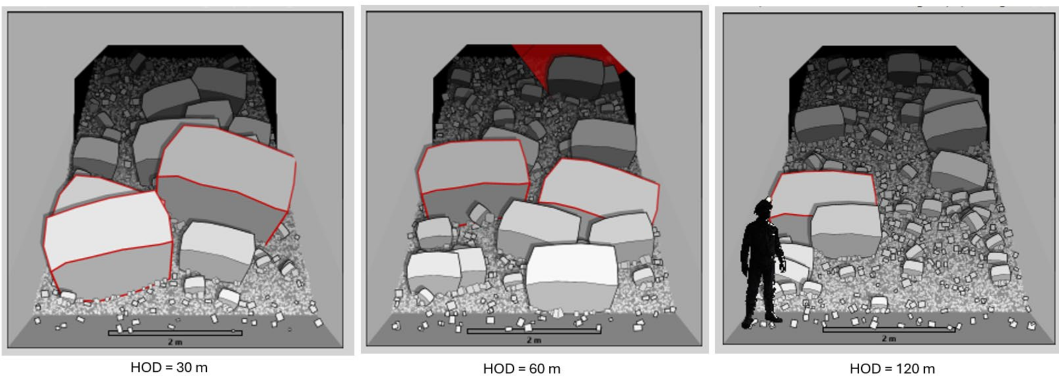


Figure 13 Block cave fragmentation generated views of drawpoints at 30, 60 and 120 m height-of-draw (HOD) for case study 4. Oversize blocks are outlined in red with a large block choking the drawpoint seen in red in the 60 m HOD case

For comparison with Figure 13, Figure 14 shows the actual drawpoint fragmentation observed in the drawpoints of the case study 4 mine. The photographs show that at a HOD of 90 m both large blocks and fines are present in the drawpoints, similar to the BCF-V4 produced images.

Figure 14 Views of 3 drawpoints at the case study 4 mine showing both large blocks and fines in the drawpoints at a height-of-draw of around 90 m

4 Conclusion

The updated version of BCF is an empirical tool, based largely on field measurements and observations made at producing block cave operations by experienced engineers and geologists. The results of recent published research, 3D FDEM modelling of block fragmentation, and application of DFN procedures provided further insights for improving BCF. The empirical experience combined with improved understanding of rock fragmentation processes were applied to update the software. The BCF-V4 software is shown to produce fragmentation results that provide acceptable estimates of the measured fragmentation at operating cave mines.

The updated BCF-V4 provides improved estimates of likely fragmentation in block cave mining operations with significant improvement in estimating the finer fraction of the fragmentation curve. This allows engineers to better optimise the extraction level layouts, select procedures and equipment for handling oversize, specification of ore handing and crushing equipment, and production scheduling.

The improved performance of BCF-V4 is related to the introduction of improved rock strength estimation and accounting for the effect of veins on block strength, incorporating the impact of veins on fines formation, applying a single-block fragmentation approach to crushing of rock blocks in the cave back and in the draw column. Block splitting in the draw column also follows the single-block failure approach in which fines and smaller fragments are created when a block splits. The capabilities of BCF-V4 are further extended by allowing users to import DFN generated blocks as primary or in situ fragmentation.

The empirical nature of BCF-V4 implies that the results are closely linked to the number and quality of fragmentation observations made in the field. Continued measurement of fragmentation in cave operations is necessary to extend the database of case histories that can be used as calibration points for BCF. As with all empirically based analysis methods, BCF-V4 should preferably be used in rock mass conditions that are similar to those used in the calibration process.

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