In situ block size determination of rock masses for engineering purposes, state of the art

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Abstract

The *in situ* block size and shape parameters of a rock mass with discontinuities have a significant role in many projects that involve rock engineering. These include the stability of the blocks and their behavior to the inevitable loads in underground excavation of civil or mining projects, tunneling, slope stability and highway cutting operations and for designing an appropriate blast pattern also. The *in situ* rocks called as rock mass contain structural discontinuities or joints. The geometric configuration of three or more such joints defines the rock blocks. Since joints are occurring in all possible configurations and directions, these depict a significant degree of spatial randomness. Due to this randomness of joints, the blocks defined by these joints also assume random distributions over a wide scale. This factor also varies with the rock type in genetic domain. Methods for predicting the in situ block size that are in vogue are presented in this paper that includes estimation of *in-situ* block size and fragmented rock using physical measurements, digital image analysis techniques and existing models and 3D unfolding models from 2D shape of *in situ* rock blocks. This paper reviews the existing methods of 3D block estimation in rock mass.

Keywords: Rock mass, *in situ* block size distribution, modeling

1. Introduction:

A broad distinction exists in genetic and engineering classifications of rocks. While genetic classifications are subjective, engineering ones try to assess the measurable parameters of rock wherever possible. In other instances ratings have been assigned to particular physical nature of the rock and with the incorporation of joints the rock is generally termed as rock mass (Bieniawski, 1982). The sub-elements of rock mass that are delimited by joints are called *in-tact* rock. The engineering classification of rock defines the *in situ* strength of the rock mass. In more recent times, the *in situ* block size distributions (IBSD) have assumed importance owing to its role in defining the overall stability or tenability of rock mass to fracture. The joints intersecting the rock mass divide the rock into blocks (Figure 1) that range from few cm^3 (fragmented or crushed rock) to several m^3 in massive rock. The sizes are a result of the spacing of joints, number of joint sets, and persistence of the joints in the rock mass.

The block size is an extremely important parameter in rock mass behavior (Barton, 1990 and ISRM, 1978). Goodman (1993) states, "Joints are extremely important in some rock masses. Even though the rock substance itself may be strong or impermeable, or both, the system of joints create significant weakness and fluid conductivity". Many scale effects in rock engineering can be explained by this feature, including compressive strength, deformation modulus, shear strength, dilation, and conductivity.

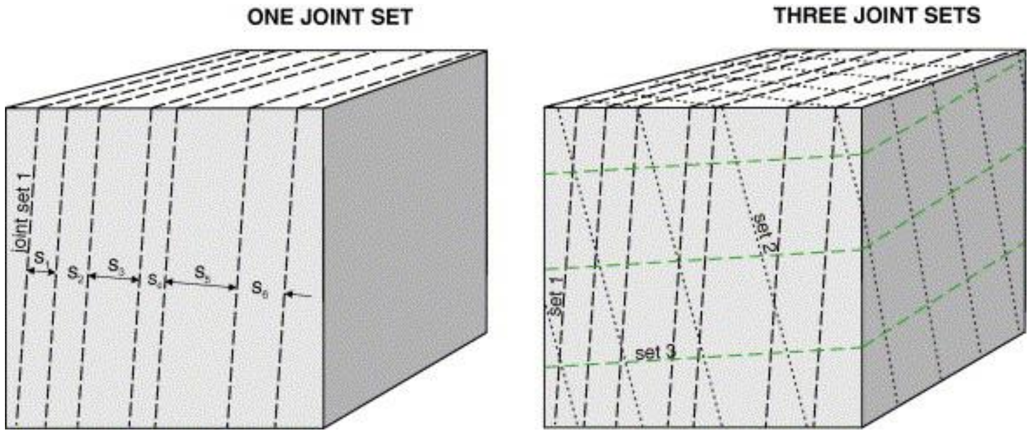

Figure 1 Joint set and joint set spacing (after, Palmstrom, 2001)

The intersection of discontinuities in a jointed rock mass creates in situ blocks of variable three dimensional (3D) geometry. The size and shape rock block in a rock mass assembly have a dominant influence on the engineering properties of rock mass.

The interplay of joints in rocks results in different size and shapes of blocks in a rock mass. The variety of structural settings, disposition of joints and spatial interaction of joints result in several probabilities for block size distribution in a particular geological setting (Figure 2). Thus prediction of IBSD becomes complex and limits its usage in engineering classifications, despite of its predominant role in behavior of rock mass.

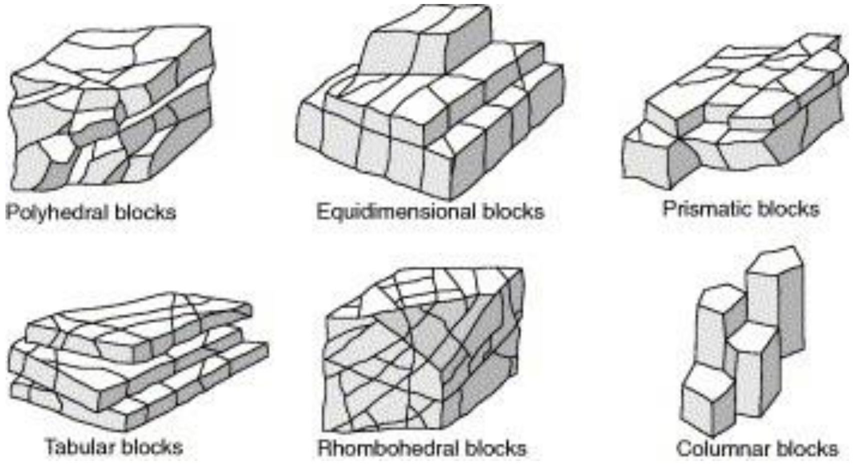

Figure 2 Examples of some shapes of defined blocks (Dearman, 1991).

Characterizing the size and shape of individual blocks with jointed rock masses has a valuable application in rock engineering viz. mineral production, tunneling slope stability, highway cutting, underground excavations.

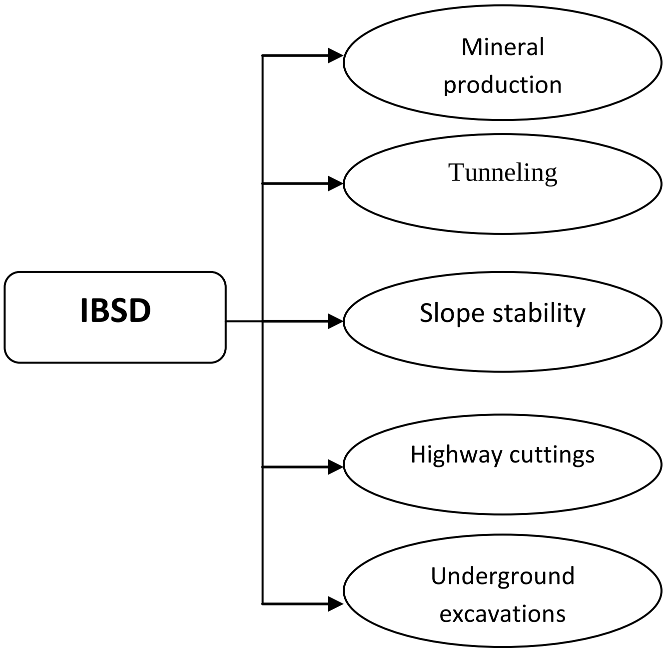

Figure 3 Application of insitu block size distribution (IBSD)

The IBSD and the shape of the in situ blocks and similarity in their equivalent sizes and shape after blasting are function of orientation, distribution and nature of the main discontinuity sets. In most of the cases, the in situ and blasted block size and shapes are greatly influenced by three main sets of discontinuities. The other discontinuity sets and random discontinuities influencing the in situ and blasted block could be included, but they have little effect on the results (ISRM, 1978; Wang et al., 1990).

According to Costa and Baker (1981), discontinuities are closely associated with both the geological structure and the regional deformation history which are dependent upon the stress field within a rock mass. A regional earth stress field is always revealed through three principle stresses. So, it may be reasonable to assume that there will be three main sets of discontinuities for many geological situations where the principle stresses have not rotated significantly. In addition to develop a procedure for tackling more than three sets of discontinuity will be much more complex than that for dealing with three sets (Figure 3). Therefore, a simplified assumption that there are three sets of main discontinuities has been sustained in study for prediction of IBSD. In mineral producing industries, the sizes of rock fragments resulted from blasting has a great influence on the downstream processing. An oversize boulder has to be reduced to desirable size which can be handled by excavating, transporting, crushing and milling machinery. The loading rate at a draw point is directly governed by block size, internal mine transport, crushing and milling can be adversely influenced by poor fragmentation (Figure 4). Poor fragmentation with excess fines or oversize block in the blasted rock size distribution (BBSD) can be affect cost more than twice of the blast itself (Scot *et al*., 1993).

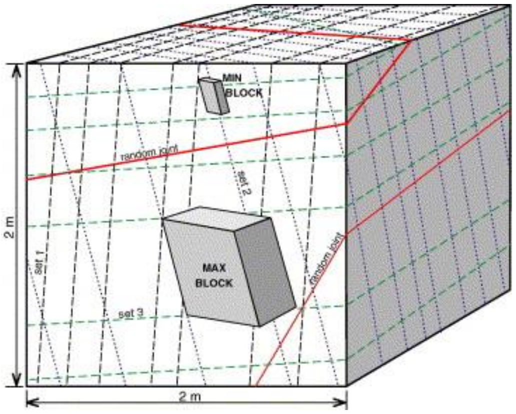

Figure 4 Regular jointing with 3 joint sets and a few random joints. The minimum and maximum block size in a rock mass volume of 2 × 2 × 2 m (Palmstrom, 2001).

Wang et al., (1991) and Wang (1992) wrote a computer program which derives the block sizes and shapes formed by predefined planar discontinuities which intersect each other. It has been examined in mining and quarrying blast operations (Cunningham, 1983; Ord and Cheung, 1991; JKMRC, 1991; Wang et al., 1991), rock mass characterization (Franklin, 1974); ISRM, 1978; Hoek et al., 1992), stability analysis of excavations in jointed rock masses (Hoek and Bray, 1981; Goodman and Shi, 1986) and indirectly in fracture network flow modelling (Rives et al., 1992; Dershowitz, 1993). The prediction of IBSD has been one of the main pursuits of mining and quarrying operations as it is believed to greatly influence blasting performance generally (Da Gama, 1983; Cunningham, 1983; Wang et al., 1990, 1991; JKMRC, 1991), and rock amour production for coastal defence in particular (CIRIA/CUR, 1991; Latham et al., 1994). Certainly, the IBSD is becoming one of the main inputs to new blast design models. Recent research (Lu and Latham, 1996; Lu, 1997) has built on an approach that Wang referred to as ‘the equation method'. His approach provided the engineer with a practical formula and a series of look-up tables (Wang et al., 1990; Wang, 1992), an alternative to computer simulation requiring licensed software, in order to find appropriate coefficients to make up the cumulative curve for the in situ block sizes.

2. Historical Review:

Previously, Rock Quality Designation (RQD) was used to explain the in situ block sizes, the proportion of borehole core that consists of 0.1 m or more of intact length of sound rock (Deere, 1964). Priest and Hudson (1976) extended RQD to scan line survey data and proposed an analytical relation between RQD and the discontinuity frequency from the scan line survey (Hudson and Priest 1979). The RQD value obtained from a borehole or a scan line is influenced by the measuring direction. To overcome this disadvantage, Kazi and Sen (1985) suggested the use of the Volumetric Rock Quality Designation (V. RQD).

This parameter, which is similar to an average block volume, tells us little about the proportions of very small or massive blocks and the distribution of block volumes as a whole.

The ISRM (1978) suggested a Block Size Index, Ib, that is estimated by selecting by eye several typical block sizes and taking their average dimensions. Obviously Ib is semi-quantitative and has more limited use in practice. It also suggested the Volumetric Discontinuity Count, Jn, which is the sum of the number of discontinuities per meter for each discontinuity set present.

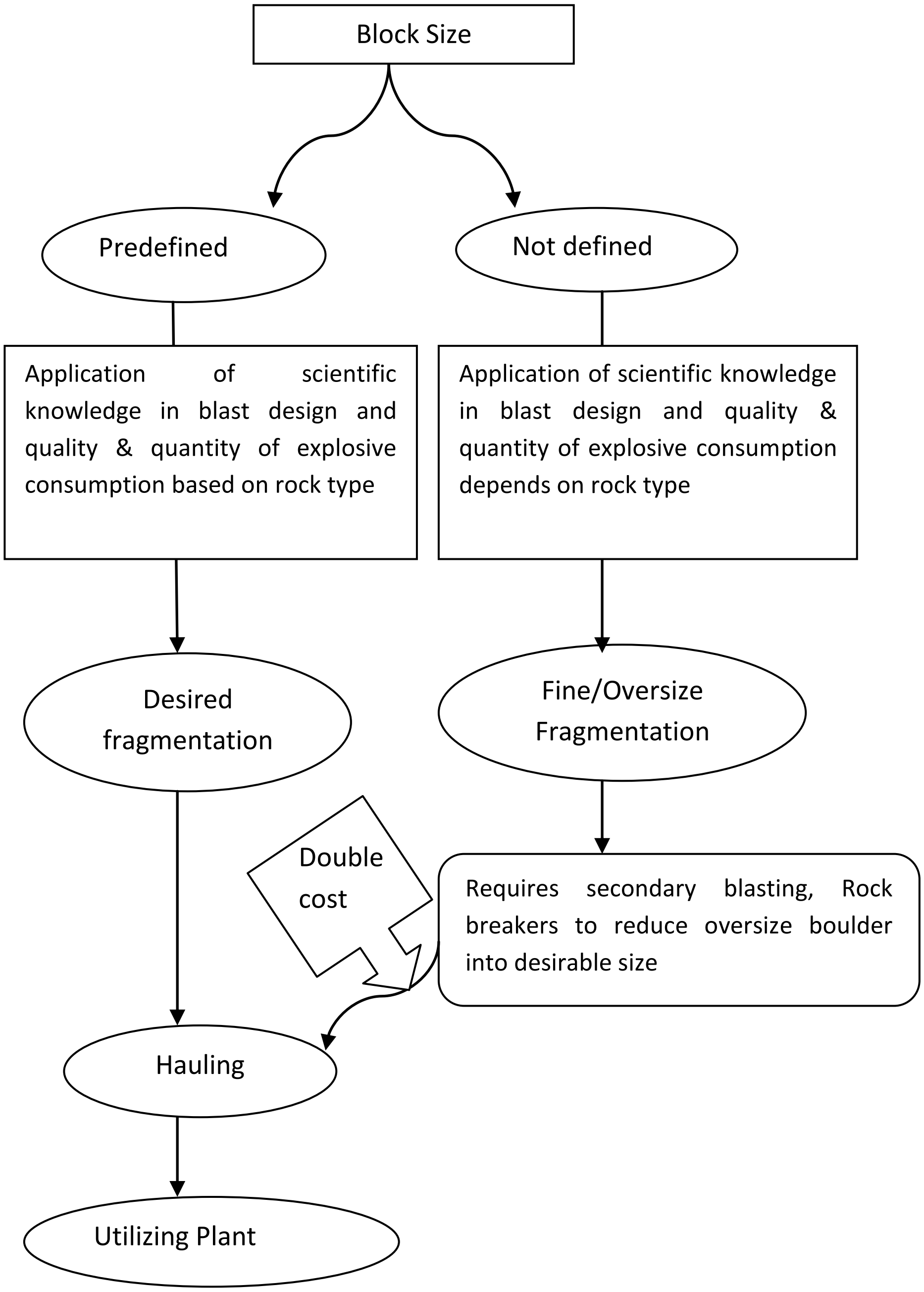

Figure 4 Importance of blasted block size on blasting costs

In recent development in the rock engineering, most of the researchers followed Wang's work, which is a general approach for deriving IBSD from simulated discontinuity network.

LU (1997) has developed a technique for predicting the IBSD of a rock mass based on fractal spacing distributions. In this technique it was assumed that all three sets of discontinuities have a fractal spacing distribution, will give an IBSD with the block sizes. Furthermore, the real IBSD should fall within the envelope formed by the lower boundary IBSD curve created with the uniform spacing distribution assumption (Figure 5) and the upper boundary IBSD curve created from the fractal spacing distribution assumption (Figure 6).

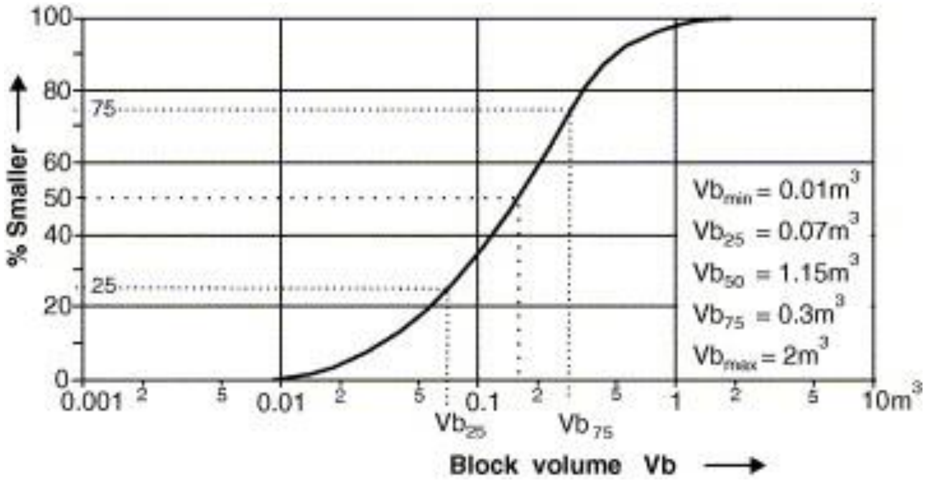

Figure 5 Example of a distribution curve for block sizes (Palmstrom, 2001)

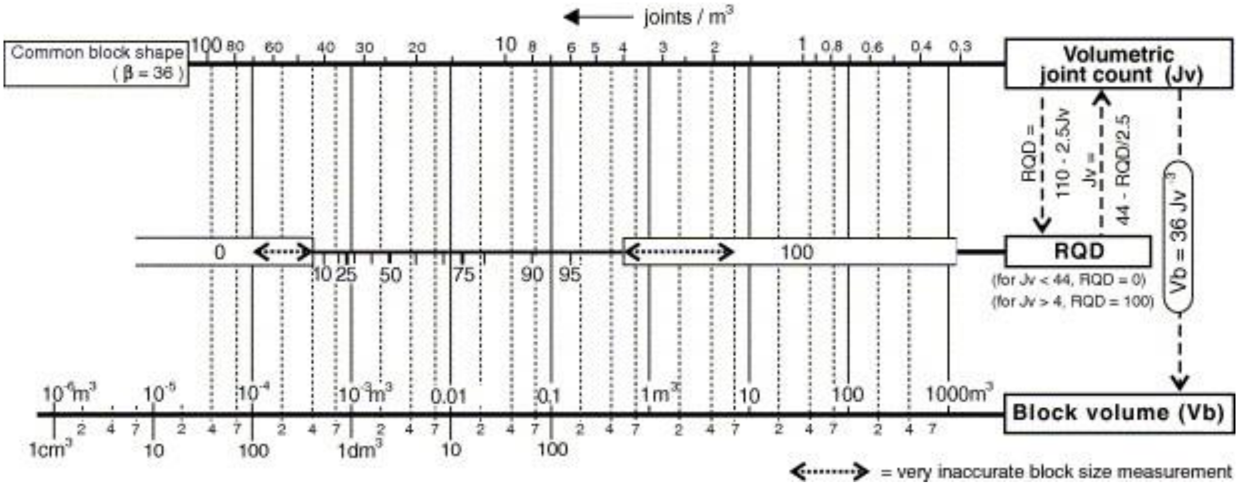

Figure 6 Correlation between different methods for block size measurement

(Palmstrom, 2001a)

A number of researchers have suggested various types of methods for prediction of IBSD. Some important methods are-discussed as under:

Miles (1972)	Examined the partitioning of space via 'sets' of discontinuities, considering several geometric configurations of infinite planes which were randomly oriented.
Franklin (1974)	Proposed a simple size strength classification in which a fracture spacing index (If), the diameter of typical block was recommended for the use of description of block size.
Da Gama (1977)	Implemented a computer algorithm to determine the volumes of in-situ blocks based on persistent representations of individual joints mapped in the field.
Hudson & Priest (1979)	Related this work to more typical geological geometries Involving three mutually orthogonal sets of persistent discontinuities.
Palmstrom (1985)	Suggested empirical equations to link Jn, RQD and linear fracture frequency, and proposed a correlation between the in-situ block size and Jn. This method could roughly estimate upper and lower ranges of block sizes.
Stewart (1986)	Developed a direct simulation of fractured rock blocks based on Discontinuity set statistics, analytical geometry and scanline mapping data.
Dershowitz (1988)	Devised a stochastic simulation procedure based on forward modeling. It repeatedly simulates a three dimensional fracture system over the sampling planes, which were the same as the surface on which the original data was collected, match sufficiently with the trace statistic of the measured data. It was claimed that this method worked well for complex fracture geometry where analytical methods prove difficult to cope with. This simulation method usually needs large exposures. Small exposures, which makes it difficult to evaluate fracture size in small exposures reliably. However, it is substantial advance as it deals with finite size discontinuities
Cojean (1990)	Developed a model was based on algorithm developed by Lin *et al*. (1987) for simulating three dimensional mass granulometry. An important advance in this model is that the connectivity of fractures, which is usually difficult to characterize, was taken into account.

Ghosh et al. (1990)	Reported one procedure to estimate the IBSD. In the procedure, the core logging, largest block, RQD and the percentage of larger than 25mm. are collectively used to estimate the IBSD assuming that the length distribution of the core fragment is representative of the IBSD. However the IBSD derived from drill hole data could be considerably underestimated since the maximum dimensions of the blocks are not often in vertical direction when cores are taken. Thus the IBSD has to be corrected.
Ord and Cheung (1991)	Described an automatic mapping system in which a video camera was used to record images produced from multiple scans of rock exposure. The information included in the images was used to establish the complete three dimensional shape of the scanned exposure. Using this system, instantaneous outputs such as the in-situ block size could be obtained in the field. This technique was based on image analysis. Therefore, the relevant equipment and a suitable field working environment have to be provided, which is considered likely that this will limits its application in practice until its accuracy has been proven to be acceptable in many working environment.
Sen and Eissa (1992)	Derived analytical expressions relating JV, RQD and block volume of different shapes such as bars, plates, or prisms, the result of which were presented in the form of charts. These charts provided a simple tool for practicising rock engineers without the need for recourse to theoretical calculations. Unfortunately, the block volumes also given in terms of average block size, and were thereby of limited use in describing the block size distribution.
Wang and his co-workers (1992)	Developed two techniques of predicting in-situ block size distribution based on location and attitude of dissecting discontinuities which sorts out the problem of block sizes and shapes formed by the dissecting discontinuities in the rock mass. In developing both the methods i.e. Dissection and equation methods, an assumption that all discontinuities within the rock masses are persistent was made. This assumption is probably acceptable for small volume of rock with highly persistent discontinuities, but the error inevitably increase with both the volume of rock mass and the persistent discontinuity in question.
Wang et. al. (1991)	Developed an algorithm to predict the volumes of blocks based on day lighting joints using the block theory developed by Goodman & Shi (1985).
Young et. al. (1995)	A matrix connectivity method was used by Young et. al. (1995) to study the effect of orientation dispersion on IBSD for three orthogonal joint sets. They concluded that as little as 10 degree dispersion in pole vectors was sufficient to fully ‘evolve’ the IBSD curve.

Maerz & Germain (1996)	Used a software package to study IBSD for some simple scenarios. Their algorithm was limited to using three sets of persistent joints.
Lu (1997)	Has developed a technique for predicting the IBSD of a rock mass for which the three sets of discontinuities have fractal spacing distributions. In this technique it was assumed that all three sets of discontinuities have a fractal spacing distribution, will give an IBSD with the largest block sizes.
Lu & Latham (1999)	Used equation-based methods to study the effect of spacing distribution on IBSD. Their analysis was limited to three sets and accounted for persistence indirectly, but they concluded that spacing distribution was an important factor.
Wang *et al*. (2003)	Provided a sophisticated software implementation of an algorithm designed to handle any number of discontinuity sets and indirectly account for persistence (assuming a persistence-spacing relationship). Their algorithm randomly chose discontinuities from a previously generated discontinuity 'database' and checked for the possibility of formation of polyhedral blocks in the rock mass.
Ahn & Lee (2004)	Attempted to account for non-persistence via analogy with the two-dimensional geometries.
Jern (2004)	Suggested that in calculating IBSD, Instead of determining the spacing of all fracture sets, three directions are chosen so that they give the best possible concordance between the governing fracture pattern and an orthogonal block model. Two directions can be simultaneously observed in a quarry wall/exposed sections; a third dimension has to be measured from a rock face perpendicular to the first face.
Kim *et al*. (2007)	Utilized a commercially available polyhedral modeler to analyze IBSD for three orthogonal sets of semi-persistent (i.e. persistent in one direction) discontinuities. They concluded that the derived IBSD for several spacing and orientations are log-normally distributed.
Rogers *et al*. (2007)	Described the use of discrete fracture networks (DFNs) consisting of polygons accurately reflecting the finite persistence of joints and other structures. Their algorithm utilized the simulated two-dimensional trace map forming on the exposure (e.g. underground cutting), identifying closed polygons on this map, and iteratively interrogating the trace maps associated with the fractures responsible for each segment of the polygons until the minimum-volume polyhedra were identified.

Elmouttie *et al*. (2011)	Outlined a new method to predict IBSD in fractured rock masses. Using realistic DFN, robust polyhedral modeling, and a Monte Carlo sampling approach, the stochastic variability in the fracture geometry can be accounted for. The method can deal with arbitrary numbers of discontinuity sets, finite persistence representations of fractures, the consequent formation of concave polyhedral, and fracture properties described via arbitrary statistical distributions.

3. Discussion:

This paper has focused on IBSD prediction on the basis of location and orientation of discontinuities. In recent work, modelling is the key tool that many authors have adopted, are primarily concerned with flow studies and jointed rock stability studies (e.g. Dershowitz and Einstein, 1988; Itasca, 1992). The UDEC programs (Itasca, 1992), based on the discrete element work of Cundall (e.g. Cundall and Strack, 1979); appear to provide the main source of rock block generator. However, as far as the authors are aware, the UDEC type block generators are potentially suitable but with UDEC it is not possible to measure the average block volumes and the IBSD of rock masses.

It has been observed that stochastic network pattern (e.g., Aler et al.,1996) has the following features: any number of discontinuity sets with their specific geometric distributions can be superimposed to create the network of fractures and blocks for study, and the spacing and orientation distributions of each individual joint set are separately accounted for. However, the visual representation of the rock mass is a stochastic one so that joint locations bear no spatial relation to a fixed origin at a field site, although the general pattern may seem realistic.

For blast modelling, this may be of little consequence. The accuracy will be poor if the theoretical best-fits cannot represent the measured spacing and trace length distributions. Expertise and a license to use sophisticated simulation software are required. Alternatively, using the dissection method, the IBSD can be well determined for a blocky rock mass with the advantage that the visual representation of discontinuities bears the same positional relationships with respect to a chosen reference origin as would the discontinuities at the field site in question. The simulation will appear to be more realistic for a rock mass with planar persistent discontinuities.

The drawbacks of the dissection method are that the influence of impersistence on IBSD is not satisfactorily included, and the implementation usually needs experience and may give long run times. The data acquisition from scan lines must be chosen optimally so as to best characterize the whole block volume. In addition, the rock mass simulation software is of restricted access. Lastly, the updated equation method with the impersistence correction as is very simple to apply and there is no need for block generation software. However, a preliminary analysis of the raw geometric data is required. This preliminary analysis mainly involves selecting the best-fit laws of discontinuity spacing distributions, which can now include fractal distributions, and estimating the principal mean spacing.

The Grey Correlation Analysis can help with the selection of the laws for discontinuity spacing distributions. Many types of scan line and area mapping surveys can be used for data acquisition. However, questions with the updated equation method remain. Possible differences in dispersion of discontinuity orientation and type of spacing distribution within the three sets cannot be accounted for at present. Also, it is assumed that three discontinuity sets can adequately characterize the rock mass geometry. This approximation often holds in practice, and grouping techniques can be applied to achieve the best three-set description. Most approaches to block creation tend to fall down in regard to structural geological mechanisms. For example, it is the episodically evolving tectonic stress fields that create the networks of natural fractures and blocks in which conjugate shear fractures and extension joint systems, including terminations of fractures against other discontinuities, are commonplace.

Stochastic models using data idealized from scan lines are not usually suited to modelling such features. The blocky rock mass generator of Heliot (1988) is one example where structural geological principles have been introduced. Lu has developed a technique for predicting the IBSD of a rock mass for which the three sets of discontinuities have fractal spacing distributions in which it was assumed that all three sets of discontinuities have a fractal spacing distribution, will give an IBSD with the largest block sizes.

4. Conclusions:

Both background to IBSD assessment and a discussion of IBSD and blocky rock mass modelling have been presented. The very simple but relatively little known methods of providing look-up tables for plotting IBSD have been further documented here. Lu has refined these methods in two important ways: by including the fractal spacing distribution, which is an increasingly popular possible choice for the best-fit model; and by reporting the relative impersistence factor that compensates for the assumption, used in the formula calibration that all discontinuities persist. Of more general interest, a novel approach to selecting the best-fit, when several theoretical discontinuity spacing distributions seem likely contenders, has been introduced by Lu.

This review outlines the progressively more sophisticated approaches to estimation of IBSD and. However, all these studies have been hindered by one or more of the following limitations in their approaches:

- Inability to accurately account for non-persistent discontinuities
- Inability to account for more than three discontinuity sets
- Detection of resulting polyhedra requires approximations and simplifications such as assumed convexity or limited numbers of facets
- Inability to access the IBSD where one face is exposed

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