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Block size determination around underground openings using simulations

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ABSTRACT: The in situ block size of the rock mass may be the single most important parameter influencing the stability and strength of some underground openings. Rock masses can often reasonably be characterized by a simple size-strength classification. The actual block size distribution is the product of the interaction between the joint orientation, spacing and persistence of that rock mass.

Despite the importance of in situ block size, it is currently difficult to quantify. Block size is typically estimated as one of three indices, Rock Quality Designation (RQD), Volumetric Joint Count (J_v), and Block Size Index (I_b). These, being index properties do not quantify actual block size.

The Centre de Technologie Noranda has initiated standardized scanline mapping techniques for the purposes of characterizing the discontinuities. This data is being used to quantify block size. Algorithms have been developed which simulate the division of a specified volume of rock by a number of joints or joint sets. These joints can be generated stochastically, based on summary statistics and inferred distributions of the field data, or deterministically, using the actual joints measured along the scanline.

1 INTRODUCTION

Block size is, in many aspects of geomechanics, one of the most critical of rock mass parameters. In terms of the stability of rock slopes and openings, it is often the only parameter needed.

Yet in most cases it is difficult if not impossible to measure directly. As a result, crude estimations of block size are typically made and incorporated into rock mass classifications.

Conceptually, block size may be considered simply the product of three simple rock mass parameters: joint set orientation, true spacing (perpendicular spacing between joints of the same set), and persistence. For every conceivable variation of these parameters either a distinct block size distribution is produced, or alternatively, the rock mass is not broken up into blocks. Of these three rock mass parameters, orientation and spacing are quite easily and routinely measured

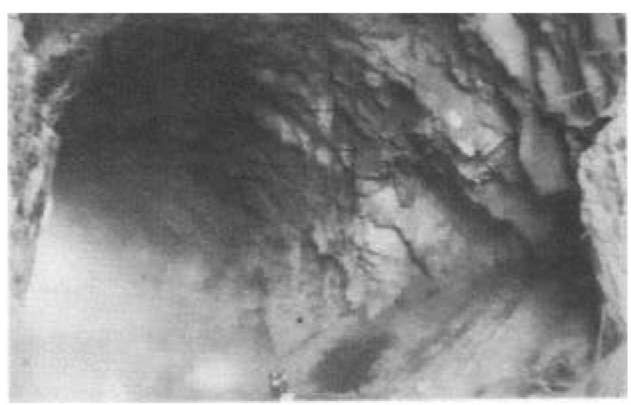

Figure 1. Blocky ground in an underground hydroelectric diversion tunnel in Mexico. A large block has failed along pre-existing joint planes

1.1 Importance of block size

The importance placed on block size in geomechanical classification schemes, is significant. In the size-strength classification (Franklin, 1986), the RMR system (Bieniawski, 1973) and the Geomechanics classification (Laubscher, 1977), fully 50% of the classification reflects block size, either directly, or through joint spacing and orientation. In the Q-system (Barton et. Al., 1974), given by the following equation, the first term, RQD/J_n, is nothing more than a crude estimation of block size:

$$Q = \left(\frac{RQD}{J_n} \right) * \left(\frac{J_r}{J_a} \right) * \left(\frac{J_w}{SRF} \right) \quad [1]$$

where RQD is the rock quality designation, J_n is the joint set number, J_r is the joint roughness number, J_a is the joint alteration number, J_w is the joint water reduction factor, and SRF is the stress reduction factor.

Hook and Brown (1980) note that the extreme values of this term range between 0.005 and 2 m, presumably in terms of block edge length.

In block caving mining applications, block size in part determines whether caving can or cannot occur. It is however not enough to know the average block size, because the largest 5 or 10% of fragments may create significant mine operating problems caused by excessive blockages at the draw points (Panek).

In blasting applications it is desirable to know the size of the pre-existing blocks in order to optimize blast design. The direction of the blast, the application of explosives energy. Back-break from the blast and ultimately fragmentation depend on the size of pre-existing blocks.

1.2 Motivation for block size simulations

For Noranda Mines, the motivation to develop methods to measure block size comes from their methods of rock mass classification, and from their method of geological mapping.

The Centre de technologie Noranda uses a modified form of the Q system (Mathews et. Al., 1980). In it, only the first two terms of the equation are used, i.e:

$$Q' = \left(\frac{RQD}{J_n} \right) * \left(\frac{J_r}{J_a} \right) \quad [2]$$

If the first term is a crude measure of block size, then it could in principle be replaced by a more objective and accurate measure.

The Centre's preferred methodology for geological mapping consists of linear scanline traverses, where joints intersecting that scanline are recorded, and entered on to a digital database. Data on joint orientation and spacing are routinely available for further analysis such as block size simulations.

2. CURRENT METHODS OF ASSESSING BLOCK SIZE

Block size is typically estimated as one of three indices. These are the Rock Quality Designation (RQD), Volumetric Joint Count (J_v), and Block Size Index (I_b). These, being index properties do not however quantify actual block size, or block size distribution. Also being index properties, there is a danger of extrapolating measurements of a small area to a larger portion of the mine.

Stereological methods which attempt to reconstruct true three dimensional size distributions from two dimensional measurements on rock cuts have been proposed (Beyer and Rolofs, 1981; Beyer and Rolofs, 1981b; Beyer, 1982)

2.1 Block Size Index

The Block Size Index I_b is estimated by selecting by eye several typical block sizes and taking their average dimensions (ISRM, 1978). In the special case of an orthogonal joint system of three joint sets, the index becomes:

$$I_b = \frac{S_1 + S_2 + S_3}{3} \quad [3]$$

where S is the spacing of each set. In this case I_b can simply be calculated from the spacing. This method is of limited use because there are not always 3 joint sets present, they are not always orthogonal, and it is often difficult to identify sets and correct spacings in the field.

2.2 Volumetric Joint Count

The Volumetric Joint Count J_v is defined as the sum of the number of joints per metre for each joint set present, and is measured along the joint set perpendicular (ISRM, 1978):

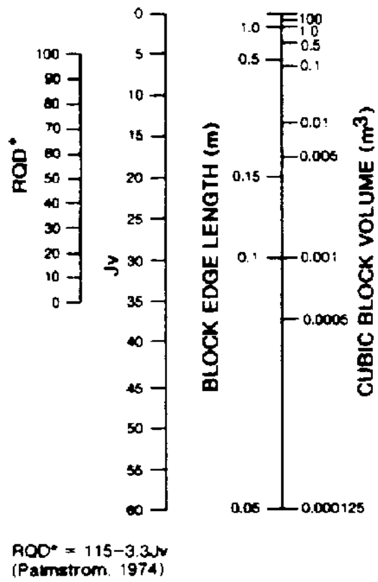

Figure 2. Relationship between RQD and block size after Palmstrom (1982).

$$J_V = \frac{N_1}{L_1} + \frac{N_2}{L_2} + \bullet\bullet\bullet + \frac{N_n}{L_n} \qquad [4]$$

2.3 Rock Quality Designation

The Rock Quality Designation RQD is defined as the percentage of drill core recovered in intact lengths of 100 mm or more (Deere, 1964). In drill core, RQD is a linear measure in the direction of drilling only.

RQD can also be estimated from joint spacing or volumetric joint count. The approximate relationship between RQD and J_v is (ISRM, 1978):

$$RQD = 115 - 3.3 J_V \qquad [5]$$

The relationship between RQD and the line intercept joint spacing (Hudson and Priest, 1979) is:

$$RQD = 100\ e^{-0.1\,l}(0.1l + 1) \qquad [6]$$

where λ (joint frequency) is the inverse of the line intercept spacing.

RQD is in some ways an ineffectual parameter because of several shortcomings.

First, it is insensitive to large and small block size distributions. Figure 2 shows that the entire span of RQD would cover blocks with cubic edge lengths between 0.08 to 0.5 m. Ground with blocks of cubic edge length of 0.5 m would have an RQD of 100, but would in many cases mean an unstable type of ground for mining applications.

Secondly, the RQD values obtained from drilling are an average over the length of a core run. For example, an RQD value of 50 could indicate a uniform block size of about 0.15 m edge length, or it could represent a rock mass with very large blocks (0.5 m or greater) that is cut by a fault or shear zone, occupying 50% of the core run.

Finally, RQD is also sensitive to sampling direction where block shapes are anisotropic.

2.4 Stereological methods

Beyer and Rolofs [(Beyer and Rolofs, 1981; Beyer and Rolofs, 1981b; Beyer, 1982) proposed to estimate the size distribution of blocks in a rock mass by measuring the apparent block size distribution on a rock cut, and by using stereological models to unfold the three dimensional distribution. Techniques such as these are frequently used to estimate size distributions in biological and metallurgical sciences(Weibel. 1980; Weibel, 1981, Underwood, 1970). This type of technique has been successfully applied to the quantification of block size distribution in muck piles of fragmented rock (Maerz, 1990, Maerz et. Al., 1987), but has not been verified on insitu block masses.

3. BLOCK SIZE SIMULATIONS

Because block sizes, are relatively difficult to measure, the alternative of using computer simulations to measure block size is very attractive. Simulations can be based on actually mapped joints, or on stochastically generated joints or joint sets.

There are two basic reasons why it is difficult to measure block size in underground openings. The first relates to the fact that only two dimensions of the exposed block can be viewed, while the third remains hidden in the rock mass. The second relates to the fact that larger blocks are only partly exposed in the underground opening.

It is relatively straight forward to build geometric block models based on joint orientations and spacing statistics, which are commonly measured in mines, tunnels, and excavations. An example of such a model is given by Peaker (1990), and is described below.

A more sophisticated model is proposed by Mathis (1988). This would be a stochastic model which incorporates a measure of joint persistence. Persistence, however important, is an elusive quantity which is difficult to define, let alone measure or predict.

The block size simulations described in this paper are based on building blocks based on joint intersections. These joints can be generated stochastically, based on summary statistics of joint sets and their inferred distributions from field data, or alternatively deterministically, using the actually joints measured along the scanline.

3.1 Field mapping

Detailed field mapping is of limited use in mines because it is time consuming. The data collected are seldom used to their full potential as an input in engineering decision.

Mapping at Noranda Mines is now limited to short scanlines. Only joints whose trace length is at least half the size of the opening are mapped, because such a persistence may have influence on the stability of the rock mass. The position along the scanline, orientation and dip of joints is the only information collected for the purpose of block size analysis. The degree of alteration and the roughness/waviness is also collected for classification purposes.

The field data is entered into a hand held computer as it is collected along the scanline.

3.2 Computer processing of field data

The field data consists of three separate but linked files. A domain file identifies the geological domain, containing a domain number and a comment if desired. A traverse file lists all traverses, their start positions in mine coordinates, and trend and plunge. A joint file lists all joints encountered along the scanline, including the associated scanline and domain identifiers, strike, dip, and joint set number.

3.3 Generation of stochastic input data

For stochastic analysis, the joint orientation and spacing data needs to be converted to measures of central tendency and distribution, in order to use Monte Carlo sampling to generate jointing distributions. The following is based on Peaker (1990).

For the orientation data, the mean normal vector for each joint set is calculated. A Fisher's two dimensional normal distribution is assumed, and fitted to the joint normals of each set. The cone angle for the 68% confidence limit is recorded.

For the spacing data, a histogram of measured spacing (for each joint set) against cumulative frequency is created. Low pass filtering is used to smooth the cumulative histogram. A list of 50 spacing variates is then generated by finding the root of the histogram curve at 50 evenly spaced frequencies, or alternatively at 50 randomly selected frequencies.

4. SIMBLOCK

SIMBLOCK is a block simulation routine developed by Peaker (1990).

The principle of SIMBLOCK is that parallelepipeds are individually formed by using all possible variations of spacing and orientation present, based on the input described in section 3.3. Only three joint sets must be present. Each block volume can be calculated as:

$$VOLUME = A * B * C * BVCF \qquad [7]$$

where A, B, C are the normal distances between the block sides (joints of sets 1, 2, 3), and BVCF is the Block Volume Correction Factor. The BVCF is a correction to calculate the volume of a parallelepiped, based on the relative angles of the sides. BVCF is equal to 1.0 for an orthogonal parallelepiped (rectangular block). The correction factor is:

$$BVCF = \frac{|(\hat{a}x\hat{c})\ x\ (\hat{b}x\hat{c})|}{[(\hat{a}x\hat{c})\bullet\hat{b}]\ [(\hat{b}x\hat{c})\bullet\hat{a}]} \qquad [8]$$

where a ,b ,c are unit vectors normal to block sides (joint sets) 1, 2, 3. The measured block volumes are summarized into classes, and the class data is written to a file for graphical output (Figure 3).

The assumptions inherent in this simulations are that three joint sets are present, joints are semi-infinite in persistence, and that all blocks are six sided parallelepipeds.

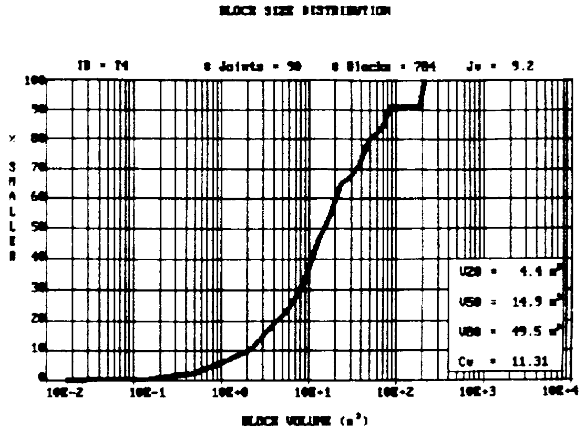

Figure 3. Block Size Distribution Graph.

5. MAKEBLK

MAKEBLK is a block simulation developed by Maerz 1990.

The principle of MAKEBLK is to sequentially and repeatedly cut a fixed volume of space (rock mass) by individual planes (joints) of different orientation and spacing. Each block consists of three linked lists, a block identifier list, a list of polygonal faces for that block, and a list of x, y, z coordinates for that face. The following is the methodology:

1. Using a defined volume of space as the first block, MAKEBLK splits it, along the plane of the first joint, (if the first joint intersects that block), creating two blocks. This is accomplished by rotation and translation and splitting algorithms.
2. Each of these two blocks are split in two by the second joint (if it intersects that particular block) to form up to four new blocks.
3. For each subsequent joint, each existing block is examined. If it is intersected by the particular joint, it is split in two.
4. Concurrently, the volume of each block is measured. At the same time, each block is flagged with the joint numbers which form the sides of that block. Each block is also flagged to determine whether it touches the edge of the defined space. The significance of this is that the blocks which touch the edge of the space are artificially truncated by the edge of the space, and thus will have truncated shapes and measured volumes which are too low.
5. The measured block volumes are summarized into classes, and the class data is written to an ASCII file for graphical output.
6. Outlines of blocks forming the perimeter of the defined space are written to an ASCII file also for graphical output (Figure 4).

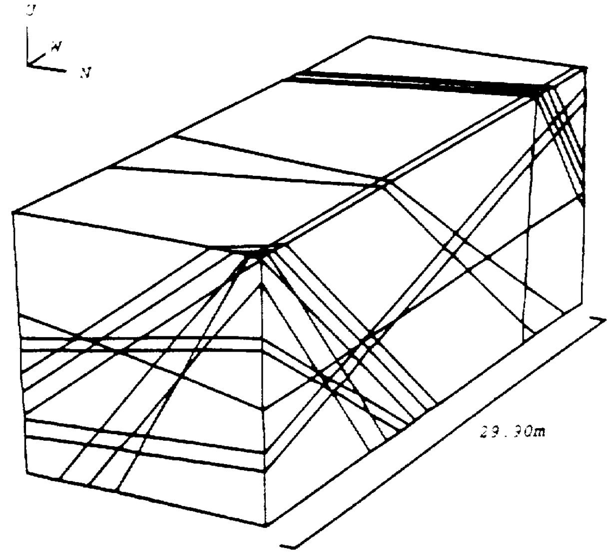

Figure 4. Graphic of the joints intersecting the outside of the simulated space.

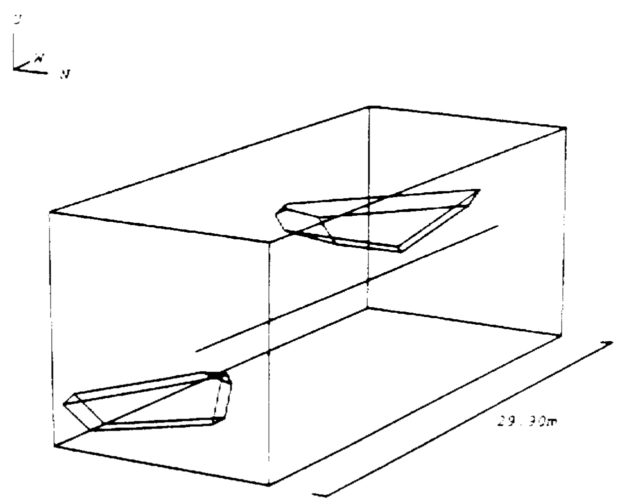

Figure 5. Graphic of two unique blocks inside the simulated space.

7. The entire data base is written to a binary file. This allows subsequent operations such as the retrieval of individual blocks for graphic output (Figure 5).
8. The defined volume of space can be "cut" at right angles to the drift, at any position along the scanline, to produce an areal cross section (Figure 6).

The algorithm can be deterministically or stochastically based or a combination of both.

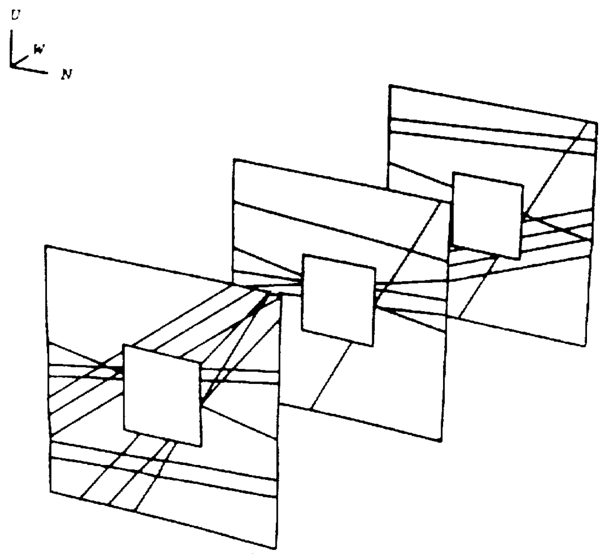

Figure 6. Graphic of three cross sections along the drift.

The deterministic analysis uses the input from the joint file of section 3.2, fitting a defined volume of space around the traverse, and extrapolating all the mapped joints throughout that space. This includes any number of joint sets and random joints. Additional joints or joint sets can be manually entered and superimposed on the space. In addition, stochastically generated joints can be used at the "ends" of the space to predict unmapped joints beyond the end of the traverse, which might project back into the defined space.

The stochastic analysis uses the input described in section 3.3, as is used by SIMBLOC. The analysis is however not limited to three joint sets, and can accommodate random joints.

Block volume calculations are based on the Gauss Divergence Theorem. The volume of each block is defined by the equation:

$$V = \tfrac{1}{3} \sum_{i=1}^{n} \vec{x}_i \bullet \hat{n}_i \; A_i \qquad [9]$$

for a block composed of n polygonal faces where A is the area of the polygon, n is a unit vector normal to the polygon, and x is a vector from the origin to any point on the polygon. The area of each polygon is calculated by the equation:

$$A = \tfrac{1}{2} \sum_{i=1}^{n} \vec{x}_i \bullet \hat{n}_i \; L_i \qquad [10]$$

for a polygon composed of n line segments where L is the length of the line, n is a unit vector normal to the line, and x a vector from the origin to any point on the line.

The assumption inherent in this calculation is that all blocks (and polygonal sides of blocks) are convex.

6. CASE STUDY

Traverses have been mapped at both the Gaspe and Brunswick mines, to evaluate the block simulation routines, and their potential for improving the estimate of block size. A composite view of the jointing pattern at the Gaspe Mine is shown in Figure 7.

The scanline mapping was done as described in section 3.1, with a typical scanline length of 15 m. Deterministic analyses were run on 5 m traverse sections using MAKEBLK. For each section, the rock mass has been classified, for tentative correlations, using the modified Q system (equation 2).

Table 1 expresses the results of the simulation in terms of average block edge length, and compares it against the Q' rating and the RQD/J_n component, determined from visual estimates.

This table shows that while RQD/J_n is a block size parameter, it is however not equivalent to the calculated mean block size based on the weighted volumetric average from the block volume distribution curves.

Block size varies from one traverse to another, and along the traverse itself. The classification ratings show a similar trend. The distinction between RQD/J_n values of different sections is less sensitive than the block sizes from the simulations. This is because in these instances, with a uniform RQD of about 100, the value of RQD/J_n depends highly on the ability of the underground observer to identify the correct number of joint sets. The actual Q' ratings suggest that a good quality rock mass will be formed with blocks averaging 0.25 m "edge length", while the simulation suggests 3.75 m blocks. From the viewpoint of the mining engineer, the first estimate of 0.25 m edge length would correspond to a very unstable ground requiring a tremendous amount of support, while 3.75 m would mean a far more stable, less fractured rock.

Note that the average block edge length in all cases is 2 m or over in all cases. If these cases were characterized by for example RQD alone, all would have values of about 100%, implying that all the above traverses are in equally very good quality rock, which is not the case.

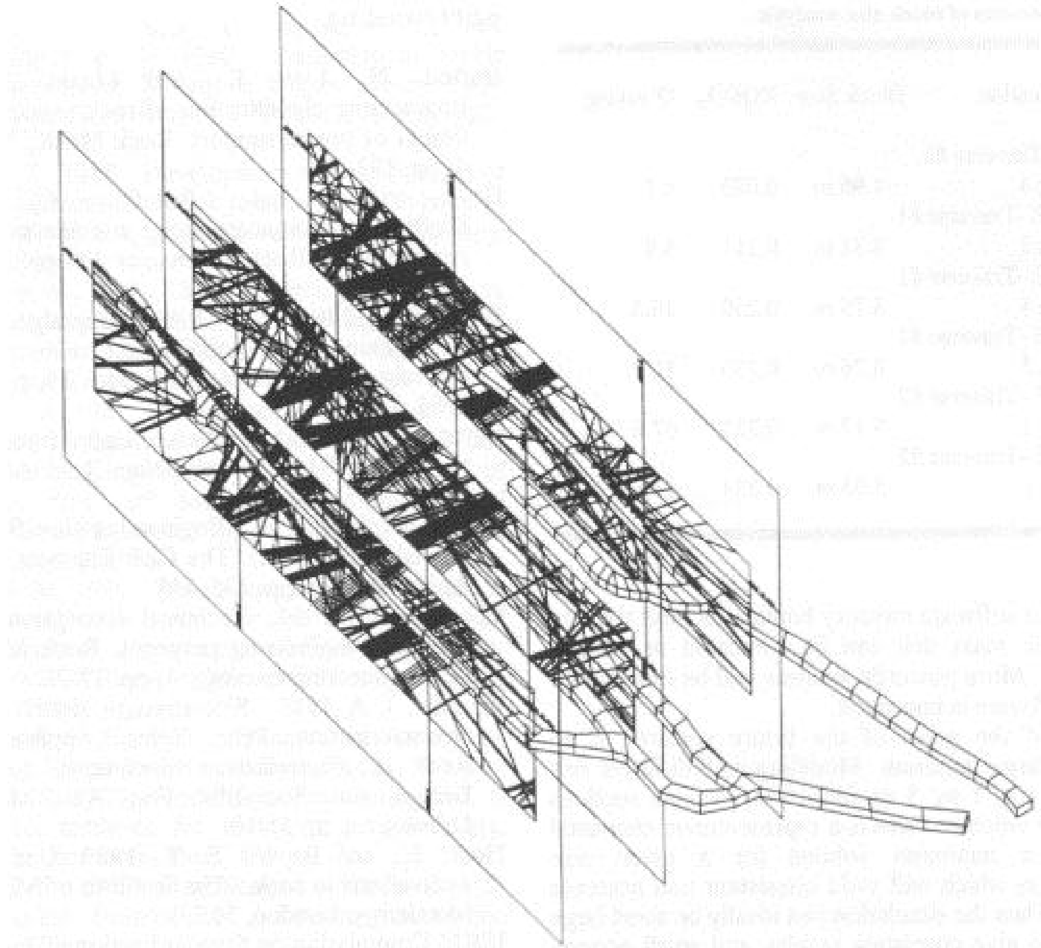

Figure 7. Composite Jointing Patterns, Gaspe Mine.

7. DISCUSSIONS

The ability to measure block size is clearly a useful tool in evaluating the rock mass and designing support for underground openings. The fact that this is a measurement and not a classification removes much of the subjectivity involved with classification systems. Unlike schemes such as RQD, there is no upper or lower limit on the size of blocks.

The ability to turn relatively straight forward field measurements quickly and easily into useful characterizations is clearly useful in the mining industry.

It can motivate the establishment of a standard scanline mapping technique as a practical tool, and provide additional justification for mapping programs in mines.

Although the simulation can be also be done on the basis of stochastically generated data, the advantage of the deterministic approach is that it can identify the exact location of critical blocks that can influence the engineering design for stability analysis or blasting practice.

The ability to determine block size would be helpful in increasing our knowledge of different types of ground by measuring its properties on a more standard basis, relying on measured values.

The actual rock mass classification process is highly subjective and requires experienced personnel. Most of the mining operations do not have that kind of manpower and must rely on external consultants. However mines do in general have the expertise to conduct adequate scanline mapping programs.

Rock engineering as a whole could benefit from this techniques. As an example, there is the possibility of somehow replacing the RQD/Jn term in the Q system with a function of an actual measured mean block size. Perhaps empirical relations between block size and maximum opening size can be determined for given rock mass types and conditions.

The algorithms described here are run on standard desktop portable computers, which are highly affordable and in general available at most mines.

Table 1. Results of block size analysis.

Identification	Block Size	RQD/J_n	Q' rating
BMS -Traverse #3			
Section 4	1.98 m	0.083	4.1
GASPE -Traverse #1			
Section 2	3.31 m	0.111	6.8
GASPE -Traverse #1			
Section 4	3.75 m	0.250	15.3
GASPE -Traverse #1			
Section 5	3.76 m	0.250	15.3
GASPE -Traverse #2			
Section 1	5.17 m	0.333	47.6
GASPE -Traverse #2			
Section 2	5.05 m	0.333	47.6

Current software memory limitations limit the size of the rock mass that can be simulated in a single analysis. More powerful analysis will be run shortly, as the software is improved.

One of the goals of the future research is to simulate larger sections. Modeling with different size sections, e.g. 1 m, 5 m and 10 m scanline sections will show whether there is a representative elemental volume: a minimum volume for a given size distribution which will yield consistent and accurate results. Thus the simulation can ideally be sized large enough to give consistent results, and small enough as not to overlap 2 geological domains. Another goal is to integrate this data with the basic mine plans, in the case of many Noranda Mines, on a digital data, typical managed by computer aided design (CAD) software.

For the blasting engineer, knowlege of insitu block size is invaluable for validation of blasting models, which often use block size as an input parameter. In addition, the engineer can use the cominution factor, the ratio of fragmentation size to insitu block size, as a measure of the efficiency of his blasting agents.

8. ACKNOWLEDGMENTS

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