Secondary Fragmentation Analysis in Block-caving mines: Assessment and Ranking of Critical Parameters Using Rock Engineering System (RES)

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Abstract

A profitable block or panel caving mining operation relies on the characteristics of the rock mass. Considering available literature on block-caving mining and application of this approach in some mines, it can be understood that assessment of rock mass caveability and fragmentation is one the most significant engineering design issues in geomechanics and mining industry. Conducted researches suggest that the caveability is not the only criterion to explain the fragmentation mechanism and probabilistic distribution of fragments in drawpoints. The identification of influencing parameters and fragmentation assessment are the prime geotechnical focus for all potential caving projects. In the caving operation, many factors, such as geometrical, geomechanical, environmental, and operational factors affect the caving and fragmentation performance. In this study, after discussing the caving process and identifying all effective parameters, the interaction matrix based on the rock engineering system (RES) is introduced to study the influencing parameters in rock mass fragmentation. The interaction matrix analyzes the interrelationship between the parameters affecting rock engineering activities. The interaction matrix for influencing parameters are established and coded by ESQ (Expert Semi Quantitative) approach. As a result, the high dominant or subordinate, and also the most interactive parameters, are introduced. The proposed approach could be a simple but efficient tool in the evaluation of the parameters affecting the fragmentation of rock mass in block-cave mines and as a result, useful in decision-making under uncertainties.

1. Introduction

The overall success and profitability of a block-caving operation will depend to a significant extent on the fragmentation produced in the ore-body during the caving process. The design and operating parameters influenced by fragmentation include (Laubscher 1990, 2000):

- Drawpoint size and spacing;
- Equipment selection;
- Draw control procedures;
- Production rates;
- Dilution entry into the draw column;
- Hangups and the need for secondary breakage with associated costs and damage;
- Staffing levels;
- Subsequent comminution processes and costs.

The prediction of rock fragmentation during block caving requires understandings of the natural fragmentation of the rock mass (caveability) and of the fragmentation processes that take place in the draw column. It is generally accepted that there are three levels of fragmentation, commencing with the in-situ blocks and then progressing to primar*y* and to secondary fragmentation.

In-situ fragmentation is represented by the blocks that are naturally present within the rock mass before any mining activity takes place. They are completely determined by the network of discontinuities pre-existing in the rock mass. More precisely, the sizes and shapes of these blocks are a direct result of the geometry of the open discontinuities present within the rock mass. Incipient or healed discontinuities having finite shear and tensile strengths do not provide faces of in-situ blocks, but rather represent planes of weakness within the rock mass on which separation may occur in the primary and secondary stages of fragmentation. The orientation, size, spacing, condition and termination are the main parameters used to describe the overall network of discontinuities.

As the undercut is mined and caving is initiated, the blocks in the vicinity of the cave back that separate from the cave back define the ***primary fragmentation***. It will result from the loading conditions imposed on the rock mass in the vicinity of the cave back. Most failures at this stage can be expected to occur on the existing planes of weakness, but under high stress or stress caving conditions, fracture of intact rock may also occur. The extent of these failures will depend on the strength of both the discontinuities and the incipient rock blocks relative to the magnitudes and orientations of the imposed stresses. The primary fragmentation size distribution produced in this case is likely to be finer than in the case of subsidence caving in which gravity rather than induced stresses causes the detachment of blocks from the cave back. To a large extent, the network of pre-existing discontinuities will govern the formation of blocks during primary fragmentation.

Secondary fragmentation will occur as the caved ore resides in, and passes through, the draw column. The nature and degree of secondary fragmentation can be expected to vary with the stress regime within the caved mass, the composition and mechanical properties of the ore-body, the rate of draw, the height through which the material is drawn and the residence time in the draw column.

It is desirable that fragmentation models be developed to provide reliable estimates of fragmentation for use in mine planning. The basic requirement of any such model is to provide a measure of the range and distribution of the sizes of the rock blocks expected to be produced at the various stages of fragmentation and, in particular, those finally reporting to the drawpoints. For prediction of fragmentation in a mass caving mine, a comprehensive analytical approach named as Rock Engineering Systems (RES), has been implied which has the ability to analyzes the interactions between the parameters affecting a rock engineering activities.

2. Assessment and classification of effective parameters in fragmentation

To assess the in-situ-, primary-, and secondary fragmentation of the rock mass, it is necessary to evaluate the influencing factors on the initiation and propagation of caving and accurate characteristic of in-situ stresses of the rock mass. Furthermore we need to evaluate the effective parameters on secondary fragmentation through draw column. By investigations of the studies made on caveability and fragmentation, the effective parameters can be divided into four category including geomechanical, environmental, geometrical and operational factors.

2.1. Geomechanical factors

Geomechanical factors including the Geomechanical properties of intact rocks and discontinuities specification are considered as the main effective factors on the caveability and fragmentation of rock mass. The geomechanical factors of the rock mass are as follows:

2.1.1. Uniaxial Compressional Strength (UCS)

Normally, rocks having lower compressional strength can have higher caveability and fine fragmentation. Since the compressional strength of rocks in the study area are different, it is necessary to divide the operational zones to different parts from similar strength point of view and the analysis should be made on each part individually (Brown, 2003).

2.1.2. Elastic modulus

Elastic modulus of rock can be static or dynamic considering the loading rate on the rock. Dynamic elastic modulus is higher than static modulus. However, as strength of the rock increases, the value of dynamic elastic modulus will be closer to the static modulus. The elastic modulus of rock indicates the deformability of the rock and similar to compressional strength is one of the key parameters in caveability and fragmentation.

2.1.3. Frequency of discontinuities in rock mass

Rocks having higher fractures frequency have more caveability. The recent studies indicate the sensitivity of fragmentation to the volume intensity of joints (P_{32}) and the importance of critical intensity value in which the in-situ and intact rock mass is converted to rock mass which can be moved (Rogers et al., 2010).

2.1.4. Aperture

Aperture is called to the distance between the two walls of discontinuities that is measured perpendicular to main plane which can be filled with materials. Aperture can have effects on shears strength of discontinuities, water transmissivity and therefore can have effect on caveability of the rock mass.

2.1.5. Persistence

Persistence is the areal extent or size of a discontinuity, and can be crudely quantified by observing the trace lengths of discontinuities on exposed surfaces. The persistence of joint sets controls large scale sliding or 'down-stepping' failure of slope, dam foundation and tunnel excavation (Einstein et al., 1983). The persistence of discontinuity among other geometric parameters of the discontinuity has the highest effect on the rock mass strength (Einstein et al., 1983). The bridges between joints planes in an intact rock basically cause to have an increase in rock mass strength.

2.1.6. Roughness of discontinuity planes

Joint surface roughness is a measure of the inherent surface unevenness and waviness of the discontinuity relative to its mean plane. The roughness is characterized by large scale waviness and small scale unevenness of a discontinuity .Discontinuities having lower shear strength are suitable for caving because they have more intension for opening and caving (Mahtab and Dixon, 1977).

2.1.7. Filling discontinuity

Filling is material in the rock discontinuities. The material separating the adjacent rock walls of discontinuities. The wide range of physical behaviour depends on the properties of the filling material .In general, filling affects the shear strength, deformability and permeability of the discontinuities. Filling is effective on rock mass caveability because this factor has a significant role on rock mass strength (Mahtab and Dixon, 1977).

2.1.8. Weathering of discontinuity plane

The natural discontinuities normally suffered weathering and alteration, which in term, also change the degree of matching of the discontinuity surfaces. It was found that the mismatched discontinuities generally have much lower shear strength than matched (interlocked) ones.

Weathering and alteration of joint plane can decrease the roughness of joint plane and therefore can decrease the shear strength of discontinuity. Thus the alteration of joint planes can increase the potential movement of blocks on each other and increase caving and fragmentation.

2.2. Environmental factors

Although the rock mass caveability is highly dependent on natural geomechanical characteristics of rock, it is also affected considerably by environmental factors. The most important effective environmental factors in caveability are ground water and in-situ stresses.

2.2.1. Ground water

The presence of water in the area can reduce the friction between joints and increase of water pressure cause increase in the caveability. The origin of water can be from ground water resources or seasonal precipitation (Laubscher, 2000).

2.2.2. In-Situ stresses

The ratio of horizontal to vertical in-situ stresses has a considerable effect on the intensity of induced stresses in cave back, cave propagation and caving rate. Despite the existence of suitable structures and geomechanical characteristics of these structures for caving of rock mass, high stresses may limit the initial caving and its propagation in the deposit. If there is no low angle discontinuities in the rock mass, the high values of these stresses can lock the blocks and create the rock mass stability against caving propagation (Brady and Brown, 2005).

2.2.3. Fine fragments proportion

The ratio of fines to medium/coarse fragmentation needs to be noted, as a high percentage of fines will cushion the larger blocks and prevents further attrition of these blocks and reduce the secondary breaking effect.

2.3. Geometrical factors

Geometrical factors such as hydraulic radius of undercut, undercut height, and block height can cause variation of induced stresses in the cave back and its propagation, if the induced factors that are effective on caveability vary.

2.3.1. Geometry of undercut

Excavation of undercut is very important for creation of initial failure in caving. A successful undercutting cause breaking and downward vertical movement of rock mass and flow downward of fragmented rocks having suitable sizes to the drawbells. A weak undercutting, leads to deformation of pillars, formation of large dimension blocks and eventually leads to lack of initial caving (kendorski, 1978). Narrow rectangular undercuts with respect to other undercuts are more suitable for forming a stable arch.

2.3.2. Undercut height

Undercut height affects the amount of induced stresses, caving propagation, the amount of caved ore to be drawn out, time to the primary production, fragmentation, and initial costs (Laubscher, 2000).

2.3.3. Draw column height

Secondary fragmentation of caved ore occurs when the ore moves downward to the drawpoint. The caving stress is the load imposed on pillars and stationary particles by the arching and direct loading of superincumbent caved material. This is likely to be significant if the height of the cave column is appreciable and there is irregular draw. The drawdown of caved material results in the formation and breakage the arches (Dorador, et al., 2014).

The blocks undergo abrasion and breakage (i.e., secondary fragmentation), which increases with draw column height. This generates rounder block shapes and smaller particles, enabling different block shape configurations and finer broken ore size distributions.

2.3.4. Drawpoint geometry

The degree of fragmentation determines the size of the draw zone and hence the drawpoint spacing. It also influences the height of the drawpoint, the need for access for secondary breaking, the shape of the major apex, the LHD size and crushing requirements. Drawpoint and drawbell design are related to the degree of fragmentation of the ore and its flow characteristics.

However, the drawpoint spacing is also a function of fragmentation. The ellipsoid of draw concept can provide the basis for the selection of an initial spacing. The application of this approach requires knowledge of the shapes and dimensions of the ellipsoid of draw and/or the limit ellipsoid. This knowledge may be obtained from model experiments (e.g. Heslop and Laubscher 1981) or from measurements made in full-scale trials or operations.

2.4. Operational factors

Operational factors affect the caveability from technical and economical point of view. The orientation and speeds of undercutting and extraction level and suitable draw of the crushed ore from drawpoints are among the effective operational factors on fragmentation (Brown, 2003).

2.4.1. Undercut direction

The shape of ore-body, distribution of grade in the ore-body, in-situ stresses, difference between the ore strengths in different zones, main structures and their orientations in the deposit and also the existence of previous cave zones adjacent to the block, are effective on the selection of starting point and advancement direction of the undercut. If the deposit is long and narrow in horizontal plan, the direction of undercutting will be in longitudinal direction (Laubscher, 2000).

The direction of undercutting in relation to the direction of main stresses is effective on the intensity of boundary stresses. For this reason to reduce the surrounding stresses in the cave back undercuts are usually excavated in the direction of main stresses (Laubscher, 2000). Advancement of caving in the direction of maximum stress can cause caving to be easier, however, only the rock masses in which support systems are installed, can bear high boundary stresses (butcher, 2000).

2.4.2. Draw rate

Control of extraction rate considerably affects caving and fragmentation behaviour of ore (Brady and Brown, 2005; Kendorski, 1978). A low draw rate will result in time dependent failure of the blocks as they are subjected to the caving and arching stresses. This is particularly important in the early stage if good fragmentation is required. The draw rate is an important factor that creates the caving space. This rate should not be high so that it causes to create an air gap and will increase probability of airburst. Weak control of the extraction rate, leads to leaving some caved rocks adjacent to walls. This can support walls and reduce the effect of undercut level. Therefore it affects caveability.

2.4.3. Anisotropic draw rate

Irregular draw is often the result of having zones of well fragmented material available, allowing for high productivity from those drawpoints at the expense of the drawpoints with coarse material. Draw control management is required not only to maximize the recovery but also to improve the fragmentation.

A uniform draw over the whole mining area means little relative movement between rock blocks compared to when zones of interactive draw are drawn on a regular schedule of one shift or one day so that high- and low-pressure areas are set up to promote differential movement.

2.4.4. Air gap

Single blocks released from the cave back can align to form numerous block arrangements. The airgap height is a relevant parameter in this regard. In the case of a negligible airgap, the blocks released from the Cave back will have less chance to rotate and thus will retain their contact with adjacent blocks. This would lead to a tighter packing and smaller initial swell factor. In contrast, the presence of a sizeable air gap would facilitate a more disordered block arrangement, increasing the initial swell factor.

2.4.5. Broken ore density

The broken ore density (BOD), commonly related to the swell or bulking factor, is an important parameter for block-caving design. It is well known that the ore column density decreases (and swell factor increases) at the drawpoint due to the development of a loosening zone generated by ore extraction. However, the broken ore in the draw column also potentially experiences stress and density heterogeneities throughout, depending on the block properties (e.g., shape, aspect ratio, and size distribution).

This generates rounder block shapes and smaller particles, enabling different block shape configurations and finer broken ore size distributions. These smaller particles migrate downwards into the draw column increasing the BOD (Dorador, et al., 2014; Elmo, 2008).

3. Rock engineering systems (RES) approach

When designing a structure to be built on or in a rock mass for mining or civil purposes, it is necessary not only to consider individual factors such as the intact rock strength, fractures, stresses, excavation and support, but also how these all interact together. As a means of linking the rock mechanics principles to the rock engineering applications, it is appropriate to consider how such interactions can be characterized. For rock mechanics modelling and rock engineering design for a specific project, the relevant physical variables and the linking mechanisms are identified and then their combined operation should be considered. Also, all the relevant factors and their interactions should be taken into account. But this vital goal is unreachable without using a guide method (Hudson, 1992).

Hudson (1992) introduced the concept of RES for rock engineering application. In order to lower down the risks to an acceptable level, there should be a decreasing in uncertainty due to the deficiency of understanding of a system.

3.1. Interaction matrices

A systematic method for thinking about all the interactions is to list them in a matrix. This is the basic device used by the rock engineering systems (RES) approach. The principal factors considered relevant to the problem are listed along the leading diagonal of a square matrix (top left to bottom right) and the interactions between pairs of principal factors form the off-diagonal terms. Then off-diagonal terms are assigned values which describe the degree of influence of one parameter on the other parameter. The assignment of these values is called coding the interaction matrix and the results are determined by carrying out calculations on the columns and rows of the matrix. Fig. 1 shows that, the parameters A and B are located in the top left and low right cells, respectively. The top right location indicates the dominance of A on B, whereas the low left is vice versa (Hudson 1992).

As an example, a 4×4 interaction matrix is shown in Fig. 2. The leading diagonal terms are rock structure, rock stress, water flow, and construction. In each of the off-diagonal terms, one example of the potential interactions is shown. The information in these off-diagonal cells is illustrative rather than comprehensive at this stage. With N leading diagonal terms the matrix will have N×(N-1) off-diagonal mechanisms (Hudson and Harrison, 1997).
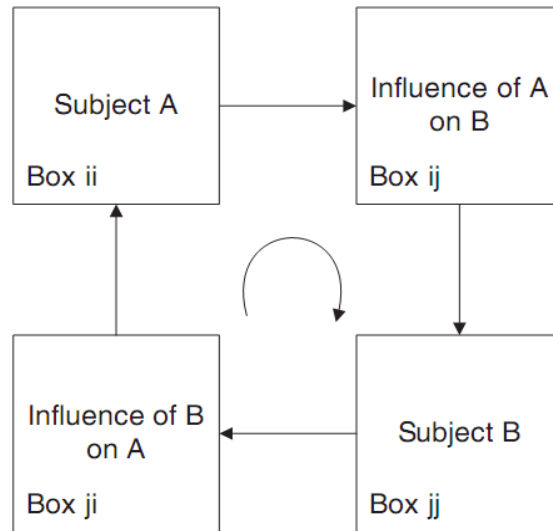
Fig 1. The principle of the interaction matrix (Hudson, 1992)

Fig 2. A 4×4 interaction matrix for mechanical parameters (Hudson and Harrison, 1997)

3.1.1. Coding the Interaction Matrix

The coding process is for propose of quantitation of interaction of parameters on each other and making up the related matrix. There are five main methods of characterizing the significance of the off-diagonal cells in the interaction matrix. These methods are:

   a)   Binary:

In binary method, mechanisms are switched on or off, as 1 or 0 respectively .The binary coding is naturally rather limited, but it can indicate the main links and the degree to which the matrix mechanisms are connected.

   b)   Expert semi-quantitative (ESQ):

The ESQ coding is helpful when the mechanisms cannot be quantified but an estimate of their significance can be made. The ESQ coding method has been used to establish parameter interactive intensity and dominance from the binary interaction matrix. There are five level of coding as shown in Table 1. In this method, coding is done by a technician or an expert, or a group of technicians.

Table 1. Concept of codes in ESQ

Code value	concept
0	No interaction
1	Weak interaction
2	Medium interaction
3	Strong interaction
4	Critical interaction

   c)   According to the slope of the linear xi vs xj state variable relation:

In this method, as it is shown in figure 3, coding is done by the case of the slope of the graph of parameters. If the graph of (Pi, Pj) is to be as a horizontal line, then Pj cannot be dependent on Pi. But if the relation between them is linear, then, their interaction could be coded in accordance to the slope of the line. Obviously, non-linearity among the factors enhance the persistence of difficulties in that most cases.
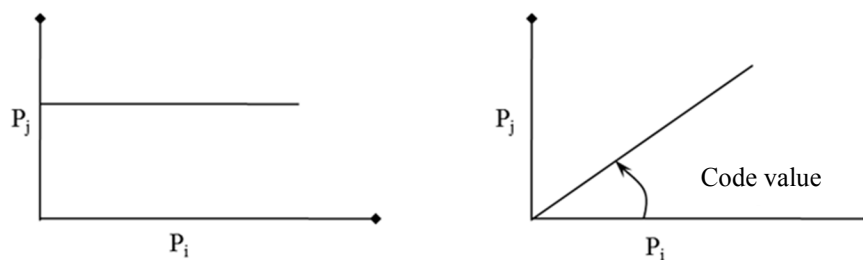
Fig 3. Coding the interaction matrix according to the slope of the line (Hudson, 1992)

   d)   Via solutions to partial differential equations:

In this method, the assumption is, all the mechanisms could be expressed as p.d.e (partial differential equations) in place of the entries of interaction matrix. Although it seems quite plausible to impose and apply second order partial differential equations solutions; yet, when the size of the matrix gets large, then

the process would be very outreaching and cumbersome. In such cases the partial differential equation ought to be solved numerically by the aids of computers.

  e) Via complete analysis of the mechanisms

In this method, it is assumed that all the mechanisms of the matrix are well known to a very high extend, therefore; the analysis of all the entries and consequently the behaviour of all interactions can be deliberated and determined.

 Among all the various methods, the ESQ method, with keeping in mind all its weaknesses, has been wonderfully successful to an accepted level, and up to the present moment (at least for the sake of simplification and being so quick to reach the solutions) has had the most number of applications.

3.1.2. Cause-Effect Plot

After coding the matrix by inserting the appropriate values for each off-diagonal cell of the matrix, the sum of each row and column can be calculated. For each parameter (e.g. for the i-th parameter, Pi), the sum of its row values is termed the "cause" (Ci) value, whereas the sum of its column values is called the "effect" (Ei) value (see Fig. 4). Such information can be summarized as coordinates (Ci,Ei) on a cause–effect plot, where each point in the graph represents a particular factor Pi. In other words, Ci represents the way in which Pi affects the rest of the system and Ei represents the effect that the rest of the system has on Pi, which is related to the parameter being "dominant" (lower right region of the (C,E) plot) or to the system being "dominant" (upper left region). Besides, knowledge of Ci and Ei can be employed to compute the level of interactivity of each parameter Pi (computed as the sum of Ci+Ei) (Hudson 1992).
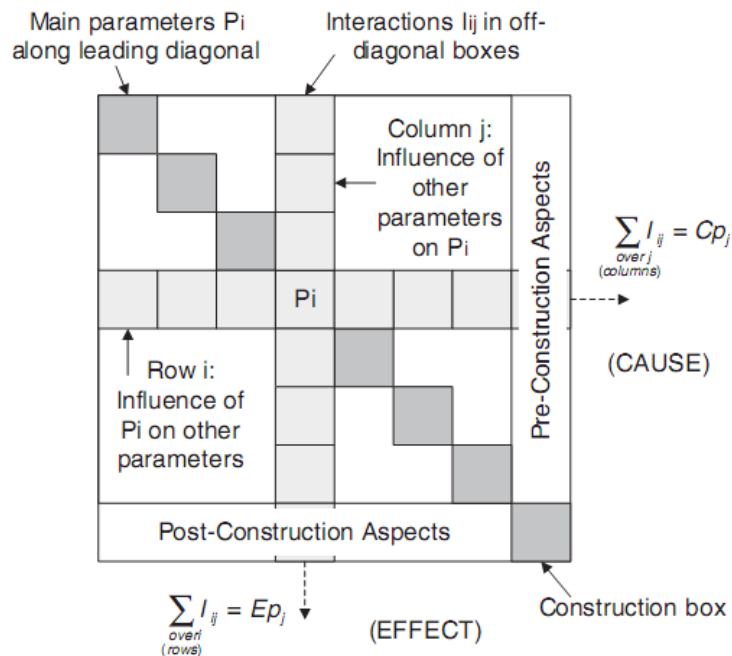
Fig 4. Summation of coding values in the row and column through each parameter to establish the cause and effect coordinates (Hudson and Harrison, 1992)

Obviously for each parameter, whatever the sum of the (C+E) be more, the more interaction intensity related to the whole system will be enhanced; whereas, the more subtracted number (C-E) is, the less dominance of the parameters on the system is revealed. The negative sign of (C-E) indicates the

dominance of the system over the prevailing parameters. Different values for each of the parameters could be transformed on the graph of cause and effect. In Fig. 5, the graph (C,E) has been generalized to N observable parameters. In such case the parameters appear like a cloudy type distributed in E and C space which shows a high complexity of a system. It is very important to note carefully to the location of each points which represent the main parameters of the system to develop and enjoy usefully the theory of the systems, described in this section.
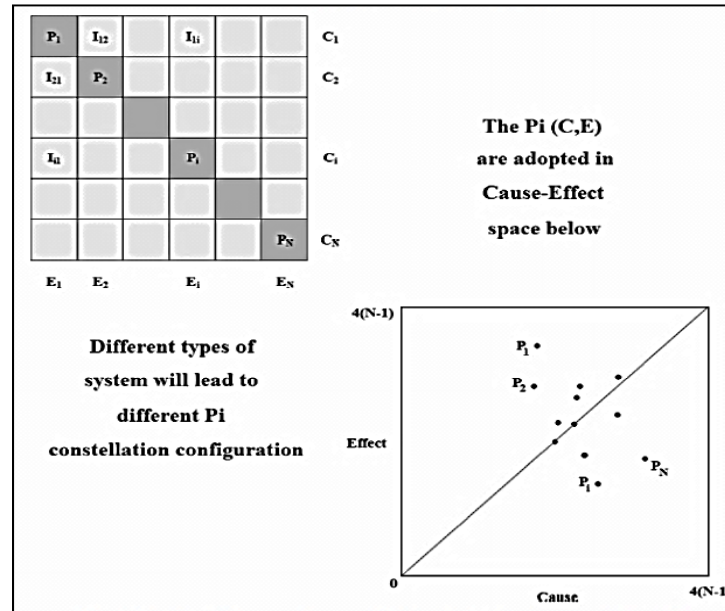
Fig 5. Cause versus effect diagram generalized for N parameters (Hudson, 1992)

3.2. Introduction of effective parameters on caveability in mass caving method

As it mentioned before, the effective factors on caveability can be divided in four main groups:

Geomechanical considerations

- Uniaxial compressive strength
- Elastic modulus
- Fracture Frequency of joints in rock mass
- Aperture of the joints
- Persistence
- Roughness of the joints surfaces
- Joint Filling
- Weathering of the joints surfaces

Environmental considerations

- In-situ Stresses
- ground water
- Fine ratio

Geometrical considerations

- Hydraulic radius

- Undercut height
- Draw Column Height
- Drawpoint geometry

Operational considerations

- Undercut direction
- Draw rate
- Anisotropic draw
- Air gap
- Broken Ore Density

3.3. Determination of interaction matrix

After investigation and definition of effective parameters on caveability, a square matrix (22×22) is formed as the interaction matrix as shown in Table 2. 21 effective parameters on fragmentation in addition to fragmentation potential are set on the main diagonal part of the interaction matrix. Then the other cells of the matrix are coded using expert semi quantitative method in which the view of experts in mass caving method is expressed.

The cause and effect values corresponding to each parameter can be represented as a point in a cause-effect coordinate system. Note that in this space the diagonal of the diagram is the locus of C=E. Along this diagonal and as we move away from the center of the coordinate system, the summation C+E increases. Then, the lines of equal interaction intensity (i.e. C+E values) can be plotted on the diagram allowing discrimination between less-interactive and more-interactive parameters. The cause-effect plot is helpful in understanding the behaviour of each parameter individually as well as studying the whole system. For example, the points tend to distribute perpendicularly to the C=E diagonal show low level of interactivity between parameters, whereas a high interactivity will result in the points distributed along the main diagonal (Mazzoccola and Hudson, 1996). So as shown in Fig. 6, filling has the least interaction in system and in-situ stresses, caveability and drawpoint geometry are the most interactive parameters respectively. Also it is shown that fracture frequency, in-situ stresses and uniaxial compressive strength are the most effective (dominant) parameters on system respectively and air gap is the most subordinate parameter in system (have minimal impact on system).

As shown in Fig. 6, a large data scatter along the main diagonal is observed, which mean a high level of interactivity between parameters.

The values of cause, effect, and interaction intensity,(C+E) for each parameter is displayed in a column chart in figure 7. Considering the column chart shown in Fig. 7. The obtained results show:

i.   In the class of geomechanical parameter, fracture frequency and uniaxial compressive strength have the highest effect on the fragmentation. Moreover, among the parameters in this group roughness and alteration of joints are the most dominated by system.

ii.   In the class of environmental factors, in-situ stresses have the highest cause and the highest effect and are the most interactive parameter in the system as well.

iii. In the class of geometric factors, the drawpoint geometry has the highest cause, effect and interaction intensity in the system among the factors in this class.

iv.   Among operational factors, the factor of draw rate has the highest cause and the highest effect and also is the most interactive parameter in this class.

Table 2. Interaction matrix of dominating parameters over caveability and fragmentation in block caving

|																						Cause	C+E
ucs	1	1	0	2	2	0	3	3	1	3	2	1	0	2	0	0	0	4	1	3	3	32	42
1	Elastic modulus	2	1	1	1	0	1	3	0	2	2	1	1	2	0	2	1	3	1	1	1	27	29
2	0	ff/m	0	2	0	0	2	3	4	4	3	2	0	3	0	2	2	2	2	4	4	41	47
2	0	0	Aperture	2	3	2	2	2	3	3	0	2	0	0	0	1	0	0	2	2	1	27	35
0	0	1	2	persistence	2	1	1	2	3	3	2	1	1	1	0	2	1	2	0	2	2	29	40
0	0	0	0	1	Roughness	0	0	1	0	3	0	0	0	0	0	0	0	2	0	3	2	12	27
1	0	0	2	0	2	Filling	1	1	1	2	0	0	0	3	0	0	0	0	0	1	2	16	21
3	0	0	1	0	3	0	alteration	1	3	3	0	0	0	2	0	0	0	1	1	2	1	21	36
0	0	2	2	3	0	0	1	Stress	3	4	4	1	0	1	0	2	1	2	4	3	2	35	80
1	1	0	0	0	2	2	3	2	Water	2	0	3	3	1	2	1	1	1	1	2	2	30	53
0	0	0	0	0	0	0	0	4	0	HR	0	2	1	0	2	0	1	2	3	4	1	20	60
0	0	0	0	0	0	0	0	3	1	3	Undercut Height	1	0	0	1	0	2	2	0	4	3	20	33
0	0	0	0	0	0	0	1	3	0	1	0	Draw rate	3	2	4	3	2	3	1	1	2	26	59
0	0	0	0	0	0	0	0	2	0	1	0	2	Uniso draw	3	2	2	2	2	1	0	3	20	44
0	0	0	0	0	0	0	0	2	2	0	0	2	2	Fine ratio	0	0	3	2	2	0	3	18	51
0	0	0	0	0	0	0	0	2	0	0	0	2	2	3	D C H	4	3	3	0	0	2	21	39
0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	4	Air gap	3	0	0	0	4	14	36
0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	0	0	B O D	2	2	0	3	13	43
0	0	0	0	0	0	0	0	1	0	0	0	4	3	1	2	3	3	Drawpoint Geometry	3	0	2	22	63
0	0	0	0	0	0	0	0	3	0	3	0	3	2	1	0	1	1	2	Undercut Direction	4	2	22	52
0	0	0	0	0	0	0	0	4	2	3	0	2	1	2	1	2	4	3	1	Caveability	3	28	65
0	0	0	0	0	0	0	0	2	0	0	0	3	2	3	0	2	3	4	3	1	fragmentation	23	69
Effect																							
10	2	6	8	11	15	5	15	45	23	40	13	33	24	33	18	27	30	41	30	37	46		
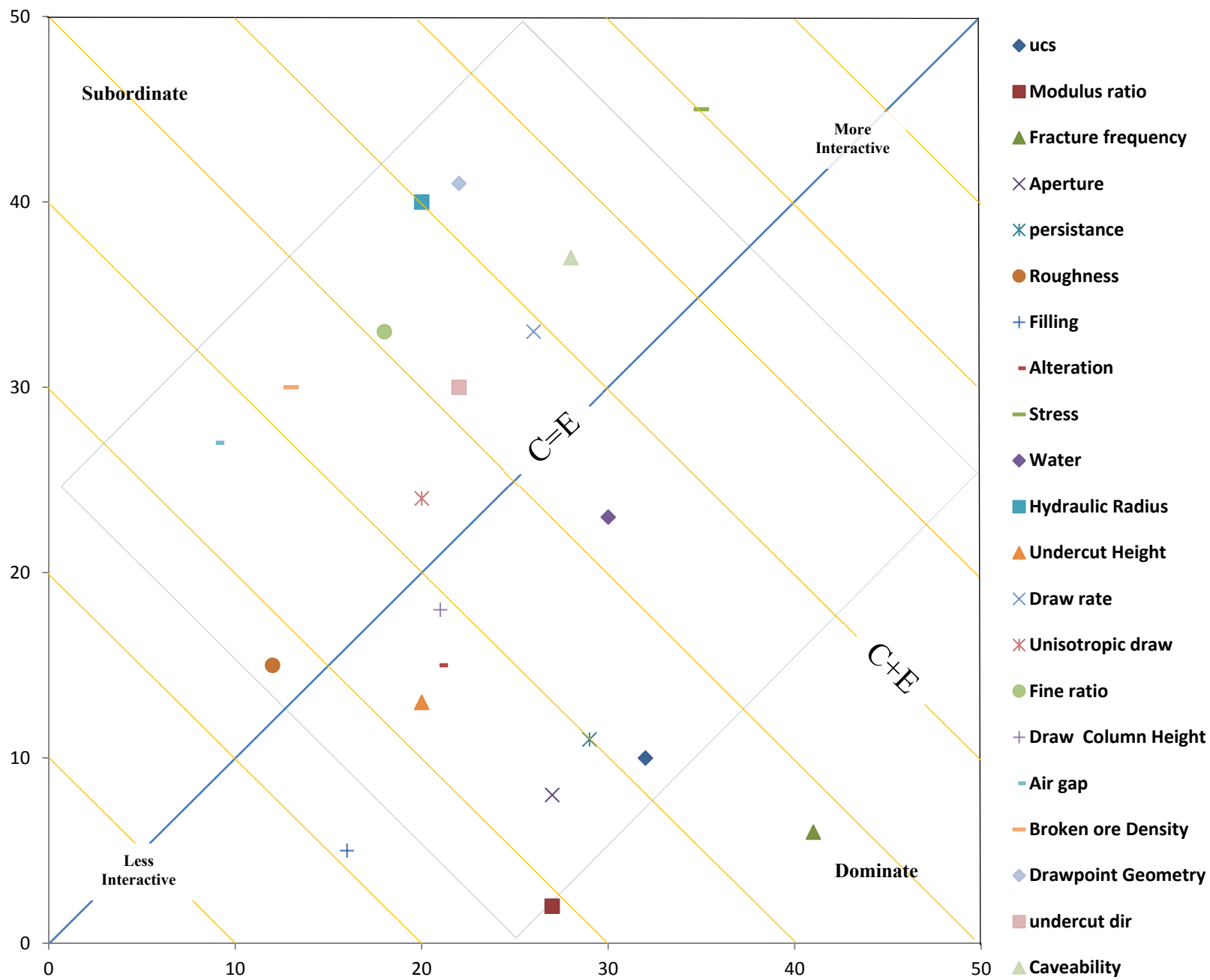
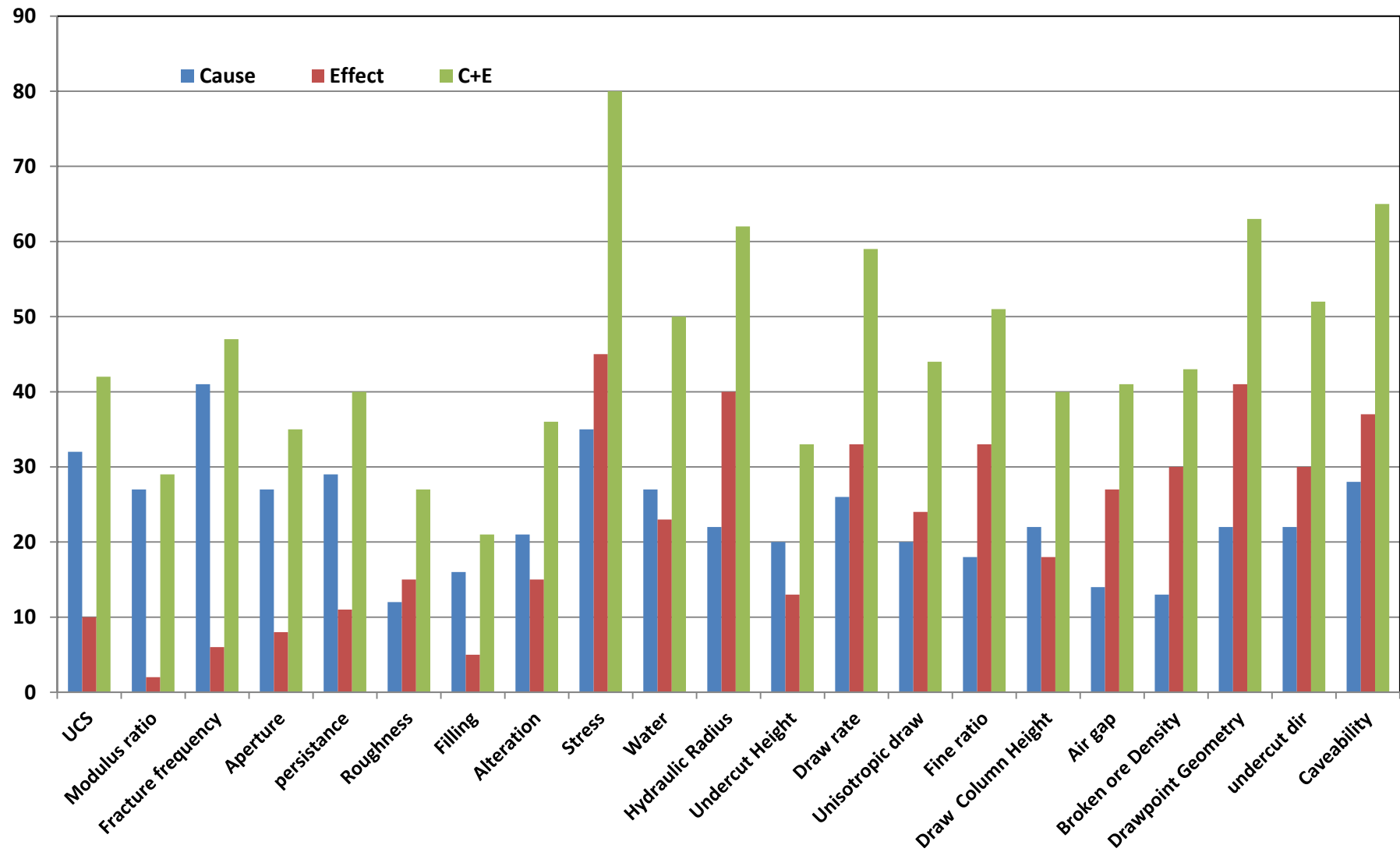Fig 6. Cause- effect diagram for ranking fragmentation

Fig 7. The histogram of domination of parameters on fragmentation

In general, as can be seen from the column chart in Fig. 7, the most dominant parameters, affecting fragmentation are: fracture frequency, stress, uniaxial compressive strength of intact rock, and persistence, respectively.

As noted, three parameters out of the four parameters that have the highest cause on the system are among geomechanical parameters. Therefore, we can surely say that geomechanical parameters and specially parameters related to discontinuities specifications have the highest effect on the system.

Geometrical and operational parameters in addition to having the highest effect compared to the other factors have also the highest interaction in the system compared to other classes of the factors.

3.4. The determination of fragmentation Index (FI)

By the time an interaction matrix is made and a (C+E) graph is drawn (the interaction intensity), a general function that covers all the effective parameters on the system could be obtained. In general, systems that are more under the effects of parameters, the more instability is expected for them, Since a little change in one parameter, makes it probable to observe a drastically changes in the behaviour of the whole system. By observing the histogram of domination of parameters in Fig. 7, it could be noted that in the most parameters the interaction intensity, (C+E), is far above the mean value. Therefore, all the parameters should be noted carefully in determining and designation of fragmentation index. In each project based on RES, each single parameter has a particular weight and portion considering the interaction matrix regardless of the real quantity of each parameter. The weight or portion of the parameter P_i, is calculated by equation (1). By dividing the portion of each parameter to the largest score that could be gained by parameters in the scoring system of the interaction matrix, the normalized weight of that parameter is obtained by equation (2).

$$W_{P_i} = \frac{(C+E)_i}{\sum_{i=1}^{n}(C+E)_i} \times 100 \tag{1}$$

$$a_i = \frac{1}{MP_{ij}} * \frac{(C+E)_i}{\sum_{i=1}^{n}(C+E)_i} \times 100 \tag{2}$$

In which;

W_{P_i} the weight or the portion of the parameter p_i, percent wise,

MP_{ij} the maximum score that the parameters could receive in the scoring system

$(C+E)_i$ the sum of the dominance and effect of the ith parameter

$\sum_{i=1}^{n}(C+E)_i$ the sum of Cause and Effect of all the parameters

For each certain block caving mine, the related score to each parameter should be determined. To clarify, a table is presented for some effective parameters. In Table 3, the parameters are categorized in five classes. It must be clear that the classification of parameters of the system is very important as far as the outcome results are concerned, due to the fact of their effectiveness on the entire system. Hence, there has been an extensive and serious study on the variation of the chosen parameters in the block-caving mines under progress. For some other parameters it is not possible to make a classification like Table 3, due to low case study and real data from previous works. In such situation we should use experts' comments. Table 4 shows the evaluation of quality of joint orientation in block-caving mines.

The fragmentation Index (FI) for each mine block should be under taken individually and separately; even for the blocks with different sections and various conditions, the index should be calculated for each section.

In order to know whether the gained fragmentation index indicates appropriate fragmentation or not, it requires real data from different block-caving operations for preparing a classification into at least three fragmentation indices; well fragmented, fair fragmented and poor fragmented. It should be noted that this part of the research has not finished yet.

4. Conclusion

After ranking of the parameters are done properly by RES method and knowledge about the amount of dominance, subordinate and interaction intensity of the parameters on the whole system, so that in case of necessity some proper changes in parameters could take place to conduct the system toward desired goals.

In order to select appropriate parameters to improve the condition of the system, the first step is to do the ranking based upon the dominance of the parameters themselves. Logically, preference is with those which have more dominant on system.

The interaction of a parameter with the rest of the system is on the second importance. Although, it must be noted that the interaction of on parameter with the rest of system, has to in the direction so that the whole system become in a better condition and it reaches to its desired goals.

The final precedency of the parameters is to be done considering technological and economic aspects. In the last stage, before enhancing the decisions to the final operations, it is wise to estimate the amount of changes in the system, using the obtained index by RES method.

The ranking of the parameters based on the interaction intensity are in-situ stress, drawpoint geometry, hydraulic radius, draw rate, undercut direction, and fracture frequency, respectively. In order to make some changes in fragmentation and caveability, some changes should be done in those parameters which have more dominancy, beside more interaction intensity in system. Whatever the dominance and interaction intensity of parameters be greater, it is possible to make greater change in system with a little change in that parameter. So in case of fragmentation in block caving, according to the rankling of the parameters the following changes can be suggested:

For in-situ stresses, in the environment with high horizontal stresses, there could be a way to get around the problem by excavation of high slots at the boundary of the blocks in order to increase the caveability.

In the group of geometrical parameters, the fragmentation, dilution, and mud rush will get in better condition by inducing the changes in the geometry of drawpoints. The primary fragmentation could be in controlled by changing the hydraulic radius through increasing the ratio of width to the length of the undercut or by creating a larger undercut or even changing the method of undercutting.

In the group of operational parameters, as mentioned before, the change in the draw rate and also anisotropic draw from the adjacent drawpoints help to control the fragmentation. The improvement in fragmentation related to the direction of undercutting is also doable, by advance in the direction of maximum main stress. The fracture frequency could be changed in order to induce primary fragmentation and initiating of caving, by using some artificial methods; like hydraulic fracturing and blasting.

It's always possible to do some proper changing for one or few parameters in order to get close to the desired fragmentation. Selecting the proper parameter, amount of change and estimation of consequence fragmentation could be done by calculating the fragmentation index (FI) after each change in parameters and comparison of the gained FI with FI of an existing mines. Evidently, for the determination of the parameters in order to create a change in any system, the economic and technological aspect of those changes ought to be under consideration.

Table 3. The classification of the parameters in the system developed to estimate fragmentation

Parameter	Unit	Class				
		0	**1**	**2**	**3**	**4**
UCS	MPa	>250	100-250	50-100	25-50	<25
Modulus ratio	-	<200	200-300	300-400	400-500	>500
Fracture Frequency	1/m	<1.6	1.6-5	5-12	12-20	>20
Aperture	mm	Without opening	<0.1	0.1-1	1-5	>5
Persistence	m	<1	1-3	3-10	10-20	>20
Roughness	-	Very rough	Rough	Rather rough	smooth	Slickensided
Filling	mm	Without filling	Very hard filling<5mm	Hard filling >5	Soft filling >5	Very soft filling <5
Weathering	-	Without weathering	Few weathering	Rather weathered	weathered	Strongly weathered
In-situ stresses	MPa	<50	50-100	100-200	200-400	>400
Ground water	-	Completely Dry	Damp	Wet	Dripping	Flowing
Hydraulic radius	m	<15	15-30	30-45	45-60	>60
Undercut height	m	<13	13-15	15-17	17-20	>20
Draw column height	m	<100	100-150	150-200	200-250	>250
Undercut direction	-	Very unfavorable	unfavorable	fair	favorable	Very favorable
Draw rate	t/day/m^2	<0.3	0.3-0.67	0.67-0.75	0.75-0.8	0.8-1

Table 4. The evaluation of the quality of oriented joints in the block caving mines

Category	Description
Very undesirable	Two joints sets or less with the slope of 60 to 90º degree.
Undesirable	Two joint sets. One set is relatively perpendicular. The others with the slope of 30 to 60º
Fair	At least three joint sets. One group with slope of 10 to 30 degree (the direction of the slope is against the direction of undercut). Two sets with slope above 60º
Desirable	At least three joint sets. One set with the slope of 10 to 30 degree (the direction of the slope is the same as that of the undercut). Two sets with cross each other with slope above 60º
Very desirable	At least three joint sets. One set with the slope of 0 to 10 degree. Two others crossing each other with slope above 60 º.

Table 5. Determination of the fragmentation index (FI)

	P_i	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	P_{19}	P_{20}	P_{21}
Proportion of P_i (%)	$\frac{(C+E)_i}{\sum_{i=1}^{n}(C+E)_i} * 100$	4.38	3.02	4.90	3.65	4.17	2.81	2.19	3.75	8.33	5.21	6.46	3.44	6.15	4.58	5.31	4.17	4.27	4.48	6.56	5.42	6.77
Normalized proportion of P_i	$a_i = \frac{1}{MP_{ij}} * \frac{(C+E)_i}{\sum_{i=1}^{n}(C+E)_i} * 100$	1.1	0.76	1.23	0.91	1.04	0.7	0.55	0.94	2.08	1.3	1.62	0.86	1.54	1.15	1.33	1.04	1.07	1.12	1.64	1.36	1.69
Score of P_i for a special case study (assumed)	p_{ij}	3	2	4	3	3	3	2	3	2	1	2	2	2	3	0	4	0	1	2	1	4
Proportion of parameter P_i in (FI)	$a_i * p_{ij}$	3.3	1.52	4.90	2.73	3.12	2.1	1.1	2.82	4.16	1.3	3.24	1.72	3.08	3.45	0	4.16	0	1.12	3.28	1.36	6.76
Fragmentation index (FI)	$FI_j = \sum_{i=1}^{n} a_i * p_{ij}$						55.22															

5. References

[1]   Brady, B., & Brown, E. T. (2005), "Rock Mechanics for underground mining", third edition. Springer Science and Business Media, Inc.

[2]   Brown, E. T. (2003), "Block Caving Geomechanics", Australia. Julius Kruttschnitt Mineral Research Centre .

[3]   Butcher, R. J. (2000), Block Cave Undercutting Aims, Strategies, Methods and Management.

[4]   Dorador, L., Eberhardt , E., Elmo, D., Norman, B. (2014). "Influence of secondary fragmentation and column height on block size distribution and fines migration reaching drawpoints", *3rd International Symposium on Block and Sublevel Caving (Caving 2014), Chile,* pp.128-137.

[5]   Einstein, H. H., Veneziano D., Baecher G. B., O'Reilly K. J. (1983), "The effect of discontinuity persistence on a rock slope stability", *International Journal of Rock Mechanics and Mining Sciences, 20, 5*, pp. 82-94.

[6]   Hudson, J. (1992), "Rock Engineering Systems: Theory and Practice", Ellis Harwood Ltd, Chchester.

[7]   Hudson, J., & Harrison, J. (1992), "A new approach to studying complete rock engineering problem", *Quarterly Journal of Engineering Geology,* pp. 93-105.

[8]   Kendorski, F. S. (1978), "Cavability of ore deposits", Mining Engineering, pp. 628-631 .

[9]   Laubscher, D. H. (2000). A practical manual on block caving. Section 6 - Cavability. International Caving Study, Julius Kruttschnitt Mineral Research Centre, University of Queensland, Australia.

[10]   Laubscher, D.H., (1981), "Selection of Mass Underground Mining Methods, Design and Operation of Caving and Sublevel Stoping Mines", SME. AIME, Stewart, New York, P 23- 38.

[11]   Laubscher, D.H., Jakubec, J., (2000), "The MRMR Rock Mass Classification for Jointed Rock Masses", Chapter 57, pp 475–481, Society of Mining Engineers, AIME, 2000.

[12]   Laubscher. D. H., (1990), "A geomechanics classification system for the rating of rock mass in mine design", J. S. Afr. *Inst. Min. Metall. vol. 90, no.10*

[13]   Mahtab, M. A., & Dixon, J. D. (1977), "Influence of rock fractures and block boundary weakening on cavability", *Trans Society of Mining Engineers of the AIME*, pp. 6-12 .

[14]   Mazzoccola, D., Hudson, J. (1996). A comprehensive method of rock mass characterization for indication natural slope instability. *Quarterly Journal of Engineering*, pp. 37-56.

[15]   Rogers, S., Elmo, D., Webb, G., & Catalan, A. (2010), "A DFN based approach to defining insitu, primary and secondary Fragmentation distributions for the Cadia East panel cave project". *Proceedings of 2nd Int. Symp. on Block and Sublevel Caving, Perth, Australia,* pp. 425-439.

[16]   A. Vyazmensky, A., Elmo, D., Stead, d., and Rance, J., (2008), *"*Numerical analysis of the influence of geological structures on the development of surface subsidence associated with block caving mining". *Proceeding of Massmin 2008, lulea, Sweden*, pp.857-867.