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Incorporating DFN Analysis in Rock Engineering Systems Blast Fragmentation Models

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ABSTRACT: The Rock Engineering System (RES) approach provides a framework for geotechnical engineering design, and has been used successfully to support a wide range of rock engineering. RES solutions require the identification of the principal parameters that play a role in the process under examination. The relationship between these parameters and other related variables are then assessed to form an interaction matrix that represents the system. Previous studies have considered blast optimization using an RES approach. However, these approaches consider few details regarding the existing fracture network. How a rock mass reacts to a blast is dependent on the rock itself and on the discontinuities within the rock mass. A set of discrete fracture network (DFN) realizations generated and assessed using MoFrac are used to derive inputs for a RES fragmentation interaction matrix. Parameters representing block size and rock mass integrity derived from fracture network models are identified that can be incorporated into a RES solution. A new parameter for inclusion in existing solutions measuring fracture intensity variability is also presented. From analysis of a fracture network, estimations of in situ block size distribution, fracture set intensity, and variability are presented that can be integrated in a RES approach to blast optimization.

. INTRODUCTION

There are two groups of parameters that affect rock fragmentation by blasting. Controllable parameters include blast design, explosive energy, and blast timing. Uncontrollable parameters relate to the physical properties of the intact rock and rock mass as a whole (Faramarzi, *et al.*, 2013b); these parameters affect the energy required for fragmentation, which is the reduction in particle size.

Bond's comminution theory has been applied to blasting, crushing and grinding. It has been shown that Bond's theory predicts approximately a third of the energy that is generally required for fragmentation by explosives (Eloranta, 1997). This fact indicates that there is the potential to optimize blasting practices to utilize less energy (explosives), thus reducing the required powder factor to fragment rock masses. Eloranta (1997) also showed that blasting has a cost advantage over crushing by as much as 3:1. This is surprising when considering that the cost per unit energy is about five times higher for explosives when compared to electricity for crushing. With optimization based on the rock mass, blasting could have an energy efficiency advantage of 15:1 when compared to crushing. To improve energy efficiency, reduced powder factors could be implemented with fewer drill holes or lighter loading.

This paper will focus on identifying parameters from discrete fracture network (DFN) models that can be used to study the effect of *in situ* fractures on blasting outcomes. Most rock masses contain discontinuities of some sort and are initially fragmented before blasting. A fracture creates an imbalance in the distribution of explosive energy through a rock mass (Singh, 2005). Explosive energy can be split into shock and gas energy. Shock waves are attenuated as they pass a joint plane. An open joint plane can attenuate a stress wave by as much as 30% (Mandal *et al.*, 2008). Dick (1992) found similar results through a series of test blasts: discontinuities only transmitted about 60% of the blast peak particle velocity (ppv), accounting for significant lost energy. Discontinuities also cause multiple reflections and refractions of shock wave energy, whether they are tight, open, or filled (Singh, 2005).

Rock fragmentation is controlled by both the rock matrix and rock mass properties, blast design, and explosives used (Thornton, *et al.*, 2002). Consideration of the fracture network separately from the rock matrix will provide insight to modifying blasting strategies (Singh, *et al.*, 2016). Figure 1 shows a schematic of the potential effect of discontinuities on fragmentation from a single blast hole. Blast induced fragmentation will only occur where cracking caused by blasting extends. Existing fractures can act to reduce the extent of blast induced cracking.

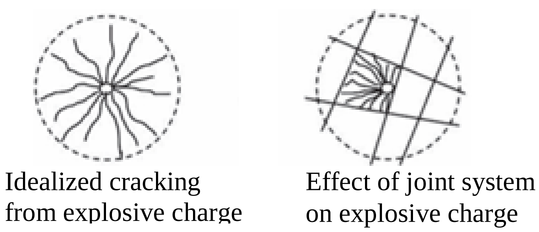

Figure 1. The effects of a joint system on fragmentation (after Singh *et al.*, 2016).

The effect of the orientation of a fracture set with respect to the orientation of a free face remains an open question. Singh (2006) reports that blast overbreak risk increases when a dominant fracture set intersects a free face at an angle between 40° and 60°. The relation between these orientations and over break was calculated through test blasts in 46 × 28 × 15 cm^3 concrete models and is shown in Figure 2. Conversely, Latham and Lu (1999) report that the best fragmentation would occur when the dominant fracture set strikes at between 25° and 65° to the blast face. Adding further complexity to the issue, the orientation of the free face impacts the blast design and sequencing. The free face moves during the blast according to blast hole sequence and timing. As a discontinuity also acts as a free face by reflecting shock energy, they must be considered as well.

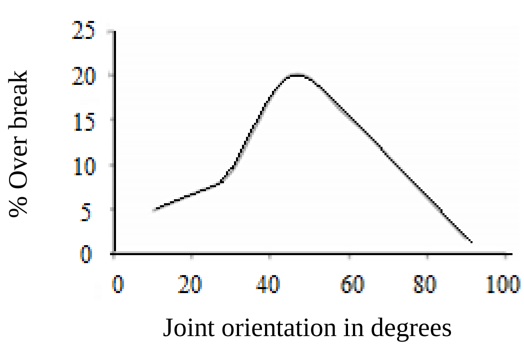

Figure 2. Observed over break in relation to the orientation of fracture sets with respect to the free face (after Singh, 2006).

There is a clear indication that discontinuities play an important role in blast optimization, especially open fractures. For an optimized blast, the quantity and placement of explosives should be determined through understanding of the structure of the rock mass (Mandal, *et al.*, 2008). This pertains to both fragmentation optimization and the reduction of blast risks. The goal of this work is to develop a methodology for the design of optimized blast patterns that account for the existing fracture network of a rock mass.

Existing fragmentation models generally combine the effects of the rock matrix and rock mass into a single parameter. The Kuznetsov equation relates the mean blasted fragment size to the amount of explosives used for an entire blast (Cunningham, 1983). For the Kuznetsov equation given as Equation (1), the rock factor, A, is determined empirically and considers the effect of the rock matrix and rock mass on fragmentation.

$$k_{50} = A\left(\frac{V}{Q}\right)^{0.8} Q^{1/6} \tag{1}$$

Where k_{50} is average fragmentation (cm), V is the volume of rock (m^3), Q is the equivalent explosive charge in kg of TNT, and A is the rock factor.

The energy-block-transition (EBT) fragmentation model incorporates Bond's theory to account for the reduction of block sizes through fragmentation (Lu and Latham, 1998; Latham and Lu, 1999). The EBT model has the feature of considering the uncontrollable parameters of a blast related to the rock mass as individual influences on blast outcome. A variety of influences can be considered through inclusion in a Rock Engineering Systems (RES) interaction matrix (Hudson, 1992). The EBT equation, Equation (2), also contains a parameter to represent the effect of the rock mass: B_i, the blastability index.

$$q_{ei} = \frac{f_c}{B_i}\frac{k_{ai}-k_{ab}}{\left(\frac{k_{ai}+k_{ab}}{2}\right)^{0.5}} \tag{2}$$

Where q_{ei} is the energy required for fragmentation (kWh/t), k_{ai} and k_{ab} are mean particle size for in situ and blasted block size distributions, and f_c is a factor that can be used to include controllable factors (eg. decoupling, timing, decking), f_c is set to 1 when no controllable factors are defined.

The similarity between the Kuznetsov and EBT equations is that both consider the energy required to reduce the *in* situ block size distribution (IBSD) to a desired blasted block size distribution (BBSD). This is demonstrated in Figure 3. The two models differ in that the EBT equation considers the IBSD explicitly and that the rock factor/blastability index can be determined based on a variety of selected parameters.

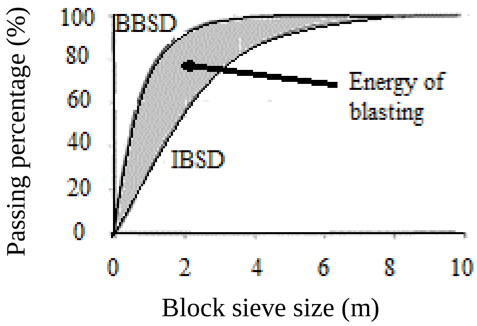

Figure 3. The comminution concept applied to blasting: the IBSD is converted to the BBSD by explosive energy (after Latham *et al.*, 1999)

An RES approach is used by Latham and Lu (1999) to determine B_i for the EBT equation. The orientation of fracture sets with respect to the free face is not included as a parameter due to the difficulties in assessing it through the course of a blast. The benefit of using an RES approach to determine B_i is that the interaction matrix can be updated to reflect different parameters when sufficient knowledge and computational power is available to do so.

An *emergent property* of a system is one that represents the system as a whole but that individual components of the system do not possess. An example of this is the IBSD of a rock mass as derived from a discrete fracture network (DFN) model. The inputs to a DFN model contain information regarding fracture sets, orientations, intensities, terminations and fracture geometry (Lu, 1996). These factors all contribute to the IBSD of a rock mass; however, the IBSD cannot be easily calculated by considering these parameters individually for complex geometries (Latham *et al.*, 2006). Traditionally, IBSD was calculated by considering the spacing of fracture sets (Lu and Latham, 1999). With the development of DFN modelling software and advancements in computing power that allow for more detailed analysis of a DFN model, the IBSD can be calculated directly from a DFN model (Elmo, *et al.*, 2014).

2. ROCK ENGINEERING SYSTEMS (RES)

Rock Engineering Systems were developed by Hudson (1992) to aid in finding solutions to rock engineering problems. The RES approach has been used successfully in a variety of rock engineering case studies over the past 25 years. Hudson (2013) reviews 34 RES case studies. These examples cover surface and underground blasting, slope stability studies, tunnel boring machine (TBM) performance, ground support and deep geological repositories for nuclear waste.

The RES methodology uses an interaction matrix to consider the cause and effect of identified parameters. The RES interaction matrix can have interactions coded in a variety of ways: binary (0-1), expert semi-quantitative (ESQ) (0-4), and continuous quantitative coding (Faramarzi *et al.*, 2014). The RES methodology allows for uncertainties in a system to be considered; this includes epistemic uncertainty related to a lack of knowledge and aleatory uncertainty related to the inherent randomness of a system (Hudson, 2013). An RES solution to fragmentation modelling allows for the response of the rock mass to be considered as individual factors. This is a valuable tool for a complex process that is not fully understood. The RES fragmentation models that have been formulated generate a variable that can be incorporated into existing fragmentation models. Latham and Lu (1999) generate a blasting designation (BD) factor whereas Faramarzi *et al.* (2014) and Hasanipanah *et al.* (2016) generate a vulnerability index (VI) that is based on previous RES solutions for TBM optimization.

The objective for this paper is to formulate a new RES solution for blast optimization based on existing models, with increased consideration of the fracture network. By using the MoFrac DFN modeling software (MIRARCO, 2019) to generate a DFN model of a volume of rock to be blasted, principal parameters that relate to fragmentation can be derived and measured. These parameters represent fracture intensity, IBSD, and variability in intensity of the fracture network. They can be used to describe the network of pre-existing discontinuities, spatially, prior to blasting. MoFrac's quantitative metrics are used to assess these variables. The metrics data is incorporated into an RES solution to better predict the rock mass reaction to explosive fragmentation.

A blast fragmentation model is proposed that utilizes information collected through analysis of DFNs. The proposed blast fragmentation model is geared towards use for blast optimization, by identifying blasts that warrant additional planning due to the nature of the fracture network. Where the variability in fracture intensity is high, there is an opportunity for optimization by adjusting a blast pattern to reflect the variability of discontinuities within the rock mass. This model allows for the potential of safer and more efficient blasting by understanding the role of natural discontinuities during fragmentation.

3. RES BLAST MODELLING

RES solutions have been applied to blast modelling by several researchers. The EBT equation put forward by Latham and Lu (1999) uses an RES interaction matrix to determine a blasting designation (BD) from which a value for B_i can be derived. Faramarzi *et al.* (2013b) and Hasanipanah *et al.* (2016) both present RES solutions to fragmentation optimization that utilize an approach of calculating a vulnerability index (VI) for the rock mass based on previous work with tunnel boring machines. Fragmentation (P_{80}) is determined directly from a relation with VI.

There have also been several studies related to blast hazard assessment using RES solutions to quantify the risk. Studies have investigated back break and over break (Faramarzi *et al.*, 2013a) and fly rock (Faramarzi *et al.*, 2014) for surface studies. Andrieux and Hadjigeorgiou (2008) used an RES approach to quantify the destressibility index to assess the likelihood of successful destress blasting in underground mines.

The fragmentation models that incorporate RES solutions utilize interaction matrices that account for factors related to the rock matrix, rock mass, blast pattern, and explosives used. The interaction matrix involves placing the parameters of interest along the main diagonal and then coding the interactions. Figure 4 shows a schematic of the interaction matrix and calculations used to determine cause and effect for each parameter as presented by Hudson (1992). Table 1 lists the parameters used for each of the three fragmentation models referenced in this paper.

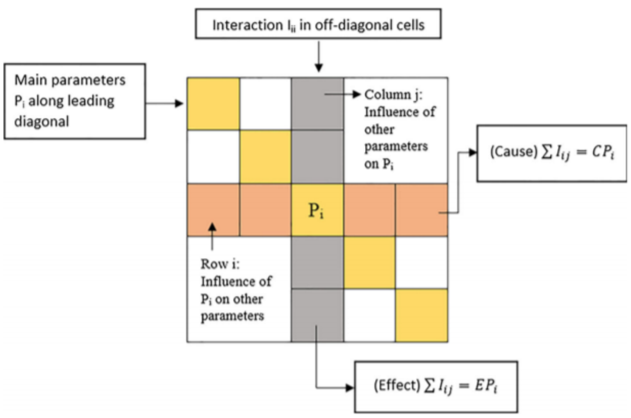

Figure 4. A generalized view of an RES interaction matrix (From Hasanipanah *et al.* 2016)

Latham and Lu (1999) present a model that uses a continuous quantitative coding that is dominated by rock matrix characteristics. Consideration of the existing fracture network is also included through P_9 IBSD, P_{11} Integrity of rock mass (RQD), and P_{12} Discontinuity plane's strength. Faramarzi *et al.* (2013b) and Hasanipanah *et al.* (2016) present fragmentation models that use ESQ coding that are mostly dependent on the blast design. The model put forward by Faramarzi *et al.* (2013b) includes the blastability index as P_{15}, B_i can be derived from BD as calculated by Latham and Lu (1999).

The interaction matrix is used as a means to quantify the ubiquitous rock factor used in fragmentation modeling. Recalling that the parameters that must be accounted for reflect the rock matrix, rock mass, blast design, and explosives used, it is evident that Faramarzi *et al.* (2013b) presents an interaction matrix that accounts for these influences on fragmentation. This is primarily through the inclusion of B_i which can be derived from the Latham and Lu (1999) interaction matrix that includes parameters related to the rock matrix and rock mass.

Table 1. Parameters used in interaction matrix for RES solution to blast fragmentation.

Model	Latham and Lu (1999)	Faramarzi *et al.* (2013b)	Hasanipanah *et al.* (2016)
Parameters	P_1 Strength P_2 Resistance to fracturing P_3 Sturdiness P_4 Elasticity P_5 Resistance to dynamic loading P_6 Hardness of rock P_7 Deformability P_8 Resistance to breaking P_9 IBSD P_{10} Fragility of rock mass P_{11} Integrity of rock mass P_{12} Discontinuity plane's strength	P_1 Burden P_2 Maximum instantaneous charge P_3 Powder factor P_4 Spacing to burden ratio P_5 Stemming to burden ratio P_6 Stiffness ratio P_7 Number of rows P_8 Time delay P_9 Blast hole inclination P_{10} Blast hole deviation P_{11} Hole diameter P_{12} J/B ratio P_{13} Blast pattern P_{14} Initiation sequence P_{15} Blastability Index P_{16} Burden to blast hole diameter ratio	P_1 Burden P_2 Maximum instantaneous charge P_3 Specific charge P_4 Spacing to burden ratio P_5 Stemming to burden ratio P_6 Stiffness factor P_7 Number of rows P_8 Blast hole inclination P_9 Blast hole diameter P_{10} Burden to blast hole diameter ratio P_{11} D_{80} of fragmentation

Methods to derive parameters from a DFN model are proposed in the following four sections. These include in situ block size distribution (IBSD), integrity of the rock mass (P_{32}), and fracture intensity variability (CV%) within the rock mass. Fracture intensity variability is a new parameter that has not been included in previous RES solutions to blast fragmentation. This parameter can be included to better characterize the existing fracture network. As it is known that a discontinuity has a significant effect on the propagation of shock and gas energy during a blast, knowledge of changes in fracture intensity would be a valuable addition to fragmentation modeling.

4. DFN MODEL

Ten realizations of a stochastic DFN model were generated and verified against inputs using MoFrac (Junkin *et al.*, 2017; 2018). When conditioning a stochastic model derived on mapped data, the number of realizations is significant and should be assessed. The DFN recipe used is defined in a companion paper (Junkin, *et al.*, 2019), and is summarized in Table 2. A single realization of this DFN is shown in Figure 5, coloured by fracture set.

Table 2. Summary of DFN recipe used for stochastic models

Attribute	Fracture set A	Fracture set B	Fracture set H
Strike	0°	90°	35°
SD of Strike	15°	15°	15°
Dip	90°	90°	0°
SD of Dip	15°	15°	5°
Min Size	50 m^2	50 m^2	50 m^2
Max Size	100 m^2	100 m^2	100 m^2
P_{32}	1.2 m^{-1}		
Strike to Dip ratio	1 – 5		
Fracture Shape	Elliptical		
Truncation	0		
Element size	2 m^3		
Model size	25 × 25 × 25 m^3		

DFN models were generated in order to propose methods to derive parameters for use in an RES interaction matrix related to fragmentation optimization. The models are entirely stochastic and defined with a low fracture intensity and with three fracture sets that include no random fractures. Intensity was chosen sufficiently low to allow reasonable computation times yet be representative for describing the methodology. For this reason, a relatively high IBSD and low RQD are expected. Since there are no fracture traces used to guide seeding at boundaries, there is an expected boundary effect where a lower fracture intensity is expected. This boundary effect can be quantified by comparing interior and exterior P_{32} intensities for inspection cubes centered inside the DFN model, as shown in the following section. By including mapped data on the surfaces of a DFN model as seed points for partial fractures, the boundary effect can be minimized.

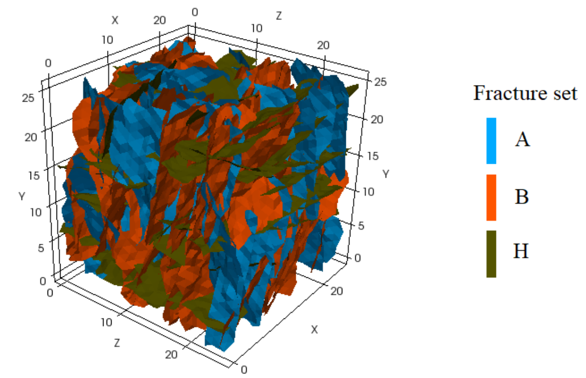

Figure 5. Single realization of the DFN model (250 fractures) used to quantify fracture network parameters for inclusion in an RES solution for a blast fragmentation index.

6. IBSD ESTIMATION

Traditionally, IBSD is determined through consideration of joint spacing to determine a block volume (V_b). V_b is related to the volumetric joint count (J_v) and RQD; estimations of all three can be made from any one known value (Palmström, 2000).

A benefit of calculating the P_{32} fracture intensity for all voxels within a DFN is that an estimate of the IBSD can be achieved by counting null blocks, that is, voxels that have a fracture intensity of 0. The smallest voxel size used for analysis is the smallest size of block that can be identified. The smallest block possible is reported, as there is a high likelihood that there is some unfractured rock in neighboring voxels, as shown in Figure 8. Where null blocks share faces with other null blocks, they are combined to form a compound null block. A block splitting algorithm is then employed to control concavity (Junkin *et al.*, 2019).

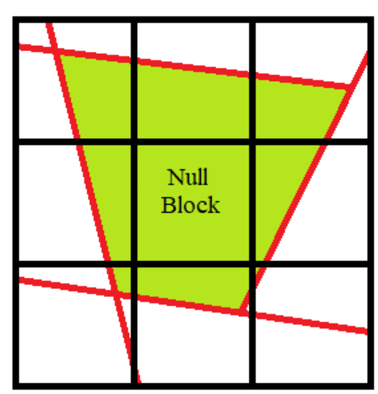

Figure 8. A null block is the smallest possible estimation of an *in situ* block (green). Fracture traces are shown in red for a 2 dimensional representation.

The input for IBSD in the Latham and Lu (1999) interaction matrix is the 50% passing block size. For the ten DFN realizations, the IBSD was determined as shown in Figure 9. The P_{50} for the ten realizations ranged from 5.8 m^3 to 8.5 m^3 with an average P_{50} block size of 6.59 m^3.

The average block size can be used as a direct input to the Latham and Lu (1999) interaction matrix. An average block volume of 6.59 m^3 would result in an RQD value just over 100% (Palmström, 2000). Although some 1 meter core sections would contain fractures, the majority would not.

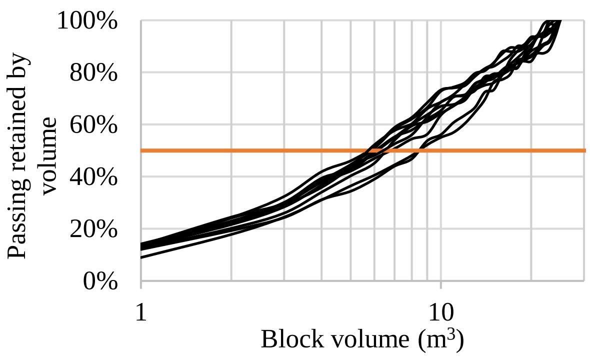

Figure 9. IBSD estimations for all ten DFN realizations. 50% passing line shown in orange.

7. FRACTURE INTENSITY VARIATION

Fracture intensity is considered for discretized columns of the DFN model. A 10 × 10 discretization of the DFN model is used to generate 2.5 × 2.5 m^2 columns that extend the depth of the DFN model. This can be visualized in Figure 10 colored by actual regions used for analysis for a 5 × 5 discretization. Fracture intensity calculations were made for each 2.5 m × 2.5 m column. This results in four fracture intensity calculations for each region shown in Figure 10. This geometry is equivalent to the blast design used for the case study by Latham and Lu (1999).

Any discretization can be used for voxelization; resolution is limited by computational power. The fracture intensity for each discretized column is calculated. Table 3 summarizes the P_{32} fracture intensities for each realization. The P_{32} fracture intensity for each column is known and can be visualized as a heat map, as shown in Figure 11. The average difference between the fracture intensity of one column and its neighboring columns can also be calculated to give a ΔP_{32} value. This value quantifies the rate of change of fracture intensity with a DFN model and can be used to determine locations where fracture intensity changes abruptly. This can also be considered as a means of identifying fracture intersections, which would result in increased fracture intensities. A heat map can be generated for ΔP_{32}, as shown in Figure 12. The average ΔP_{32} value and the number of cells with ΔP_{32} above a given threshold can then be calculated and incorporated into an RES interaction matrix to represent the variability of a DFN model. Two DFN realizations are shown in both Figures 11 and 12; these realizations were chosen as realization #5 shows the least variability in fracture intensity and realization #6 shows the highest variability in fracture intensity.

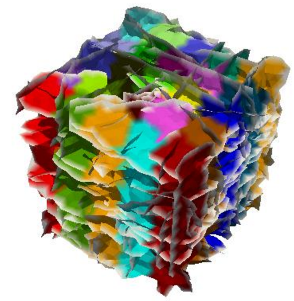

Figure 10. Regions used for fracture intensity analysis; 25 (2.5 × 2.5 m^2) regions are shown.

Table 3. Summary of fracture intensities for each DFN resolution.

Model	Mean P_{32}	SD P_{32}	% high	Mean ΔP_{32}	SD ΔP_{32}	% high
1	1.20	0.31	39	0.26	0.10	29
2	1.18	0.26	38	0.23	0.10	19
3	1.19	0.31	38	0.27	0.13	23
4	1.20	0.27	42	0.23	0.09	23
5	1.19	0.23	37	0.20	0.09	15
6	1.21	0.31	43	0.27	0.10	36
7	1.19	0.29	36	0.25	0.09	29
8	1.20	0.26	36	0.22	0.08	29
9	1.21	0.28	41	0.22	0.08	18
10	1.19	0.25	30	0.22	0.09	17
Average	1.20	0.28	38	0.24	0.10	23.8

In order to utilize a single parameter to represent the variation in fracture intensity, it is proposed to use the percentage of voxels with a high ΔP_{32}. It can be seen in Table 3 that, there is no strong correlation between the mean value or standard deviation of ΔP_{32} with the percentage of voxels with a high ΔP_{32} value. An arbitrary threshold to determine a high ΔP_{32} value allows for flexibility in modelling. A change in the value considered high for ΔP_{32} can be used to calibrate a fragmentation model based on rock type and empirical findings from initial blasts.

Priest and Hudson (1976) relate the Rock Quality Designation (RQD) of a rock mass to the mean fracture frequency with both linear and exponential relations. This work was extended by Elmo *et al*. (2014) to give the linear relation given in Equation 3. Using this linear relation, given an average P_{32} intensity of 1.2, an RQD of 96.7% is expected. The predicted RQD was visually verified by cutting simulated cores from the DFN models and estimating RQD values.

Fracture intensity	P_{32} Low	P_{32} High	Color
Very low	0	1	
Low	1	1.3	
Medium	1.3	1.5	
High	1.5	1.5+	

Fracture intensity variability	ΔP_{32} Low	ΔP_{32} High	Color
Low	0	0.3	
High	0.3	0.3+	

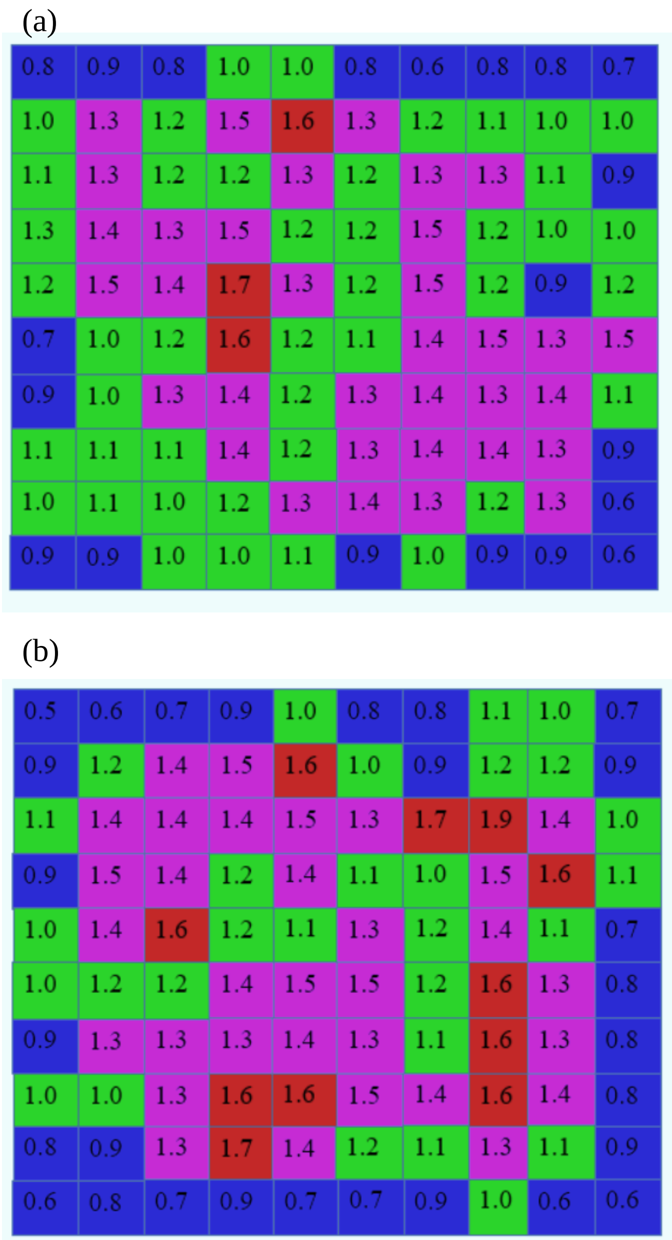

Figure 11. P_{32} fracture intensity shown as a heat map for DFN realization #5 (a) and #6 (b). Colors are coded as shown in legend.

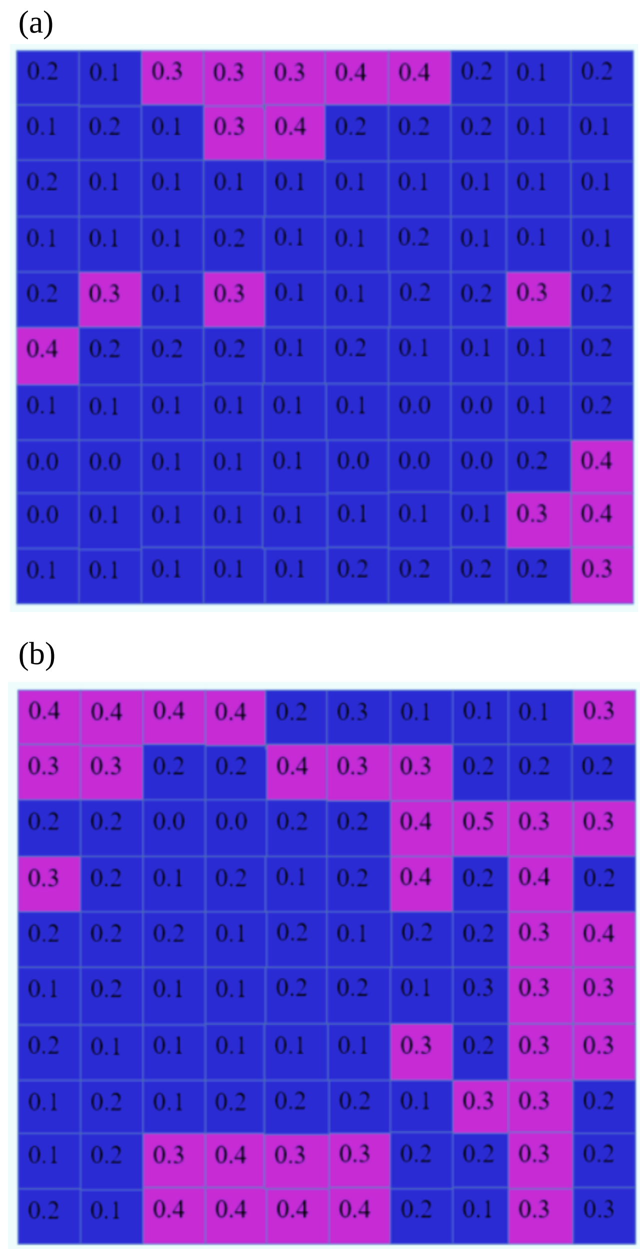

Figure 12. ΔP_{32} fracture intensity shown as a heat map for DFN realization #5 (a) and #6 (b). Colors are coded as shown in legend.

Palmström (2000) uses simulated cores to consider the relation between RQD and known DFN recipes. An example of a simulated core is given in Figure 13. This simulated core gives an RQD value very close to 100%; one meter sections are divided by the vertical red lines shown in the figure. RQD is used as an input quantifying the integrity of a rock mass in the

$$P_{32} = -0.36(RQD) + 36 \qquad (3)$$

Figure 13. Simulated core showing an RQD in agreement with the predicted value. Red vertical lines show one meter long segments of core.

8. TESTING SITES AND MEASUREMENTS

Laboratory and field testing are required in order to determine the interactions between ΔP_{32} and other influencing parameters on blast fragmentation. Ideally, an interaction matrix can be formulated to determine a more accurate value of B_i to be incorporated into an EBT model for blast fragmentation. Laboratory scale models can be built similar to those of Dick (1992) and Singh (2006) that will allow for the effect of ΔP_{32} to be initially investigated. The estimates for IBSD and RQD can be included in pre-existing RES interaction matrices.

Following laboratory scale tests it will be necessary to calibrate an interaction matrix using actual data. The ideal site would have a consistent rock type (rock matrix properties) and variations in fracture intensity. Ideally fractures would be easily mapped on free faces and surface to allow for accurate conditioning of DFN models. This ensures that as much actual data can be included in the model as possible and that the boundary effect of DFN models generated for analysis is minimized.

The proposed interaction matrix will be geared towards predicting energy requirements for fragmentation and include new parameters related to the existing fracture network. There is an opportunity to investigate blast hazards during this process. Mitigating blast risks in combination with efficient fragmentation is a key to successful blast optimization. Blast vibrations, over break, fly rock, noise, among other parameters, can be used to quantify blast hazards and develop relationships between blast risk, blast design, fragmentation, and the existing fracture network.

In order to consider fragmentation and quantify blast risk, several controls are necessary. Blast designs for analysis should not include decking or decoupling; blast patterns and geometry should also remain constant. Powder factor, which quantifies the amount of explosives used, can be altered by adjusting the spacing and burden of a blast. An interaction matrix can be calibrated and verified as giving a useful measure of the effect of the existing fracture network on fragmentation. Further blast design options can then be incorporated to optimize fragmentation and reduce blast risks.

9. DISCUSSION

This paper has provided a brief review of RES solutions to blast optimization and to the effect of natural discontinuities on fragmentation. An opportunity has been identified to improve on existing solutions by incorporating data derived from DFN models. IBSD and RQD are both inputs to interaction matrices previously developed for fragmentation optimization. It is proposed to derive these variables from actual DFN models generated and analyzed using MoFrac. A new parameter is also proposed, ΔP_{32}, to characterize the variability of fracture intensity within the rock mass.

Future work will require the calculation of interactions between ΔP_{32} and existing parameters that influence fragmentation. An attempt to nest interaction matrices would allow for solutions to determine the ease of fragmentation as well as to quantify the risk associated with defined blast hazards. As the interaction matrix used by Faramarzi *et al.* (2013b) uses an output from Latham and Lu's (1999) matrix; a similar approach is thus proposed for this work.

The long term goal of this study is to develop a means to predict blast results through use of RES interaction matrices and existing fragmentation models. This approach should be friendly to the blaster, requiring minimal geotechnical knowledge and incorporating simple methods to map and measure discontinuities. This allows for characteristics of the existing fracture network to be flexibly incorporated into solutions. With knowledge of the effect of discontinuities on a blast as a whole, an opportunity will be present to design blasts with irregular patterns and irregular loading (decoupling/decking). At that point consideration can be given to blast sequencing, timing, stemming, and alternative explosives.

10. ACKNOWLEDGMENTS

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