A Rock Fragmentation Prediction Model for Mining Excavations

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Mathematical and empirical models exist for calculating the inherent fragmentation of the rock mass as defined by its discontinuities. So, too, are models available for determining the expected fragmentation of a blast pattern given a homogeneous, unjointed rock mass. Attempts have been made to combine these models to produce a more accurate prediction of expected fragmentation from a rock mass, either from a caving operation, or from a specific blast pattern.

This paper addresses an attempt at the latter - a combination of an inherent fragmentation model with an elementary, but proven, blast fragmentation predictor. While the model is not perfect due to the assumptions that have been utilized within the calculations, it can be of practical use for mine design. Case histories of this model's usage in potential, and ongoing, mining operations are included within the paper.

A rock mass is dissected by joints. These joints define individual rock blocks. The distribution of size of these blocks is, within this paper, called the inherent fragmentation distribution.

The inherent fragmentation distribution was calculated from the joint spatial characteristics derived from statistical mapping of the rock mass. These values included, for each joint set, orientation, mean trace length, and center density. Calculation of the distribution assumed that:

- *the major joint sets were approximately orthogonal*
- *each joint terminated against another joint to from a free block surface*
- *each joint set had a definable joint surface area per unit volume of rock*
- *certain acicular block aspect ratios cannot be supported in nature with breaking*

The central portion of the inherent fragmentation distribution (30%-70%) was calculated using a Monte-Carlo technique based on simulations of the joint spatial characteristics. The tails were then calculated from the intermediate points using a Weibull distribution.

Predictions of blasting fragmentation were obtained by combining the inherent fragmentation distribution with the Kuz-Ram fragmentation model. Blocks within a pre-determined distance of the blasthole were assumed to break according to the Kuz-Ram model. Blocks not intersected by this damage cylinder were assumed to follow the inherent fragmentation distribution.

Comparisons of model predictions with actual situations have been carried out on a limited basis. The fit is, in general, quite good.

INTRODUCTION

The fragmentation model discussed in this paper was developed for two reasons. These were:

- limitations of the Kuz-Ram model
- dissatisfaction with inherent fragmentation models using infinite joint lengths

The Kuz-Ram model is quite simplistic. It attempts to account for variations in rock strength and joint orientations through a series of empirical "factors". However, no account is made for the inherent fragmentation distribution of the rock mass. Blasting can, and will, fragment blocks that are not intrinsically cut by the blasthole both by shock and by displacement induced impact. However, it appears that the majority of the rock between blastholes will break along pre-existing discontinuities (joints). As such, neglecting the inherent fragmentation of the rock mass could result in a considerable error in estimating the resulting fragmentation from a blast.

Thus, including the inherent fragmentation model in the blasting estimation process appears to be a worthwhile concept. However, the common, published, inherent fragmentation models are based on the assumption that:

- the joint sets follow a specific spacing distribution and;
- joint lengths are assumed infinite within the confines of the model

Having mapped a considerable number of rock faces, it does not appear reasonable that joint lengths will be infinite except in a relatively small model space. In most cases, this model space will be much smaller than blast hole spacing. As such, it did not appear that a model of this type would accurately reflect the inherent fragmentation distribution.

Given this conclusion, but with the goal of obtaining an inherent fragmentation distribution, a new course for determining inherent block sizes was embarked upon.

Joint spatial characteristics are those properties that describe a joint "set" in space. These include the distributions of orientation, density, and area (or length-continuity). Of these:

- orientation can be described by a number of mathematical distributions, or the simple empirical distribution obtained from a contoured polar net can be utilized;
- density, or the number of joint centers per unit volume, may be assumed to be a random process. This can be disputed, successfully, for specific environments. However, in absence of a site specific model, it is a useful starting position;
- joint trace length is a one dimensional representation of the two dimensional world occupied by the joint area. This is the surface area of the joint and is described by the joint's shape.

The definition of a block for an inherent fragmentation distribution is a block defined on all sides by a pre-existing discontinuity. The infinite joint length models assume that joints will intersect and the blocks created thereby will exist. However, if the joint continuity is insufficient, this assumption is false, resulting in an underestimation of the fragment size.

If the assumption is made that a statistically definable joint surface area exists per unit volume of rock, as is inherent from the discontinuity area and density functions noted above, then it should be possible to estimate the number of free blocks within this unit volume.

Of course, this assumes that all discontinuities intersect to form a block and that these blocks will be of uniform shape and size, both of which are inherently false. However, for a preliminary test of an alternative modelling approach, this did not appear to be too steep a price to pay, as workarounds could be derived to compensate, in part, for these deficiencies.

INHERENT FRAGMENTATION THEORY

The inherent fragmentation distribution was calculated from the joint spatial characteristics derived from statistical mapping of the rock mass. These included, for each joint set, orientation, mean trace length, and center density. Calculation of the distribution assumed that:

- the major joint sets were approximately orthogonal
- each joint terminated against another joint to from a free block surface
- each joint set had a definable joint surface area per unit volume of rock
- certain acicular block aspect ratios cannot be supported in nature with breaking

The assumption of orthogonal jointing was made for two reasons. First, this simplified model development as blocks could be assumed rectangular solids. Second, the joint set orientation distribution could be disregarded, further simplifying calculations. It should be noted, however, that the test cases examined later in this study approximate the assumed conditions of three approximately orthogonal joint sets.

Joints were assumed to terminate against another joint. This has some basis in reality as many joints do, in fact, have both termini in cross cutting joints. This, however, is not universal and in some rock masses, "tag ends" on joints can be found within the rock mass. Additionally, if circular joints are assumed, it is impossible to have complete termination of one joint against the other without violating the assumption. However, randomly formed polygons should behave statistically as do circles and these would allow termination. For this study, it was assumed that a sufficient percentage of all joints did terminate in the prescribed fashion and that, in the cases that didn't, "random" or non-set described jointing would make up the difference.

The concept that each joint set has a definable joint surface area per unit volume can be attacked in the following manner:

Assume that inherent discontinuities in the rock mass are circular ("penny shaped") in nature (Figure 1) and that their diameters follow a negative exponential distribution.

Where:

P(d) = probability of diameter d

$$P(d) = e^{-d/\bar{d}}$$

d = expected discontinuity diameter

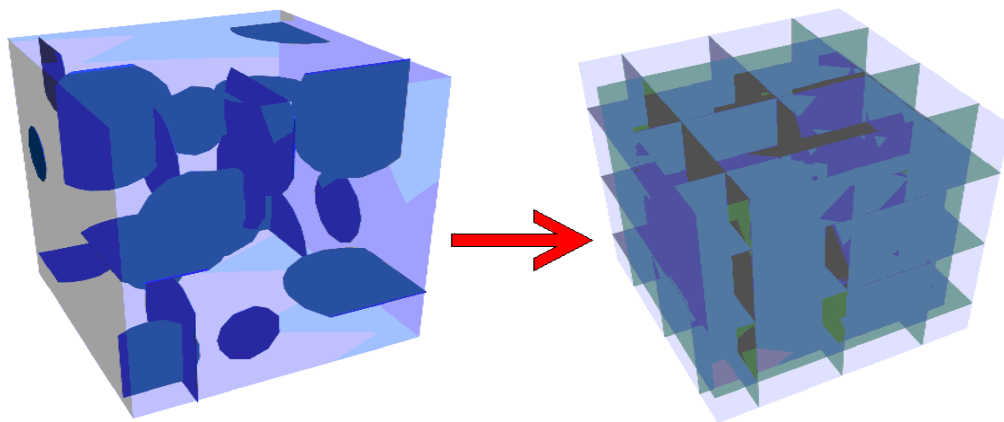

Figure 1 - Transformation of circular joints to finite area planes

The mean diameter, d, can be obtained from the mean discontinuity trace length, assuming an exponential distribution, using the following equation:

$$\overline{d} = E(l) / \pi$$

Where:

d = expected discontinuity diameter

E(l) = expected discontinuity trace length

The expected area of a discontinuity, assuming an exponential distribution, is simply:

$$\overline{a} = \overline{d}^2 / 2$$

Where:

a = expected discontinuity area

Given the above, it is relatively uncomplicated to calculate the mean joint surface area expected within a unit volume of rock. If the surface area is known, per joint set, the mean block dimensions can be calculated readily with the above stated assumptions.

However, extending the derivation to encompass the distribution of block sizes that would be encountered appeared to be non-trivial. As such, a simulation routine was written in order to approximate this distribution.

The simulation was conducted in the following manner:

- a specific number of simulation blocks (in this case 5000) of dimensions 1 by 1 by X long were constructed in computer memory. X was determined to be the length required to encompass sufficient volume so that a joint area of 1 was enclosed for the joint set with minimum area/continuity;

- Monte-Carlo simulation was then conducted in the 5000X by 1 by 1 space for each of the 3 orthogonal joint sets (see Figure 2 for visualization);

- the joint areas found within each simulation block were then combined to determine the dimensions of a rectangular solid. This determined both volume and aspect ratio;

- those simulation blocks which contained inherent blocks with an aspect ratio of greater than 3.5 (field experience, measured) were discarded;

- the resulting percentage of simulation blocks passing the aspect ratio test was calculated. If this value was less than pre-determined threshold, the X dimension was increased and the process repeated;

- volumes and aspect ratios for the individual simulation blocks were accumulated in memory, then analyzed once the threshold was passed. This included calculating a volume distribution and a mean aspect ratio;

- an uncorrected inherent fragmentation distribution was then derived based on the volume distributions and/or the maximum block lengths.

It is obvious that the above simulation will force the calculated block size distribution towards the mean. Further, this bias will increase proportionately to the distance from the mean. Due to this fact alone, the tails of the distribution are not to be trusted as the oversize will be artificially forced towards the mean.

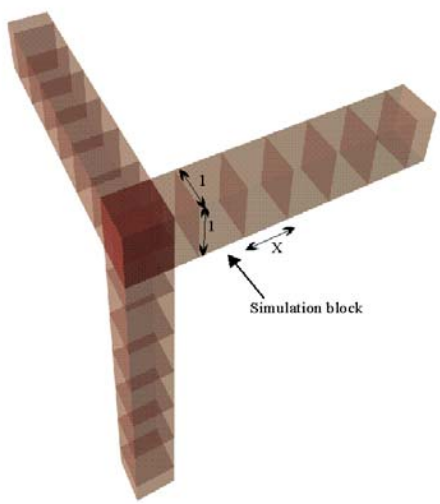

Figure 2 - Simulation model space

In order to compensate for this bias, an adjustment was made to the fragmentation distribution.

It was assumed, without testing, that a Weibull distribution should approximately describe the inherent fragmentation distribution. This was based on the Kuz-Ram model for fragmentation, which is essentially a Weibull model, and the common usage of the Weibull failure model in statistical failure analysis.

The model utilized was as follows:

$$P(x) = e^{-(x/\overline{x})^{\gamma}}$$

The equation was solved simultaneously at the 30% and 70% points on the cumulative fragmentation distribution in order to yield χ and γ. These percentage values were chosen as levels where the inherent modelling bias, while still possibly significant, would not overwhelm the general character of the Wiebull distribution curve.

A comparison of the corrected and uncorrected inherent fragmentation distributions for two lithologic units is presented as Figure 3. Note the difference in the tails of the distributions.

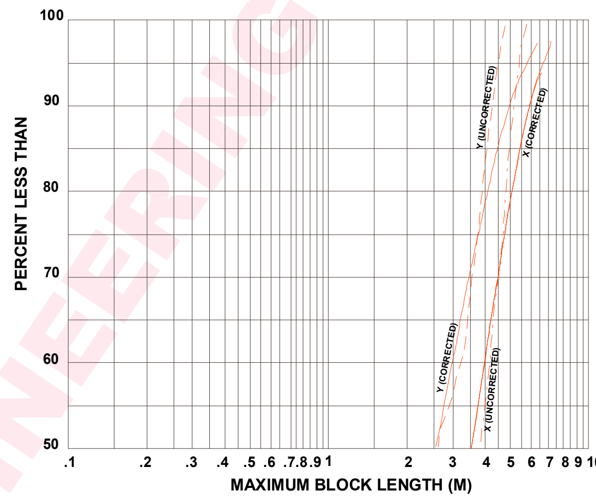

Figure 3 - Comparison of raw and corrected fragmentation

KUZ-RAM THEORY

The Kuz-Ram fragmentation model was first presented at the 1983 Luleå Conference on Fragmentation by Blasting (1). Since then, the model has been evaluated, improved, and likely surpassed in performance by more complex models. However, it is a relatively simple model that gives reasonable approximations of blasting fragmentation results.

As this paper focuses primarily on the development of an in-situ fragmentation distribution and the melding of this with a blasting fragmentation model, the Kuz-Ram will only be discussed briefly.

In essence, the Kuz-Ram model is a Weibull model of the form:

$$P(x)=e^{-(x/xm)^{N}}$$

The shape parameter of the distribution, N, is described by:

N=2.2-14B/D)(((1+S/B)/2.)**.5)(1.-W/B)*(ABS(BCL-CCL)/L+0.1)**0.1*L/H

Where:
B = burden (m)
S = spacing (m)
BCL = bottom charge length (m)
CCL = column charge length (m)
L = total charge length (m)
W = standard deviation of drilling accuracy (m)
H = bench height

The location parameter of the distribution, XM', is described by the equation:

XM=A*(VO/QE)**0.8*QE**0.167*(E/115)**(0.6333)

Where:
XM = mean fragment size (cm)
VO = rock volume
QE = mass of explosive per hole
E = relative weight strength of explosive

XM is transformed to XM' by the relationship (Maynard, 1990):

XM' = (XM/(0.693^(1/N))

COMBINATION BLASTING FRAGMENTATION

The fragmentation resulting from a blast is a combination of the fragments produced by breakage of in-situ rock blocks with the in-situ blocks simply displaced by blast motion. Therefore, a combination of the two aforementioned fragmentation distributions should not only be feasible, but also yield a more accurate fragmentation prediction than the relatively simplistic Kuz-Ram model.

The combination of the models was straightforward. It was decided that any inherent block intersecting a damage zone around the drill hole would suffer fragmentation as predicted by the Kuz-Ram model (Figure 4). This zone was arbitrarily taken as being 12 times the blast hole radius. The probability of intersecting a particular size block with a cylinder of a radius 13 times the blast hole diameter was then calculated for discrete intervals within the inherent fragmentation distribution. This resulted in a "new" inherent fragmentation distribution for the material not intersected by the blast hole cylinders. The "new" distribution was biased towards smaller block sizes as larger blocks enjoyed a greater probability of being intersected by the blast holes than did the smaller blocks. The volume intersected by the blast damage cylinders was simply fragmented as would be expected by the Kuz-Ram model. These two distributions were assembled in numerical "bins" and accumulated in a resulting blast fragmentation distribution.

CASE HISTORIES

Two case histories will be discussed herein:

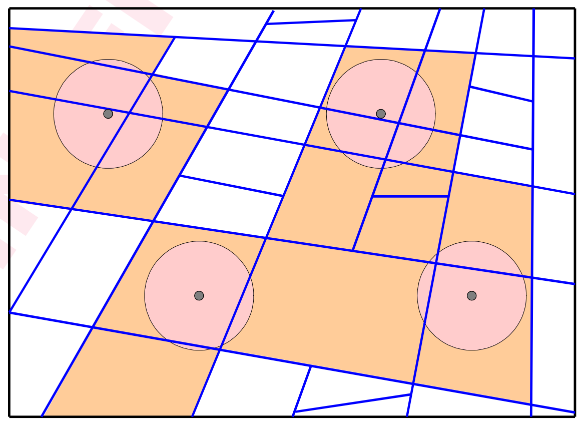

Figure 4 - Schematic diagram of the combination of blast and inherently fragmented rock

- a mine which desired to determine the expected fragmentation of a blast pattern given pre-existing stopes performance

- an active block cave operation required fragmentation distributions for method and layout optimization

Case history 1

Access was gained to the top of a large open stope at an existing operation. Due to the danger involved, it was impossible to accurately map the size distribution of the blocks while in the stope. Instead, PVC pipes of known length were placed throughout the stopes and photographs taken. These were later analyzed to produce a fragmentation distribution. Corrections were made for particle size (exposure bias) during this process. However, little could be done with regards to obtaining a true cross sample through the stope.

Discontinuity spatial characteristics had been collected for the two lithologies, each of which composed approximately 50% of the ore, in the mine area. Some difference was noted between these units, however, it was relatively insignificant.

Data regarding the blasting techniques used for the stope were collected and a fragmentation study undertaken for the stope. The results, shown in Figure 5, indicate very good agreement between the predicted and experienced fragmentation.

In addition, in order to further verify the model, the secondary blasting conducted for the previous mining operation was analyzed. Given that the grizzly size and aspect ratio of the blocks was known, an estimate of the expected secondary blasting required for the predicted stope could be obtained. The model predicted that between 0.26 kg/tonne (mudcapping) and 0.08 kg/tonne (blockholing) of explosive would be utilized. As the mine used a mixture of both types of secondary blasting, a reasonable predicted range of explosive consumption would be between 0.20 - 0.10 kg/tonne. What the mine had experienced was approximately 0.18 kg/tonne early in the stope's operation dropping to about 0.06 kg/tonne later in the stope's life. This drop would, however, be consistent with attrition in the draw column.

Given the two possible checks on the model for the mining operation showed reasonable agreement, the blasting fragmentation study was continued. An example of the results are shown in Figure 6. Note the difference between the Kuz-Ram, inherent, and predicted blast fragmentation.

Case history 2

This case history involved fragmentation prediction for a block cave operation. The operation was planning on changing the cave layout and extraction techniques in order to improve productivity. This required that fragmentation be predicted for the new levels in order that the drawpoint spacing and dimensions could be correctly designed.

Fabric mapping was conducted both above and below the planned, and producing, cave areas in order to acquire the required discontinuity spatial characteristics. These were then reduced to produce an inherent fragmentation curve according to the previously described methodology.

Although this would seem a straightforward application of the inherent fragmentation distribution, it is not. While material produced from the initial cave may, depending on undercut breakage, approximate the inherent fragmentation, the fragmentation over the life of the cave block will be considerably different. This is due to attrition in the caved material above the drawpoints.

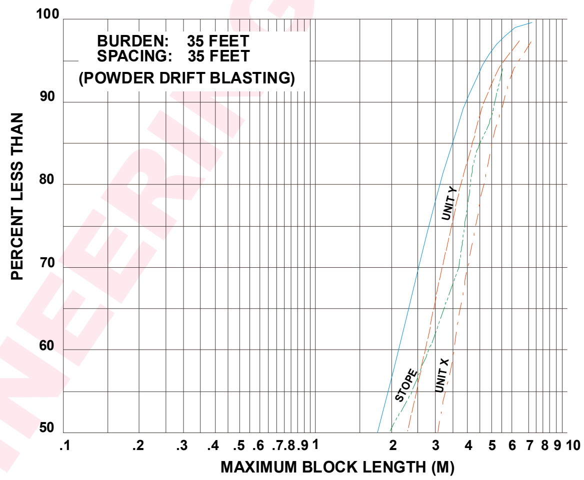

Figure 5 - Comparison of actual and predicted fragmentation, Case 1

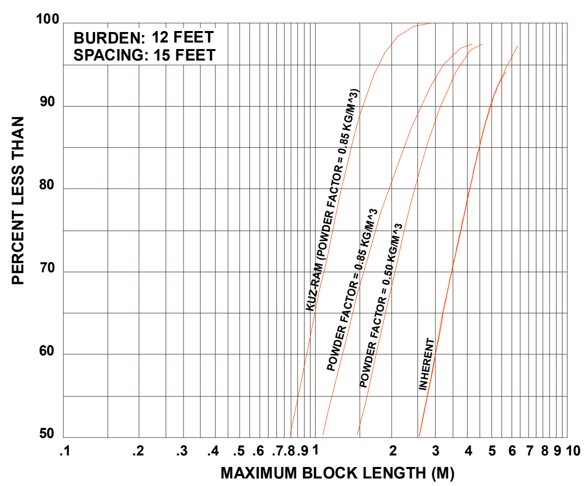

Figure 6 - Blast fragmentation prediction - Case 1

This was realized and an attempt was made to correlate the production oversize from a recently developed cave with model predictions. Results are shown in Figure 7. Relatively good agreement was shown, given the paucity of data. Additional data is being collected in order to place more "cave draw" points on the distribution curve.

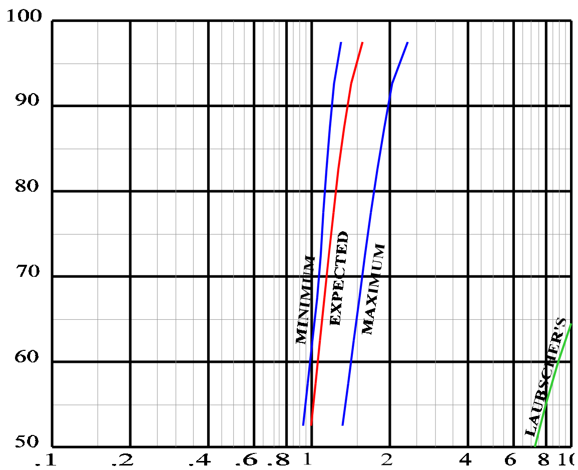

Figure 7 - Fragmentation prediction - Case 2

An additional fragmentation prediction was made using Dennis Laubscher's fragmentation program. His results are based on visually adjusted joint spacings. In addition, Laubscher's program outputs a volume, instead of a maximum length, dimension requiring a block aspect ratio to convert the comparable quantities. Even so, the comparisons do not indicate agreement with the methodology presented herein. More work would be required for a true comparison between Laubscher's, or any other, fragmentation predictor.

CONCLUSION

The initial purpose of the project was to develop a model that would provide a reasonable estimate of fragmentation for mine design. Along the way, this incorporated what was, and is, believed the rather novel approach of using the expected joint surface area per unit volume of rock to predict the inherent fragmentation distribution. There are a number of drawbacks with the methodology, most of which have been mentioned within this article. Improvements can be made in all aspects of the modelling process.

In spite of all this, it appears the model does its job reasonably well. However, only a limited number of cases are available for comparison with what actually happens in the real world. Only further applications will provide insight of the model's usefulness.