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The Kuz-Ram fragmentation model – 20 years on

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ABSTRACT: The Kuz–Ram model is possibly the most widely used approach to estimating fragmentation from blasting, and renewed interest in the field of blast control has brought increased focus on the model. The author reviews the strengths and weaknesses of the model, indicating the limitations, corrections and modifications he has been using, and suggesting how it can best be used. The basic strength of the model lies in its simplicity in terms of the ease of garnering input data, and in its direct linkage between blast design and rock breaking result. The algorithms are easily incorporated into spreadsheets, but a problem with this is the danger of incorrect entries. A further danger is the tendency of inexperienced users to push it beyond its proper range of application. Many criticisms and improvements have been suggested over the years, and these have tended to miss the point that the model is less about precision than about guidance. The major modification from the author has been to factor in the effect of precision timing, as is available from electronic delay detonators.

1 INTRODUCTION

The primary purpose of blasting is to fragment rock, and there are significant rewards for delivering a fragmentation size range that is not only well suited to the mining system it feeds but also minimises unsaleable fractions and enhances the value of what can be sold. Various models have been put forward over the years, attempting to predict the size distribution resulting from particular blast designs. The approaches fall into two broad camps:

– empirical modelling, which infers finer fragmentation from higher energy input, and

– mechanistic modelling, which tracks the physics of detonation and the process of energy transfer in well-defined rock for specific blast layouts, deriving the whole range of blasting results.

The mechanistic approach is intrinsically able to illustrate the effect of individual mechanisms, something beyond purely empirical models. However, it is more difficult to apply from day to day, as it is limited in scale, requires long run times and suffers from the difficulty of collecting adequate data about the detonation, the rock and the end results. It also requires greater or lesser degrees of empiricism, so is not necessarily more accurate.

For all practical purposes, the empirical models are the ones used for daily blast design, and the present author published a scheme as the Kuz–Ram model in the 1980s (Cunningham 1983 & 1987). There are three key equations:

The adapted Kuznetsov equation

$$x_m = AK^{-0.8}Q^{1/6}.\left(\frac{115}{RWS}\right)^{19/20} \quad (1)$$

where x_m = mean particle size, cm; A = rock factor [varying between 0.8 and 22, depending on hardness and structure – this is a critical parameter and its derivation is given in equation (4)]; K = powder factor, kg explosive per cubic metre of rock; Q = mass of explosive in the hole, kg; RWS = weight strength relative to ANFO, 115 being the RWS of TNT.

The adapted Rosin–Rammler equation

$$R_x = \exp\left[-0.693\left(\frac{x}{x_{\mathrm{m}}}\right)^n\right] \tag{2}$$

where R_x = mass fraction retained on screen opening x; n = uniformity index, usually between 0.7 and 2.

The uniformity equation

$$n = \left(2.2 - \frac{14B}{d}\right)\sqrt{\left(\frac{1+S/B}{2}\right)}\left(1-\frac{W}{B}\right)\left(\mathrm{abs}\left(\frac{\mathrm{BCL}-\mathrm{CCL}}{L}\right)+0.1\right)^{0.1}\frac{L}{H} \tag{3}$$

where B = burden, m; S = spacing, m; d = hole diameter, mm; W = standard deviation of drilling precision, m; L = charge length, m; BCL = bottom charge length, m; CCL = column charge length, m; H = bench height, m.

Because of the ease with which the model can be parameterised for blast layout spreadsheets, it has become widely used, but has not been seriously changed since the 1987 publication. Significant queries seeking clarification about the model and indicating its use in serious applications, use which has not always been wise, as well as ongoing interest in adapting it, demonstrate that it continues to provide a useful springboard for blast design. In addition, the author has been deeply involved in evolving the understanding of detonation for blasting, in building mechanistic models and in evaluating digital fragmentation systems and electronic detonator systems. During these processes, the idea of upgrading the Kuz–Ram model was always in the background, and various modifications have been incorporated in personal spreadsheets. The lack of publication has been due, largely, to an expectation that mechanistic models would overtake empirical models, but this has yet to happen, so it is necessary to rework Kuz–Ram.

This paper discusses how thinking has evolved, introducing new algorithms for the effect of blast timing on fragmentation. Most importantly, it points to the appropriate use and limitations of such modelling, and refers to associated developments by other workers in the field. Importantly, there is still no modification for energy partitioning: explosive weight strength is the only input. This will be given attention in due course, but it is far from simple.

2 DEFICIENCIES IN EMPIRICAL FRAGMENTATION MODELLING

Most modelling errors arise through simplistic application or narrow appreciation of blasting as a technology. A brief review of common stumbling blocks is therefore appropriate. These fall broadly into the following categories:

- parameters not taken into account;
- limited ability to measure fragmentation;
- difficulty in scaling blasting effects.

A grasp of these issues is crucial if reasonable and not blind application of modelling is to be undertaken.

2.1 *Parameters not taken into account*

The primary assumption of empirical fragmentation modelling is that increased energy levels result in reduced fragmentation across the whole range of sizes, from oversize to fines. This is generally valid, but not necessarily applicable to real situations. Some of the other factors that may override the expected relationship include:

- rock properties and structure (variation, relationship to drilling pattern, dominance of jointing);
- blast dimensions (number of holes per row and number of rows);
- bench dimensions (bench height versus stemming and subdrilling);
- timing between holes, and precision of the timing;
- detonation behaviour, in particular detonation velocity (VoD);
- decking with air, water and stemming;
- edge effects from the six borders of the blast, each conditioned by previous blasting or geological influences.

Thus, unless these parameters are catered for, it is possible for a model to be seriously wrong in its estimation of blasting fragmentation. Assessing and dealing with the whole range of inputs is the essence of blast engineering.

2.2 *Limited ability to measure fragmentation*

The difficulty of measuring fragment distribution from full-scale blasting is a fundamental obstacle to proving or applying any fragmentation model.

The only complete measure of blasting fragmentation is at the working face, before any mixing takes place, or large boulders are removed for secondary blasting, or fines are lost to wind or water, or generated by the action of the loaders on the rock pile. It is almost impossible to put all of the rock from a properly dimensioned blast through a sieving system, but reduced numbers of holes and rows compromise the actual degree of fragmentation control that would be realized in full-scale blasting procedures. Representative sampling is really difficult owing to the scale of operations and mass of suitable sample sizes, the great variability of fragmentation within the mass, and the tendency of the system to exclude the important fines and oversize fractions.

Resorting to imaging as a means of estimating fragmentation has its best application over a conveyor belt, but this is well away from the working face. Resolution problems are a serious impediment to assessing smaller fractions adequately, compounded by the inability of imaging methods to determine the mass represented by an image of a muckpile. This means that fractions cannot be determined by subtraction, especially since imaging techniques typically use necessarily gross approximations (such as equivalent cube) to determine particle mass. Imaging of truck loads does permit relating particle distribution to weighed masses, but getting a clear image and associating it with a particular part of a blast is not necessarily easy.

Because it is so difficult, really good datasets are hard to come by, and hard evidence for agreeing blasting success is scarce.

2.3 *Inability to scale blasting effects*

The use of transparent plastic or glass models containing tiny charges of molecular explosive is a dramatic way of demonstrating the mechanisms of blasting, but neither the material nor the explosive bears tolerable resemblance either to their equivalents in commercial blasting or to the numerical dimensions and ratios of the effects. This is less true of shots in concrete blocks, but the scale of the blocks and the edge effects in them are still problematic for quantitative modelling. Thus, attempts to align laboratory tests with field blasting tend to cause confusion and sometimes lead to false conclusions.

3 PRECISION REQUIREMENT OF FRAGMENTATION MODELLING

In view of the above obstacles, it can be tempting to abandon the idea of blast modelling, but this is counterproductive, since it cuts off the whole process of learning and the use of genuine blasting knowledge. A good option is to broaden the focus to where results really impact, which is in any case the purpose of modelling.

In a sense, knowing the fragmentation range of the rock is irrelevant, as the objective of blasting is to achieve productivity and profitability. Even if the fragmentation itself is hardly known, its impact is felt, so if, for example, there is conclusive evidence that implementing a change lifts productivity by 30%, then this is the real justification for making that change, whether or not the fragmentation can be measured. Therefore, it is wise to focus as much on the effects of fragmentation as on the size fractions. If the effects cannot be measured directly, then it is usually possible to identify some point at which the ill effects are costing money (e.g. excessive waste tonnage of fine material) or the good effects are paying dividends (e.g. costs of engineering spares).

Therefore, in general, it is necessary to consider the macro effects of the blasting, and to focus less on absolute outcomes than on relative performance. Unfortunately, human psychology and rivalry for recognition can delay the introduction of very helpful measures, so as much evidence of actual fragmentation as possible is needed to complete the case for improved blasting measures.

With this in mind, it is clear that a fragmentation model needs to conform with trends rather than absolutes, and must be used with an understanding of why a trend emerges when changes are made to inputs. With this background, upgrading of the Kuz–Ram model itself can be considered.

4 CHANGES TO THE KUZ–RAM MODEL

Thought has been given to improving the algorithms for mean fragmentation and uniformity in the light of experience and needs in various conditions. The major changes to the model, however, have developed as a result of the introduction of electronic delay detonators (EDs), since these have patently transformed fragmentation. Both the effect of assigned timing and the

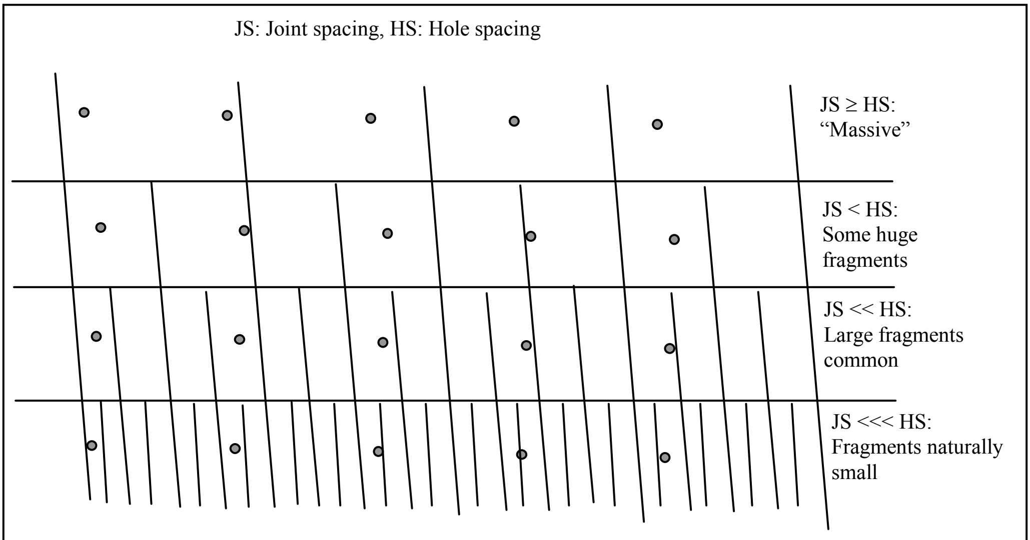

Figure 1. JPS – effect of ratio of hole spacing to joint spacing on blasting fragmentation.

effect of timing scatter are now accommodated.

4.1 Rock characterisation: factor A

It is always difficult to estimate the real effect of geology, but the following routine addresses some of the major issues in arriving at the single rock factor A, defined as

$$A = 0.06\ (\mathrm{RMD} + \mathrm{RDI} + \mathrm{HF}) \qquad (4)$$

where RMD is the rock mass description, RDI is the density influence and HF is the hardness factor, the figures for these parameters being derived as follows.

4.1.1 RMD

A number is assigned according to the rock condition: powdery/friable = 10; massive formation (joints further apart than blasthole) = 50; vertically jointed – derive jointed rock factor (JF) as follows:

$$\mathrm{JF} = (\mathrm{JCF}\ \mathrm{JPS}) + \mathrm{JPA} \qquad (5)$$

where JCF is the joint condition factor, JPS is the joint plane spacing factor and JPA is the joint plane angle factor.

4.1.1.1 Joint condition factor (JCF)

Tight joints	1
Relaxed joints	1.5
Gouge-filled joints	2.0

4.1.1.2 Vertical joint plane spacing factor (JPS)

As illustrated in Figure 1, this factor is partly related to the absolute joint spacing, and partly to the ratio of spacing to drilling pattern, expressed as the reduced pattern, P:

$$P = (B \text{ x } S)^{0.5} \qquad (6)$$

where B and S are burden and spacing, m.

The values of JPS are as follows for the joint spacing ranges:

– joint spacing < 0.1 m, JPS = 10 (because fine fragmentation will result from close joints);

– joint spacing = 0.1–0.3 m, JPS = 20 (because unholed blocks are becoming plentiful and large);

– joint spacing = 0.3 m to 95% of P, JPS = 80 (because some very large blocks are likely to be left);

– joint spacing > P, 50 (because all blocks will be intersected).

Clearly, if the joint spacing and the reduced pattern are both less than 0.3 m, or if P is less than 1 m, then this algorithm could produce strange results. In the original derivation, the index was linked to the maximum defined oversize dimension, but this is clearly not an appropriate input and has been omitted.

4.1.1.3 Vertical joint plane angle (JPA)

Dip out of face	40
Strike out of face	30
Dip into face	20

'Dip' here means a steep dip, >30°. 'Out of face' means that extension of the joint plane from the vertical face will be upwards. This is a change from the 1987 paper and is supported by Singh & Sastry (1987), although the wording in the latter is slightly confused and requires careful interpretation.

4.1.2 Hardness factor (HF)

If $Y < 50$, HF = $Y/3$
If $Y > 50$, HF = UCS/5

where Y = elastic modulus, GPa; UCS = unconfined compressive strength, MPa.

This distinction is drawn because determining the UCS is almost meaningless in weak rock types, and a dynamic modulus can be more easily obtained from wave velocities. In the crossover area there are sometimes conflicts, and it is necessary to use personal judgement for these. It is better to use figures where there is less scatter in the range of data.

4.1.3 Correcting the derived rock factor

Arriving at the rock factor A is a critical part of the process, but it is impossible to cater for all conditions in this simple algorithm. Normally, it is soon apparent if A is greater or smaller than the algorithm indicates, and, rather than trying to tweak the input, possibly losing some valid input, a correction factor $C(A)$ is now introduced. If preliminary runs against known results indicate that the rock factor needs to be changed, then $C(A)$ is used as a multiplier to bridge the gap from the value given by this algorithm. The final algorithm is therefore

$$A = 0.06(\mathrm{RMD} + \mathrm{RDI} + \mathrm{HF})\cdot C(A) \qquad (7)$$

The correction factor $C(A)$ would normally be well within the range 0.5–2.

4.2 Interhole delay

Even before electronic delay detonators (EDs), it was clear that millisecond or short-period delay blasting yielded more uniform and finer fragmentation than half-second or long-period delay blasting. Many papers from respected researchers quoted optimum interhole delay times of 3–6 ms per metre of burden for reducing fragmentation size (Bergmann *et al.* 1974, Winzer *et al.* 1979). This can be tied to the evolving fracture network around a blasthole: the optimum interhole time was found to correlate with twice the time for cracks to propagate across the burden. Bergmann's granite had a compressional stress wave velocity, C_p, of 5.2 km/s (5.2 m/ms), and the influence of delay on fragmentation can be scaled by this value, with 3 ms/m the standard.

Thus, if the value of C_p is C_x km/s, then the optimum delay timing for maximum fragmentation T_{max} will be

$$T_{max} = \frac{15.6}{C_x} B \qquad (8)$$

where T_{max} is the time between holes in a row for maximum fragmentation, ms; the scaling factor is 15.6 = 3 ms/m x 5.2 km/s; B is the hole burden, m; and C_x is the longitudinal velocity, km/s.

Delays shorter than T_{max} suppress fragmentation owing to destructive interference of the stresses with the evolving fracture system. Longer delays result in rock between the holes beginning to shift and hence being less vulnerable to fragmentation mechanisms, but the effect on fragmentation is not as sharp as that of reducing the delay. Weaker rock has slower wave velocities and requires longer delays.

In the work by Bergmann *et al.* (1974), a curve of fragmentation versus delay is given for blasting single rows of five holes in granite blocks. The blocks were not large enough to be able to test the effect of long delays properly, and in full-scale blasting delays longer than T_{max} led to coarser fractions. Certainly, in South Africa's Narrow Reef mines, where capped fuse and shock tube systems enable a very wide range of delays to be employed, there is keen awareness of the increased fragmentation with short delays, and it is qualitatively clear that there is a peak, but fragmentation studies have always been dogged by the extreme variation in every rock breaking situation. The model thus shows that, if interhole delay is increased from instantaneous, the degree of fragmentation rapidly attains a maximum, then gradually deteriorates as delay increases. Very short delays are needed to create strong movement of a rock mass, and, depending on the depth of the blast, fracture arising from mass movement can result in good fragmentation with shorter delays than those given above.

This peaking of fragmentation at T_{max} corresponds to a crucial window where stress waves and fracture growth operate optimally before movement within the rock mass interferes with these mechanisms. The effect is supported in principle by the modelling work of various researchers, e.g. Rosmanith (2003), who affirm that EDs have opened a window of short delay times. There is significant debate as to the validity of ultrashort delays which will no doubt be resolved as work progresses, but real rock breaking conditions ensure that this will not be a quick or easy process.

An algorithm has been developed that simulates the above effect. The form of the algorithm is shown in Figure 2, overlaid on the work by Bergmann *et al.* (1974). The output is a timing factor A_t, which is applied to Equation 1 as a multiplier, and now incorporates the effect of interhole delay on fragmentation. Note that the dataset includes results with different spacing/burden ratios.

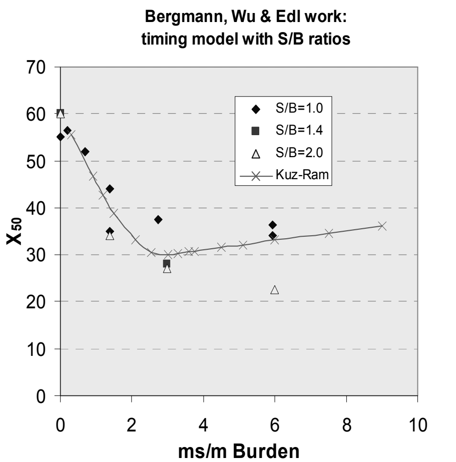

Figure 2. Tentative algorithm for the effect of interhole delay on mean fragmentation.

The form of the algorithm for T/T_{max} between 0 and 1 is

$$A_t = 0.66(T/T_{max})^3 - 0.13(T/T_{max})^2 - 1.58(T/T_{max}) + 2.1 \quad (9a)$$

and for higher values

$$A_t = 0.9 + 0.1(T/T_{max} - 1) \quad (9b)$$

It would be misleading to include this curve in a model that purported to provide precise prediction of fragmentation, but this the Kuz–Ram model does not do. It is a vehicle for exploring the expected behaviour in terms of relative changes to fragmentation, and is therefore a useful way of refining understanding. Until the trend is incorporated, it cannot be tested properly. AEL's engineers are confident that the effect is, if anything, conservative.

4.3 Timing scatter

Because nothing much could be done about controlling timing scatter, while pyrotechnic initiation systems were the only practical way of timing blasts, little serious consideration has been given to this issue. However, the evidence has long existed that, quite apart from delay affecting fragmentation, the scatter in delay itself is key. A quote from Winzer (1979) is particularly pertinent:

> Accurate timing must be considered imperative in producing consistent blasting results and in reducing noise, vibration, fly rock, backbreak and poor fragmentation. In the overwhelming majority of cases that we have studied in detail (37 production shots), poor performance can be directly related to timing problems, which tend to overwhelm other blasting parameters.

It is self-evident that, if timing influences the fragmentation in blasting, then timing scatter will affect the uniformity of blasting fragmentation. This is why there has to be adjustment both for the delay used and the scatter. For more precise timing, at any particular delay, there should be less oversize and fewer fines. However, if there is a simultaneous decrease in all sizes caused by improved timing, the fines could actually increase in spite of the uniformity being greater. This explains the experience of a quarry in the Cape that managed to increase the sand content from blasting by using EDs (Cunningham *et al.* 1998).

To address the adverse effect of timing scatter on uniformity, it is necessary to invoke the scatter ratio. The author described the crucial effect of precision on blasting effects at the EFEE in 2000, and introduced the concept of the parameter 'scatter ratio', R_s, defined as

$$R_s = \frac{T_r}{T_x} = 6\frac{\sigma_t}{T_x} \quad (10)$$

where R_s = scatter ratio; T_r = range of delay scatter for initiation system, ms; T_x = desired delay between holes, ms; σ_t = standard deviation of initiation system, ms.

The higher the scatter ratio, the less uniform will be the fragmentation curve. The following algorithm has been introduced to illustrate the expected effect of precision on blasting results:

$$n_s = 0.206 + (1 - R_s/4)^{0.8} \quad (11)$$

where n_s is the uniformity factor governed by the scatter ratio.

Figure 3 shows how the factor is currently configured, illustrating the assumption that delays used previously had a scatter ratio of about 1, i.e. that the shots would not overlap but could occasionally fire together. Adopting low scatter delays would increase uniformity by up to 20%, while the adverse affect of increasing numbers of out-of-sequence shots decreases uniformity by about the same amount.

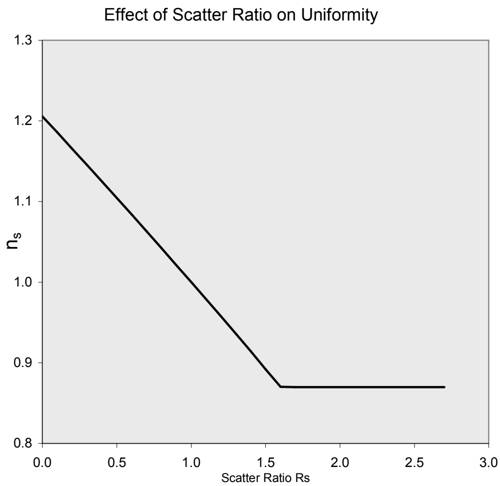

Figure 3. Influence of timing precision on the Rosin–Rammler uniformity parameter.

A useful aspect of this algorithm is that it portrays how precision becomes less important for long delays. A precision of 1 ms is very beneficial if the interhole delay is 10 ms. It hardly matters if the delay is 100 ms.

4.4 Effect of rock strength on uniformity

Something that has become increasingly evident over time is that the fragmentation is intrinsically more uniform in harder rocks. An expression has therefore been added to raise uniformity with rock factor A, taking 6 as the 'neutral' position:

$$F(A) = (A/6)^{0.3} \quad (12)$$

4.5 Rationalisation of geometric uniformity parameters

When the original parameters listed in (3) were being assembled, the exercise was undertaken in a controlled environment, and limiting values were not discussed. In addition, the parameter set was addressed as a whole with the information then to hand. Over the years the desire grew to improve the algorithm and make it less liable to generate obviously wrong answers. This has now been addressed, and will be under continual review.

Two issues resulted in a tendency to skewed results: (a) the lack of capping on the values, so that, for example, increasing the *S*/*B* ratio indefinitely led to infinite improvement in uniformity, and (b) the effect of pre-existing rock conditions often severely limits the ability of a blast design to change certain components of the fragmentation. This is difficult or impossible to cater for adequately in this kind of model. Therefore, the uniformity equation in particular needs to be viewed with caution, understanding the logic behind it. However, inasmuch as the rock is reasonably unjointed and solid, the ratios should nudge the uniformity in the indicated direction.

The *S*/*B* function is now capped so that, if it increases beyond 1.5, the *n* factor will not exceed 1.12, while if *S*/*B* falls below 0.5, the factor will not fall beneath 0.92. Increasing *S*/*B* becomes strongly detrimental with rectangular patterns, since it brings blastholes into widely spaced ranks of closely spaced holes. On the other hand, staggered patterns progress through a cycle of better and worse geometry, none of which is particularly bad.

Similarly, the burden/diameter expression has been capped between 25 and 35 diameters, and the expression for different charge lengths in the same hole has been removed owing to the complexity of expressing the effect meaningfully.

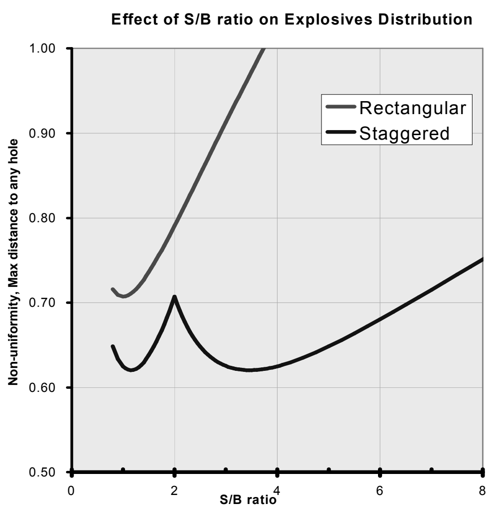

Figure 4. Effect of *S*/*B* ratio and layout on the maximum distance of any point from any hole.

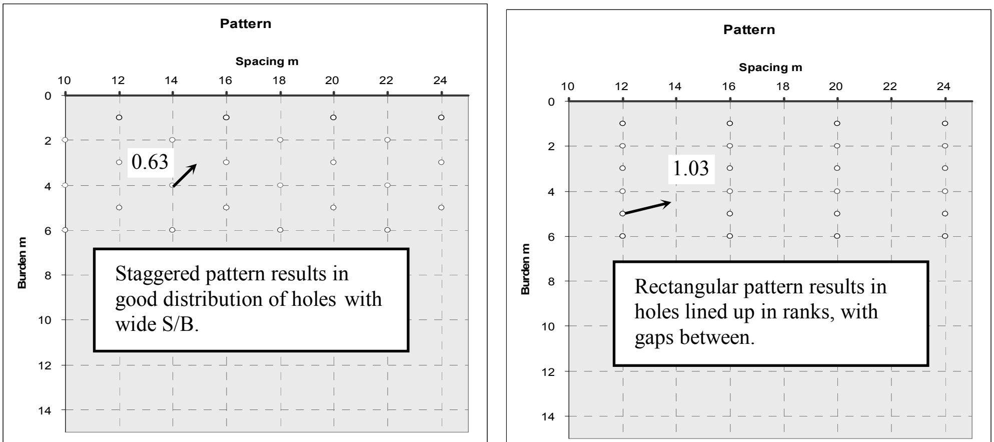

Figure 5. Effect of an *S*/*B* ratio of 4 with equivalent staggered and rectangular patterns. The arrow in each plot indicates the greatest distance from any one hole.

4.6 *Spacing/burden ratio*

The real effect of *S*/*B* is strongly dependent on whether the pattern is rectangular or staggered, illustrated in terms of uniformity by Figure 4, which, for a fixed drilling density, plots the furthest distance from any hole against spacing/burden ratio. Of course this is meaningless for less than two rows of holes, which is why the paper by Bergmann *et al.* (1974) cannot be used to advantage for this.

There is a clear disadvantage of rectangular patterns: as the *S*/*B* increases, the holes begin to line up in ranks, leaving large spaces between, while staggered patterns at their worst equal the best distribution of the rectangular pattern (which occurs at *S*/*B*=2, equalling a square pattern of *S*/*B* = 1). Figure 5 shows the comparison for *S*/*B* = 4 with both patterns.

It is not only the maximum distance to a hole that affects the uniformity: the breaking mechanisms are more favourable for reduced burdens, and the debate becomes considerably confused by referring to *S*/*B* ratios achieved by timing. However, the model treats the actual layout of the holes as the measure, leaving others to debate the merits of echelon ratios, with the caution that these are often skewed, especially if the basic layout is rectangular. The debate belongs outside this paper.

The algorithm for the *S*/*B* ratio has evolved with the assumption that, in practice, the ratio lies between 0.7 and 1.5, giving maximum and minimum multipliers of 0.92 and 1.12.

4.7 *Other ratios*

The current uniformity index parameter set and capping values are detailed in Table 1, showing a number of significant changes.

The burden/diameter ratio expression has been altered to have less influence, as has the charge length/bench height ratio. Because of some difficulty in adequately defining the effect of different explosives in the column, this expression has been omitted.

Table 1. Geometric parameters for uniformity equation.

Parameter α	$f(\alpha)$	α range	$f(\alpha)$ range
S/B	$[(1+\alpha)/2]^5$	0.7–1.5	0.92–1.12
30B/d	$(2-\alpha)^5$	24–36	1.2–0.9
W/B	$1-\alpha$	0–0.5B	1–0.5
L/H	$\alpha^{0.3}$	0.2–1	0.62–1
A	$(\alpha/6)^{0.3}$	0.8–21	0.5–1.45
Scatter ratio	n_s	0–1.6	0.87–1.21

S = spacing, m; *B* = burden, m; *W* = standard deviation of drilling, m; *d* = hole diameter, mm ; *L* = charge length affecting fragmentation, m; *A* = rock hardness factor.

As with the rock factor *A*, it can happen that the uniformity index is just not what the algorithm suggests, in which case correction factor *C*(*n*) is provided to overlay the above inputs and enable estimation of the effects of changes from a common base.

The new equations for mean size and uniformity are therefore

$$x_m = AA_T K^{-0.8} Q^{1/6} \left(\frac{115}{RWS}\right)^{19/20} C(A) \quad (13)$$

$$n = n_s \sqrt{\left(2 - \frac{30B}{d}\right)} \sqrt{\left(\frac{1 + S/B}{2}\right)} \left(1 - \frac{W}{B}\right) \left(\frac{L}{H}\right)^{0.3} C(n) \tag{14}$$

5 APPLICATION

With the wide range of key blasting parameters offered by this model, it has long been possible to test the likely effect on blast fragmentation of various options, and this capability is now somewhat enhanced. There is insufficient space in this kind of paper to illustrate the process in detail, but Figure 6 shows the kind of effect expected when introducing electronic delay detonators with shorter delays and no other change.

Reduced intervals have decreased the mean size, while eliminating scatter has improved uniformity, resulting in the virtual elimination of material in excess of 1 m, and a significant decrease in 1 mm fine material. The promised outcome is sufficiently attractive to motivate test blasting, as there should be an immediately apparent difference in working the rockpile. Whether the detection systems will easily pick up the actual rock fractions meaningfully is questionable, and an actual sieving may yield a different curve, but the strong trend should be evident.

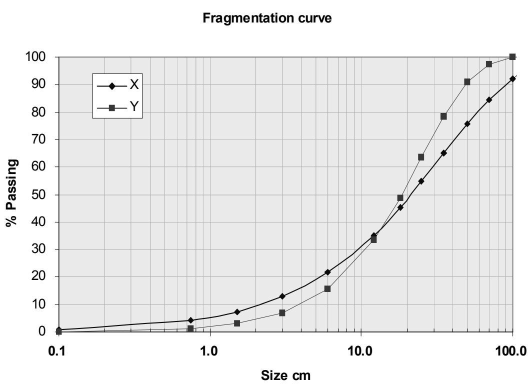

Figure 6. Effect of timing delay and precision on fragmentation. Identical geometry and powder factor, but *Y* has electronic delays with a 9 ms interval. *X* is pyrotechnics with a 25 ms interval.

6 PARALLEL MODELLING WORK

The main deficiency of Kuz–Ram modelling has been in the area of estimating fines, and the key work for remedying the deficiency is probably that of Djordevic (1999), Ouchterlony (2004) and Spathis (2004). These contributions cannot be discussed adequately here, other than to provide brief comment.

Djordevic (1999) attributes the excess of fines to the crush zone around each blasthole, and introduces a term to incorporate this ratio into the Kuz–Ram model. Ouchterlony (2004) recognizes that the Rosin–Rammler curve has limited ability to follow the various distributions from blasting, and introduces the more adaptable Swebrec function, which is able to define fines better. Spathis (2004), on the other hand, noticed that this author's use of the x_{50} term from Kuznetsov was at odds with the definition of the Rosin–Rammler 50% passing term, and that, for low values of n, there is a large deviation between the values. When corrected, the fines fraction in Kuz–Ram was considerably increased, which again improved the model. The disadvantage of these improvements is that they introduce yet another factor into a predictive model that is already somewhat extended. In view of the acknowledged coarse fit for this kind of approach, the introduction of these mathematically more satisfying models needs to be justified by the application.

The current situation is fluid, and the years ahead could see general convergence on a preferred approach. In the meantime, practitioners will experiment with and adopt what is at hand. The most important function of Kuz–Ram is to guide the blasting engineer in thinking through the effect of various parameters when attempting to improve blasting effects. Introduction of the blast timing algorithm should be of considerable help in this, especially with regard to electronic delay detonators.

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