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Rock Engineering Systems and Rock Blasting

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ROCK ENGINEERING SYSTEMS AND ROCK BLASTING

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ABSTRACT

Numerous rock blasting design methodologies have been developed over the years, relating either to the primary objectives of blasting, such as the size distribution of the blasted material, for example, or to its undesirable side effects, such as damage to the remaining rock mass, for example. All these existing methodologies do work to various extents and are useful, but are affected by more-or-less serious shortcomings. The question remains whether further improvements can be achieved in the field of practical rock blasting engineering. One alternate approach that seems to hold promise is the relatively new matrix-based rock engineer systems methodology. Various authors have demonstrated theoretically that this technique could be efficiently adapted to blasting – the question however lingers on the practical usefulness of the approach. This paper provides a brief overview of where practical rock blasting design techniques currently stand, and discusses some of the principal shortcomings associated with them. The basic concepts governing rock engineer systems are then presented, followed by a discussion on their pertinence to blasting.

SOMMAIRE

Systèmes d'ingénierie du roc et tirs à l'explosif. *De nombreuses méthodologies de conception d'abattage du roc à l'explosif ont été développées au cours des années, qui ont adressé soit les principaux objectifs des tirs, comme par exemple la granulométrie du matériel dynamité, soit ses effets secondaires indésirables, tels les dommages au massif rocheux. Toutes les méthodes existantes fonctionnent dans une certaine mesure et sont utiles, mais elles sont pour ainsi dire toutes affectées par des limitations ou défauts plus ou moins sévères. La question demeure quant à savoir si des améliorations supplémentaires peuvent être apportées dans le domaine de la conception pratique des opérations d'abattage du roc à l'explosif. Une autre approche qui semble prometteuse est celle relativement récente des systèmes matriciels d'ingénierie du roc. Divers auteurs ont démontré théoriquement que cette technique pourrait être efficacement adaptée aux dynamitages. Reste à savoir si cette approche peut offrir des solutions pratiques à ses usagers. Cet article présente brièvement l'état actuel des techniques existantes de conception des tirs du roc à l'explosif, et discute quelques-unes des principales limitations qui leur sont associées. Les concepts de base régissant les systèmes d'ingénierie du roc sont ensuite présentés, suivis d'une discussion sur leur pertinence à l'abattage du roc à l'explosif.*

KEYWORDS: blastability, rock blasting design and engineering, rock engineering systems.

1 – INTRODUCTION

Numerous rock blasting design methodologies have been developed over the years. They can broadly be categorised into simple rules-of-thumb, empirical procedures, analytical approaches, or numerical methods. The information sought after with these techniques can either relate to the primary objectives of blasting, such as the fragment size distribution of the blasted material, or the profile of the muck pile, or focus on the undesirable side effects, such as damage to the remaining rock mass, ground vibrations, air over-pressures and fly rock projections, for example. All of the existing methodologies are useful and do work to various degrees. Nevertheless, they all have shortcomings that may be critical, depending on the site conditions.

A key question remains whether further improvements can be achieved in the field of practical (as opposed to fundamental) rock blasting engineering. An interesting approach that seems promising is the relatively new matrix-based rock engineering systems methodology. Various authors have demonstrated that this technique in theory could be adapted to blasting. A lingering question is whether rock engineering systems can make the link between theory to practice, and provide a practical tool for blast design. This is the topic of a research programme currently underway at Laval University.

This paper provides a brief overview of where practical rock blasting design techniques currently stand, and discusses some of the shortcomings associated with them. The basic concepts governing rock engineering systems are then presented, followed by a discussion on their pertinence to blasting.

2 – CURRENT ROCK BLASTING ENGINEERING APPROACHES

Despite recent and spectacular advances over the past fifteen-twenty years, blasting engineering is still often perceived more like an art than a science. Blast design, similarly to geomechanics design techniques, can be grouped in four broad categories, which are rules-of-thumb, empirical procedures, analytical approaches and numerical methods.

2.1 – Rules-of-thumb

Rules-of-thumb are simple relations that typically link two blast parameters together. For example, statements such as "burden should be 25 to 30 times the blasthole diameter", or "spacing should be 1.0 to 1.8 times the burden" are typical rules-of-thumb. Even though useful, these rules are quite crude and simultaneously consider very few of the numerous parameters known to play an important role in blasting.

2.2 – Empirical techniques

Empirical techniques attempt to predict the outcome of the blasting process based on observed past behaviour and readily available input parameters – they are the result of a matching process between the results obtained, the design parameters used and observed prevailing pre-blast conditions. Numerous such empirical schemes have been developed over the years, such as the Kuz-Ram method (Cunningham, 1983 and 1987), the comminution theory-based Da Gama approach (Da Gama, 1983), the Blastability Index concept (Lilly, 1986), and the JKMRC concept (Scott, 1996), to name only a few. Empirical techniques typically encompass only some of the numerous parameters actually influencing blasting results. The parameters considered in each method are usually a reflection of the governing factors present in the case studies used to derive it. As a result, a given method is generally best suited at solving specific problems in which only the few parameters it addresses are varying or are dominant. The difficulty and tediousness associated with an empirical method often increase with the number of parameters considered in it. Despite some limited theoretical foundations, empirical design techniques are widely used, as they are fast and easy to apply, and typically not too susceptible to small assessment errors in their governing parameters. Empirical methods can provide reasonably accurate answers, as long as they are used inside the limits within which they were developed.

2.3 – Analytical techniques

Analytical techniques attempt to analyse blasting by using fundamental physical principles. In such schemes, thermodynamics equations are often used to consider the detonation energy, fracture mechanics are used to describe how the explosive energy is breaking the material, ballistics are used to study throw and muck pile profile, etc. Such approaches describe the blasting process well, are based on sound and well-established physical concepts, and treat the problem from a "scientific" point of view.

These methods are however not without limitations, particularly due to their explicit nature. For example, even though they can very well take into account the effect of a given pre-existing fracture within the rock mass, much of this information is rarely available beforehand in a detailed way. Furthermore, a number of physical parameters required for such analyses are seldom available, unless extensive site investigation is carried out. In other words, analytical techniques are very powerful and thorough, but often require more input data than is usually available. An analytical representation of the geological structural regimes is often not possible. This results in the "missing data" being approximated or derived from experience, which undermines some of the credibility of the approach by rendering it more empirical. Another limitation is the near-impossibility to use such techniques on a daily basis, due to their complexity. Even two-dimensional problems usually require the usage of powerful computer codes. The BLASPA programme (Favreau, 1980 and 1983) is probably one of the best examples of an analytical approach.

2.4 – Numerical methods

Numerical techniques attempt to resolve the stress-deformation-displacement state through a mathematical representation – or model – of a real-life problem by subdividing this model into small zones on which "manageable" and relatively simple calculations can be applied. By performing a large number of such calculations on each small zone, it can be possible to study complex mechanical behaviours anywhere throughout the zones of interest in the inner part of the model. Engineering numerical approaches have made tremendous progress in the past fifteen years, as computing power has become both more powerful and affordable. These techniques, although very effective, are also not without limitations. Firstly, due to the gigantic amount of calculations typically involved, the complex numerical models needed to study the blasting process must typically be run on powerful computers over significant periods of time, which basically precludes their routine usage. Secondly, setting up numerical models takes time, with the amount of time required rapidly increasing with the complexity of the situation to analyse, which further precludes their routine usage. Importantly, numerical modelling is always a simplification of the real-life situation, and provides only indications on the likely behaviour of the full-scale problem when subjected to the set of conditions considered in the model. Contrary to other engineering disciplines involving well-known processes, like in the field of electronics, for example, the numerical modelling of rock does not provide absolute results. The main reasons are the many unknowns involved, such as the rock mass structural characteristics, the exact loading regime applied to it and the actual failure mechanisms involved. The static numerical analysis of stress, deformation and displacement is difficult enough – dynamic analyses are far more complex, and, in the particular case of blasting, the difficulty is compounded by the fact that blast-related codes must also be inelastic. Few "civil" inelastic numerical codes (by opposition to the generally classified and unavailable "military" codes) can reproduce somewhat properly the blast-induced fracturing process, and those who can require so much computing power that only small-scale problems can realistically be addressed. Numerical instability can quickly develop with even the most advanced of numerical codes available in geomechanics for quasi-static conditions, due to the tremendous forces acting on the numerical elements over extremely short periods of time, which create problems such as numerical elements interpenetrating, for example. Material separation is also not easily addressed numerically when starting with a continuum, or even with discrete elements.

The PRONTO (Attaway, 1990), Bedded Crack (Margolin, 1981), NAG-FRAG (McHugh, 1983), SHALE (Adams *et al.*, 1983) and DDA (Shi, 1993; Ohnishi *et al.*, 1995) models are examples of numerical methods for blasting. Overall, and despite the promise they hold, numerical methods are not commonly used.

2.5 – Hybrid methods

Hybrid techniques were also developed, usually encompassing some physics-based concepts supplemented by empirically-developed relationships. Such approaches constitute an interesting compromise as they provide a better scientific basis than purely empirical methods, while remaining easier to use than full-fledge analytical or numerical techniques. The Orica Sabrex programme (Harries, 1973) is one example of a hybrid method.

Although each method has its own advantages and benefits, it is the authors' opinion that there is neither a general concept nor a technique that encompasses and considers all the relevant aspects of blasting.

3 – BLASTING PARAMETERS OF INTEREST

The relevant aspects of blasting can be broadly regrouped in four categories: the small-scale mechanical properties of the intact material comprising the rock mass; the larger scale mechanical properties of the rock mass itself; the parameters relating to the explosive products used; and, the parameters relating to the way these explosive products are used. The next four sections discuss each category.

3.1 – Small-scale mechanical properties of the intact material comprising the rock mass

The most widely considered small-scale mechanical properties of the intact rock are the density and the uniaxial compressive strength. There are however numerous other properties that can be argued to have an impact on blasting, such as the friction angle, the cohesion, the tensile strength, and, to a certain extent, the triaxial compressive strength at various levels of confinement. This later property essentially leads to the consideration of failure envelopes, which are generally considered in inelastic numerical methods. Other parameters such as stiffness, brittleness, acoustic properties and porosity, among others, can also be argued to affect blasting performances to various extents.

3.2 – Large-scale mechanical properties of the rock mass

The mechanical properties of the rock mass play a crucial role and heavily influence the blasting results. Those properties of particular interest with regard to blasting can be argued to be, at a minimum, a broad description of the rock mass (massive, jointed, or friable, as with the Cunningham-enhanced Kuz-Ram approach), and, a step further, a consideration of the small-scale geological structures (such as bedding, foliation, jointing, or inclusions), as well as a consideration of the large-scale geological structures (such as slips, shears, contacts, intrusions, or faults). Ideally, the full in situ block size distribution of the rock mass should be considered, since it has been shown to have a profound influence upon the post-blast fragment size distribution. Previously accumulated damage and the local stress state within the rock mass can also be argued to be relevant parameters with regard to blasting.

3.3 – Parameters relating to the explosive products used

In terms of the parameters of the explosive products used, the most often encountered is the density. Strength, when considered, is usually expressed in terms of either the weight strength (strength of a given mass of the product as compared to the same mass of AnFO), or the bulk strength (strength of a given volume of the product as compared to the same volume of AnFO). The velocity of detonation is sometimes considered in higher-end techniques, as it governs the detonating pressure of the product. Only very few approaches do consider more advanced explosives parameters such as the energy partition (shock *vs.* gas), or the full non-ideal thermodynamic properties of the products used.

3.4 – Blasting design parameters

The most widely used blasting parameters are a scaled explosive charge weight, usually expressed in terms of powder factor, and the burden and spacing. Few approaches go far beyond these simple terms, to address more complex parameters such as the *effective* charge confinement (also sometimes referred to as the "fixation factor"), the spatial charge distribution (heavily influenced by the drilling pattern, which can be fanned, square, diced, zipper, etc.), and the charge coupling ratio, for example. The all important initiation issue, in terms not only of the sequence, but also of the detonators chosen to implement it and the scatter associated with them, is addressed only in the most advanced of design methods.

The key question remains whether or not we can do better, and whether or not we can improve our ability to rationally design blasts in a practical manner.

4 – ROCK ENGINEERING SYSTEMS

As discussed in Section 2, the blast design methodologies currently available all suffer from some sort of limitation. The rules-of-thumb are overly simplistic, the empirical methods only consider a few of the relevant parameters, the analytical approaches are impaired by the fact that the required input parameters are rarely all available, and the numerical techniques typically require both time, computing power and advanced skills to be effective. There certainly is a need for a "pseudo"-empirical approach that would consider "all" the relevant parameters, as discussed in Section 3, address the scale of a full blast, implicate simple mathematics and be intuitive.

One approach that seems to combine these requirements in the Rock Engineering Systems (RES) approach proposed by Hudson (1992). Figure 1 illustrates the basic principle of the interaction matrix, as derived by Hudson. As with every matrix, the data are arranged in boxes tagged *(i,j)*, *i* referring to the position along the horizontal axis, and *j* referring to the position along the vertical axis, the reference *(1,1)* being located in the upper left corner of the matrix. With this approach, the engineering parameters of interest are located along the diagonal of the matrix, i.e., in boxes*(i,i)* and *(j,j)* in Figure 1.

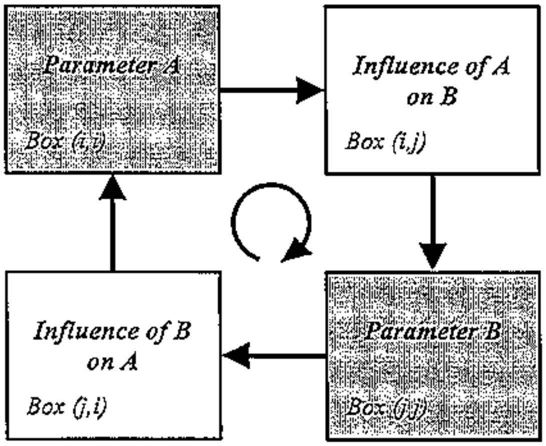

Figure 1. The basic principle of the interaction matrix. (After Hudson, 1992.)

The upper path between Parameter A in box *(i,i)* and Parameter B in box *(j,j)* corresponds to the influence Parameter A has on Parameter B. Reciprocally, the lower path between Parameter B in box *(j,j)* and Parameter A in box *(i,i)* corresponds to the influence Parameter B has on Parameter A. This approach essentially recognises that every pair of parameters *influence each other*: changing one affects the other, which, once adjusted consequently, affects the initial parameter back again.

One simple example of the usage of this scheme is provided by Hudson himself, and concerns construction projects in hard rock, as shown in Figure 2. In this case, four parameters are retained, located along the diagonal of the matrix, and highlighted in light grey. These are the structure of the rock mass, the ground stresses, the quantitative hydrology and the construction itself.

The qualitative interactions between the various parameters are shown in the off-diagonal boxes. As shown in Figure 2, each of the four parameters affects all the other ones. All the direct influences are indicated on the top part of the matrix (in the upper-right side from the diagonal), while the indirect, or "back" influences are indicated on the bottom part (in the lower-left side from the diagonal). For example, considering the rock structure and water inflow parameters, we have the following relationships. From rock structure to water inflow : "the fracture network governs the secondary permeability" [box (1,3)]; and, from water inflow to rock structure : "continual water flow in fractures affects their properties" [box (3,1)]. The interaction matrix, by nature, is non-symmetrical.

Such interaction matrices are normally larger that four by four. There is conceptually no limit on the number of parameters one can include in a single matrix, albeit it becomes impractical to consider too many. An alternate way to building a difficult to handle single large matrix is to build a number of sub-matrices. With this approach, a given parameter in a matrix can be related to another matrix that deals specifically with it.

Rock Structure F_{ij} Box (1,1)	Fractures affect the values and orientations of the stresses Box (1,2)	The fracture network governs the secondary permeability Box (1,3)	Fractures can influence the size and orientation of excavations Box (1,4)
Stresses can open or close fractures, and also create them Box (2,1)	*Rock Stress* σ_{ij} Box (2,2)	In general, the higher the normal stress, the lower the permeability Box (2,3)	High rock stresses can cause construction failures Box (2,4)
Continual water flow in fractures affects their properties Box (3,1)	Normal stresses are reduced by water pressure Box (3,2)	*Water Flow* K_{ij} Box (3,3)	Grouting and drainage may be required during construction Box (3,4)
Blasting can damage old fractures and create new ones Box (4,1)	In the vicinity of excavations the principal stresses are altered Box (4,2)	An excavation will always become a sink for the water flow Box (4,3)	*Construction* C_{ij} Box (4,4)

Figure 2. Four by four interaction matrix for a construction project in hard rock, with four leading diagonal terms: rock structure, rock stress, water flow and construction. (After Hudson, 1992.)

Assigning numerical values to the interaction boxes (*i,j*) is referred to as "coding" the matrix. There are a number of procedures that can be used to perform this task, such as the binary approach (whereby the values can be either 0 or 1), the expert semi-quantitative (ESQ) method (where the interaction between parameters is ranked on a 0 to 4 scale), or continuous quantitative coding schemes (based upon the slope of the P_i *vs.* P_j relationship, or on analytical or numerical analyses-derived relationships) by order of increasing complexity.

Figure 3 illustrates what coding allows to do. The sum of each row, called the cause C of the parameter P_i, quantifies the way in which P_i affects the system, while the sum of each column, called the effect E of the parameter P_i, quantifies the way in which the system affects P_i.

These C and E values can be plotted against each other in a C-E plot, which identifies the major contributing factors and the principal interactions within the system. The C-E plot can also be used to assess various values, such as parameter dominance (defined as the perpendicular distance of a given parameter's C-E point from the C=E line), or parameter intensity (defined by how large a given parameter's C and E values are), for example.

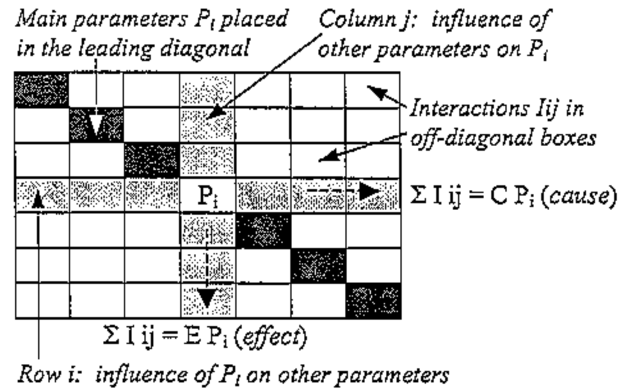

Figure 3. Coding of the interaction matrix, and cause and effect co-ordinates. (After Latham & Lu, 1999.)

This engineering scheme is intuitively quite adequate to represent the blasting process, whereby pairs of parameters do influence each other reciprocally. For example, one can consider the lowering of the explosive strength and the required burden. Selecting a weaker explosive product does require the burden to be reduced accordingly. Once the burden has been diminished, it may influence, in turn, the effective strength of the explosive product by changing the amount of confinement the charges are subjected to. Indeed, reducing the confinement reduces the amount of time before the high pressure detonation gasses find a free face and vent back to atmospheric pressure, effectively reducing the amount of useful breaking work done.

Contrary to the empirical methods commonly employed, which become more cumbersome and difficult to use as the number of parameters considered increases, the matrix-based approach provides an orderly scheme whereby large numbers of parameters can be considered in an thorough, organised and practical fashion.

5 – ROCK ENGINEERING SYSTEMS AND PRACTICAL ROCK BLASTING

Some work has been accomplished in trying to adapt the RES approach to rock blasting, mainly through the concept of blastability, which is an empirical concept that was "formally" introduced by Lilly in 1986, and is defined as the ease with which a rock mass can be fragmented by blasting. Blastability is interesting because it aims at considering the overall mechanical properties of the rock mass, which are often a large oversight of many common empirical blast design approaches.

A basic premise with blastability is that the blasting process changes the size distribution of the rock from a natural in situ block size distribution to a fragment size distribution. This intuitively sound concept, suggested by Hudson and Harrison (1997), is illustrated in Figure 4.

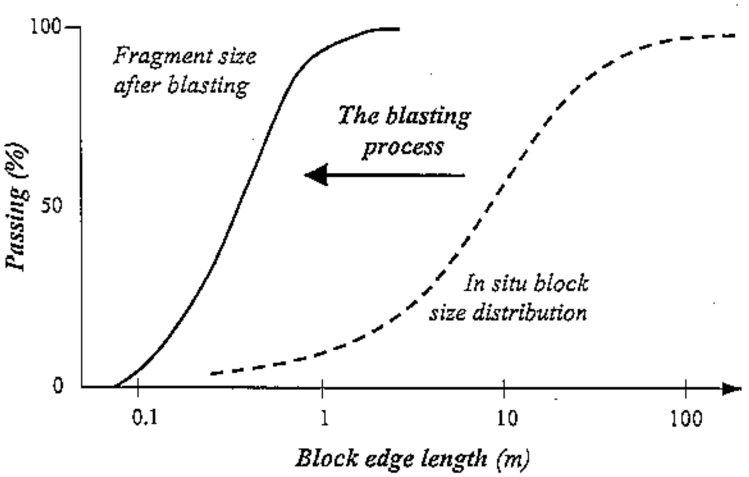

Figure 4. The blasting process in rock. (Adapted after Hudson & Harrison, 1997.)

Grenon *et al.* (1998) have validated this approach by presenting case studies from an underground mine where the excavation processes that control the passage from the in situ block size distribution to the post-excavation fragment size distribution were investigated. In their work an in situ block size distribution was determined by using the results of scanline mapping to develop a realistic three-dimensional joint network using a joint generator scheme (Stereoblock). Figure 5 shows the in situ block size distribution (represented by the "Stereoblock" curve) of a rock mass at the Noranda Heath Steele mine, and the post-blast block size distribution of the same rock mass, as determined by two image analysis software packages (the Split and the Canmet systems). These results clearly show that the blasting process involved a reduction in the block size distribution, from a coarse in situ state to a finer post-blast one.

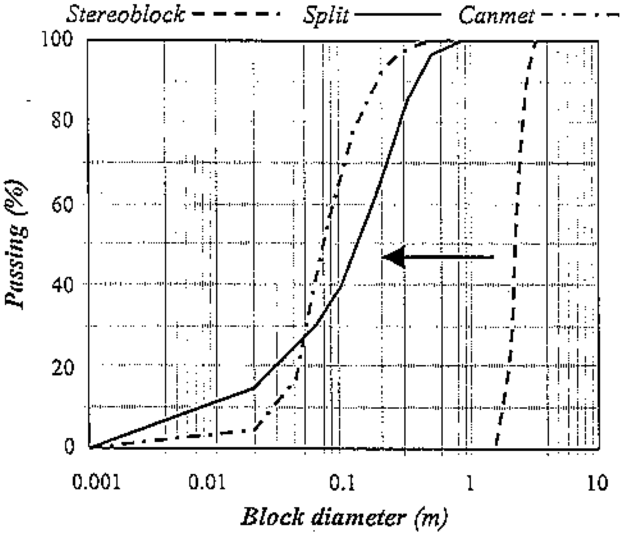

Figure 5. The change of the rock mass block size distribution prior to blasting ("Stereoblock" curve) to after ("Split" and "Canmet" curves). (After Grenon *et al.*, 1998.)

Latham and Lu (1999) have investigated the opportunity of using rock engineering systems to specifically describe the overall interactive mechanisms of rock blasting, and explored, in particular, the possibility of employing RES specifically for the assessment of the blastability of a rock mass. As shown in Figure 6, Latham and Lu suggested that two rock masses having identical natural in situ block size distributions (referred to as the In situ Block Size Distribution-Common, or IBSD-C) subject to the same blast design can have two distinct blasted rock size distributions (Blasted Block Size Distribution-1 and -2, or BBSD-1 and BBSD-2, respectively). Since both rock masses are blasted the same way and, hence, are subject to identical amounts of explosive energy, then the resulting distinct fragmentations can be argued to be necessarily controlled by the inherent blastability of each rock mass. This is a powerful approach since it considers the properties of the rock mass to the extent that they can significantly affect the predicted results, even if the explosives used and the blast design implemented are similar.

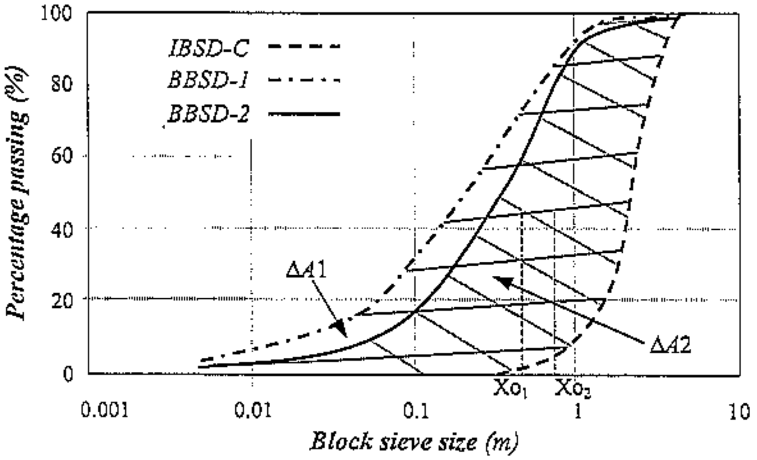

Figure 6. The concept of blastability. (After Latham & Lu, 1999.)

The quantities $\Delta A1$ and $\Delta A2$ in Figure 6 are the transformation areas for the two different rock masses subjected to the same amount of explosive energy and the same blast designs. Rock mass #2 is intrinsically more difficult to blast than rock mass #1 as indicated by $\Delta A2$ being smaller than $\Delta A1$, which results in curve BBSD-2 being coarser than curve BBDS-1. The difference between $\Delta A1$ and $\Delta A2$ indicates the difference in blastability between the two rock masses. The values Xo_1 and Xo_2 along the x-axis of Figure 6 represent the centres of gravity of the transformation areas of rock mass #1 and #2, respectively. As the value of Xo_i moves left towards finer material, the blastability of the rock mass improves. The explosive energy input per unit rock mass that is consumed in reducing the rock mass from its in situ block size distribution IBSD to a finer blasted fragment size distribution BBSD has been shown by Latham and Lu to be related to the transformation area ΔA and, hence, to Xo. This scheme thus not only considers an all-encompassing blasting-relevant property of the rock mass, but also the explosive energy input per unit rock mass, which is dependent upon the explosive products used and the blast design implemented. In developing a blasting interaction matrix to construct a rock mass Blastability Index, Latham and Lu identified a series of relevant parameters P_i, as shown in Figure 7.

P_i	*Factors affecting blastability*	*Depicting parameter*
P_1	Strength	Uniaxial compressive strength
P_2	Resistance to fracturing	Uniaxial tensile strength
P_3	Sturdiness	Density
P_4	Elasticity	Young's Modulus
P_5	Resistance to dynamic loading	P-wave velocity
P_6	Hardness of rock	Schmidt hardness value
P_7	Deformability	Poisson's ratio
P_8	Resistance to breaking	Fracture toughness
P_9	In situ block size	Mean block size (K_{50})
P_{10}	Fragility of rock mass	Fractal dimension of in situ rock mass
P_{11}	Integrity of rock mass	Ratio of P-wave in field to that in lab RQD
P_{12}	Discontinuity's plane strength	Cohesion, friction angle

Figure 7. Coding values of the blastability interaction matrix. (After Latham & Lu, 1999.)

Based upon the RES principles discussed earlier, these parameters are placed along the leading diagonal of a 12 by 12 interaction matrix. Using a normalised scaled continuous quantitative scheme, Latham and Lu (1999) have coded this matrix with the values shown in Figure 8. (They have acknowledged that in this case, and due to the complexity of the process, some of the coding ended up being carried out by means of objective measurements and/or subjective judgement.)

$$\begin{pmatrix}
P_1 & 0.65 & 0.70 & 0.85 & 0.65 & 0.55 & 0.40 & 0.75 & 0.50 & 0.55 & 0.30 & 0.40 \\
0.75 & P_2 & 0.40 & 0.45 & 0.65 & 0.50 & 0.40 & 0.65 & 0.60 & 0.45 & 0.50 & 0.50 \\
0.90 & 0.75 & P_3 & 0.80 & 0.70 & 0.80 & 0.45 & 0.50 & 0.25 & 0.25 & 0.20 & 0.20 \\
0.80 & 0.50 & 0.70 & P_4 & 0.60 & 0.60 & 0.55 & 0.25 & 0.45 & 0.30 & 0.45 & 0.15 \\
0.45 & 0.65 & 0.70 & 0.45 & P_5 & 0.50 & 0.25 & 0.45 & 0.45 & 0.40 & 0.25 & 0.45 \\
0.70 & 0.50 & 0.75 & 0.40 & 0.50 & P_6 & 0.25 & 0.45 & 0.35 & 0.35 & 0.45 & 0.40 \\
0.40 & 0.20 & 0.40 & 0.65 & 0.25 & 0.45 & P_7 & 0.50 & 0.20 & 0.25 & 0.25 & 0.15 \\
0.50 & 0.70 & 0.20 & 0.20 & 0.15 & 0.50 & 0.35 & P_8 & 0.40 & 0.25 & 0.20 & 0.30 \\
0.25 & 0.30 & 0.25 & 0.50 & 0.35 & 0.25 & 0.30 & 0.40 & P_9 & 0.80 & 0.65 & 0.45 \\
0.65 & 0.60 & 0.30 & 0.35 & 0.25 & 0.35 & 0.40 & 0.55 & 0.65 & P_{10} & 0.80 & 0.20 \\
0.45 & 0.45 & 0.20 & 0.60 & 0.60 & 0.45 & 0.20 & 0.15 & 0.50 & 0.55 & P_{11} & 0.25 \\
0.25 & 0.65 & 0.10 & 0.30 & 0.45 & 0.25 & 0.15 & 0.50 & 0.55 & 0.25 & 0.30 & P_{12}
\end{pmatrix}$$

Figure 8. Results of the blastability interaction matrix coding. (After Latham & Lu, 1999.)

The interest of this approach lies first in identifying the critical factors that affect blastability. Whether the selected parameters are adequate or even whether they include redundant elements can undoubtedly be the topic of spirited discussions. In reviewing existing literature it certainly can be argued that there is no consensus regarding exactly which parameters should be considered in rock blasting engineering. The second important question lies in how the selected parameters are defined.

In certain cases, as with the uniaxial compressive strength the authors have chosen to represent the strength parameter, values are easy to determine. In other instances, however, deriving the parameter value is not so easy. The rock mass fragility parameter is a good example, whereby the authors suggested to use the fractal dimension of the in situ rock mass to represent it.

As mentioned earlier, this approach has the merit of considering the blastability of the rock mass, which itself encompasses a number of relevant rock mass properties. Figure 9 is a comparison of the parameters addressed in the Blastability Index proposed by Latham and Lu in 1999 with those discussed in sections 3.1 and 3.2.

Mechanical properties	*Considered in Blastability Index*	*Appearance in Blastability Index*
Small-scale mechanical properties of the intact material comprising the rock mass		
Density	Directly	P_3 (sturdiness parameter)
Uniaxial compressive strength	Directly	P_1 (strength parameter)
Friction angle	No	---
Cohesion	No	---
Tensile strength	Directly	P_2 (resistance to fracturing parameter)
Triaxial compressive strength at various levels of confinement	No	---
Failure envelopes	No	---
Stiffness	Directly	P_4 (elasticity parameter – via Young's Modulus)
Brittleness	Indirectly	P_6 (hardness of rock parameter – via Schmidt hardness value)
Acoustic properties	Directly	P_5 (resistance to dynamic loading parameter – via P-wave velocity)
Porosity	No	---
---	---	P_7 (deformability parameter – via Poisson's ratio)
---	---	P_8 (resistance to breaking parameter – via fracture toughness)
Large-scale mechanical properties of the rock mass		
Small-scale geological structures (bedding, foliation, jointing, inclusions)	Partially	P_{12} (discontinuity's plane strength parameter – via cohesion and friction angle)
Large-scale geological structures (slips, shears, contacts, intrusions, faults)	Partially	P_{12} (discontinuity's plane strength parameter – via cohesion and friction angle)
Full in situ block size distribution	Partially (but the basic approach does fully consider it via the energy-related transform area concept)	P_9 (in situ block size parameter – via K_{50} value)
Previously accumulated damage	Indirectly	P_{11} (integrity of the rock mass parameter – via $V_{P\ field} / V_{P\ lab\ sample}$)
Stress state	No	---
---	---	P_{10} (fragility of rock mass parameter – via fractal dimension of in situ rock mass)

Figure 9. Comparison of the parameters addressed in the Blastability Index as per Latham & Lu (1999) with those discussed in sections 3.1 and 3.2.

The mechanical properties of the rock mass, at both the scales of the intact rock material and the full rock mass, as discussed in sections 3.1 and 3.2, respectively, are listed in the left hand-side column. The parameters considered in the Blastability Index scheme of Latham and Lu (1999) appear on the right hand-side column. The centre column comments on whether or not both match. Certainly, the mechanical properties discussed in sections 3.1 and 3.2 are arguable, in terms of their relevance, completeness and redundancy, but the objective of this comparison is merely to try to assess how far the Blastability Index goes in considering relevant rock mass properties. As can be seen in Figure 9, the method falls short of considering the triaxial compressive strength of the intact rock material, or its complete failure envelope. The cohesion and friction angle are also not considered – these would allow to easily derive triaxial strength values and a linear Mohr-Coulomb failure envelope, which, even though static, would better represent the strength of the material comprising the rock mass.

The Blastability Index addresses rather well the rock mass properties. In terms of the natural in situ size distribution, and even though only the mean K_{50} value is explicitly considered, the approach, as shown in Figure 6, is conceptually based upon the full-scale size distributions before and after blasting, as it uses them to derive the transform area between the two, which is representative of the explosive energy inputted into the system during the blasting process. It is unclear at which scale the P_{12} parameter, which addresses the discontinuity's plane strength via its cohesion and friction angle, applies.

6 – CONCLUSIONS

A sizeable number of design methodologies for rock blasting have been developed over the years. Despite their popularity and range of applications they do have some inherent technical and practical limitations. The matrix-based rock engineer systems methodology is a novel approach that seems to hold promise. Previous authors have shown that this technique holds good potential to quantify the blastability of a given rock mass and that it could be efficiently adapted to describe blasting at large. Certainly, the RES approach does provide a rational structure to describe the blasting process and the interaction between the various parameters governing it.

Besides considering the rock mass properties to a significant extent through the Blastability Index, the method conceptually addresses the impact of the explosive products used and the blasting design retained. It is these factors that control the energy input per unit rock mass, which, when combined with the Blastability Index, govern the resulting post-blast size distribution.

The challenge now consists in integrating the explosives and blast design aspects to the Blastability Index. For this purpose, an Energy Block Transition (E-B-T) model needs to be developed, based upon the assumption that the explosive energy released in the blasting process essentially results in a transition from an in situ rock mass block size distribution to a blasted fragment size distribution. Current work at Laval University aims at better conceptualising the blasting process within the matrix-based framework provided by the RES approach. As mentioned, efforts are underway to derive a practical and comprehensive rock engineering system for rock blasting.

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