Evidences of the influence of the detonation sequence in rock fragmentation by blasting – Part I

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Abstract

Drilling and blasting are fundamental operations in the mining cycle and constitute an important component of the mining costs. Rock fragmentation can in principle be managed by means of two options: by increasing or reducing the specific consumption of explosives, or by modifying the drilling pattern. The choice of one or other type of control depends on the relationship between the unit costs of drilling and explosives, and on technical restrictions or regulations imposed by different reasons. It is then necessary to identify the link between the blast design and some factors affecting the downstream processing of the product. This paper analyzes the theoretical basis aimed at evaluating the main parameters involved when organizing a production blast in open pit quarries. In particular, a method developed through the analysis of the results in a large number of limestone open pit quarries in Italy is described and commented. The first experimental results in Brazil have been obtained by applying this method at the Experimental Mine of the Research Center of Responsible Mining of the University of São Paulo. Experimental methods and results will be analyzed and discussed in the second part of this paper.

keywords: Drill & blast, bench blasting, rock fragmentation, downstream processing, KPIs.

1 Introduction

In most mining operations, the rock is subjected to several processes to become a commercial product (Kanchibotla, 2003). In designing a blast, the geometry is a very important factor (shape and size of the charges and the volume assigned to them, position and extent of the free surfaces, position of the charges with respect to that volume), but also the amount and type of explosive and the timing sequence play an important role. Everything should be established in view of the desired effect, and containing, as much as possible, the side effects (Mancini & Cardu, 2001).

Drilling and blasting is an important step in this process and the results, such as fragmentation, muck-pile shape and looseness, dilution, damage and rock softening affect the efficiency of downstream processes (Richard *et al*., 1982, Roy & Singh, 1998; Konya & Walter, 1990; Oriard, 2005). The importance of blasting for downstream processes has been studied and discussed by many researchers. Nielsen and Kristiansen (1996) investigated the effect of blasting on crushing and grinding operations and discussed how to evaluate the application of the comminution system. From industrial tests and laboratory experiments, they found some relationships between blast-hole diameter, amount of explosives, detonation velocity, and percentage of fines generated after blasting and crushing. They pointed out that the gap between mining and mineral processing should be harmonized, and suggested that blasting could be considered as the first step of the integrated comminution process for the optimization of the mine operations.

Eloranta (1995, 1997) compared energy requirements for blasting, crushing and grinding; Nielsen (1998, 1999) studied the effect of blasting on grinding using the micro-crack concept. He suggested that the P-wave may generate two sets of micro-cracks in the rock: upon detonation, a longitudinal wave propagates outwards from the borehole; the wave has a compressive component in the radial direction and a tensile component in the tangential direction. Due to the deformations from the tensile component, new cracks may be formed when the stress level exceeds the dynamic tensile strength of the rock. Blast-induced micro-cracks generated by the shock-waves emitted throughout the rock mass by the explosive affect the reduction of the crushing resistance.

Kanchibotla (2003), Kojovic *et al*. (1995) and McCarter (1996) presented typical problems of the traditional approach to blast optimization, introducing an approach where the influence of blast results on processing costs (crushing and separation), throughput (revenue and operating costs), and profit. All of them showed that the optimum blasting effect should consider all of the above components.

An important parameter, often linked to the distribution of explosive energy in the blast, is the drill-hole diameter: it controls the distribution of energy in the blast and thus it affects fragmentation (Clark, 1987; Hustrulid, 1999; Eloranta, 1995). Large diameters are often associated with the expansion of drilling patterns; however large holes intersect fewer in-situ blocks of rock, resulting in more oversize, especially in the case of jointed rock (Rajpot, 2009). Typically, the drill-hole diameter is changed depending upon the rock or drill machine type. Similarly, changes in the bench height when a new loading machine is introduced or for any other reason, affect changes on all dependent parameters or on the blast muck-pile size mix. Modifications in a drill-hole diameter or a bench height or a product size tend to change all other relevant blast design parameters. Changes in the bench height or drill-hole diameter, when the product size is required to be kept constant due to market demand or crusher/grinder requirements, result in changes in all other parameters and ultimately changes in the capital and operational cost of drilling, and the cost of blasting (Jimeno *et al*., 1995). Comparative calculations in every case allow the designer to determine the optimum cost parameters.

Size reduction represents one of the most energy-intensive and costly processes in the excavation of rocks. Drilling and blasting, being the first operation in the size reduction chain, may have a significant downstream effect (Kim, 2010). Since the effects of blasting on size reduction, crushing and throughput have been well established (Nielsen and Kristiansen, 1996;McCarter, 1996, Eloranta, 1995, 1997), the main focus of this research is to examine the effect of different timing sequences on fragmentation, although the subject has been extensively treated in many aspects: Katsabanis *et al*. (2006) conducted a series of multi-hole blasting experiments to examine the effect of delays on fragmentation using igneous rock samples. The tests showed the influence of the interaction of stress waves on fragmentation. Kim S.J. (2010) performed four different blasts with different charging methods adopting the same powder factors to compare how energy distribution affected changes in fragmentation. Experimental evidence under small scale conditions (Katsabanis *et al*., 2008) has suggested that fragmentation is very coarse when zero delay is used but the average fragment size does not change much once small delays are used.

The blasting size reduction effect due to timing was also investigated(Cho & Kaneko, 2004) through a number of models they used to consider the effect of specific charge and geometry in bench blasting. To investigate the influence of blast condition on fragmentation in bench blast simulations, the fragmentation obtained using the numerical approach was compared and analyzed. After having simulated widely spaced blast patterns, they compared the fracture process and fragmentation with that in wide-ranging bench blasting, also discussing controlled fragmentation with respect to delay timing. They concluded that the optimal fragmentation with respect to delay time depends strongly on the gas flow through the fractures caused by the stress wave.

Stagg (1987) refers to some reduced-scale tests in dolomite benches, using 0 to 45 ms delay intervals, equivalent to 0 to 118ms/m of burden. All fragmented rock was screened. The finest fragmentation occurred at blast-hole delay intervals of 3 to 56ms/m of burden; coarse fragmentation resulted from short delays (<3ms/m), where breakage approached presplit conditions with a major fracture between blast-holes and large blocks in the burden region. Coarse fragmentation also resulted from long delays (>17 ms/m), with explosive charges acting independently. The acceptable range provides blast design tools useful for a variety of purposes, including optimum muck-pile displacement and vibration control.

The optimization of the final rock fragment size on a cost basis must result in the minimum total cost that the drilling and blasting design parameters can generate: it is common for operators to search for the optimum drilling and blasting cost. However, when no fragmentation specifications are provided, this is an unclear target. In the same way, it is quite common for quarry operators to be concerned with fragmentation when difficulties in drilling and loading are encountered, or when a large amount of oversize is produced, resulting in a general loss of productivity in secondary blasting: this was the problem encountered at the quarry site under study and, on this basis, a number of experimental blasts were performed and the blasting size reduction effect was recognized, as shown below.

2. Blast design method

A specific method was determined to establish the Powder Factor to achieve a fragmentation with the desired top-size. The method was developed by Clerici *et al*. (1974), based on the analysis of the results of over 250 blasts in Italian limestone quarries for different applications (Figure 1). Diagram I represents the particle size of the blasted material (cumulative distribution), in dimensionless form, as the abscissa shows the ratio between the "desired size" of the fragments D and that of the maximum block size in the blasted material D_{max}. Diagram II shows the correlation between two dimensionless ratios: on the vertical axis, the relationship between the specific consumption PF to be adopted and the minimum PF_{min}, that is the specific charge that allows detaching blocks as large as the burden V; on the horizontal axis is the ratio between the maximum desired size of fragments and the burden. This method was originally designed either to: predict the size obtainable by a blast where drilling mesh and PF are known, or estimate the specific consumption of explosive that is necessary (once established the drilling mesh), to obtain a certain particle size, or estimate what burden is required to obtain the desired particle size, once having established the specific consumption. For Italian limestone such as the one encountered in the Alps, the value of PF_{min} ranges between 150 and 200g/m³.

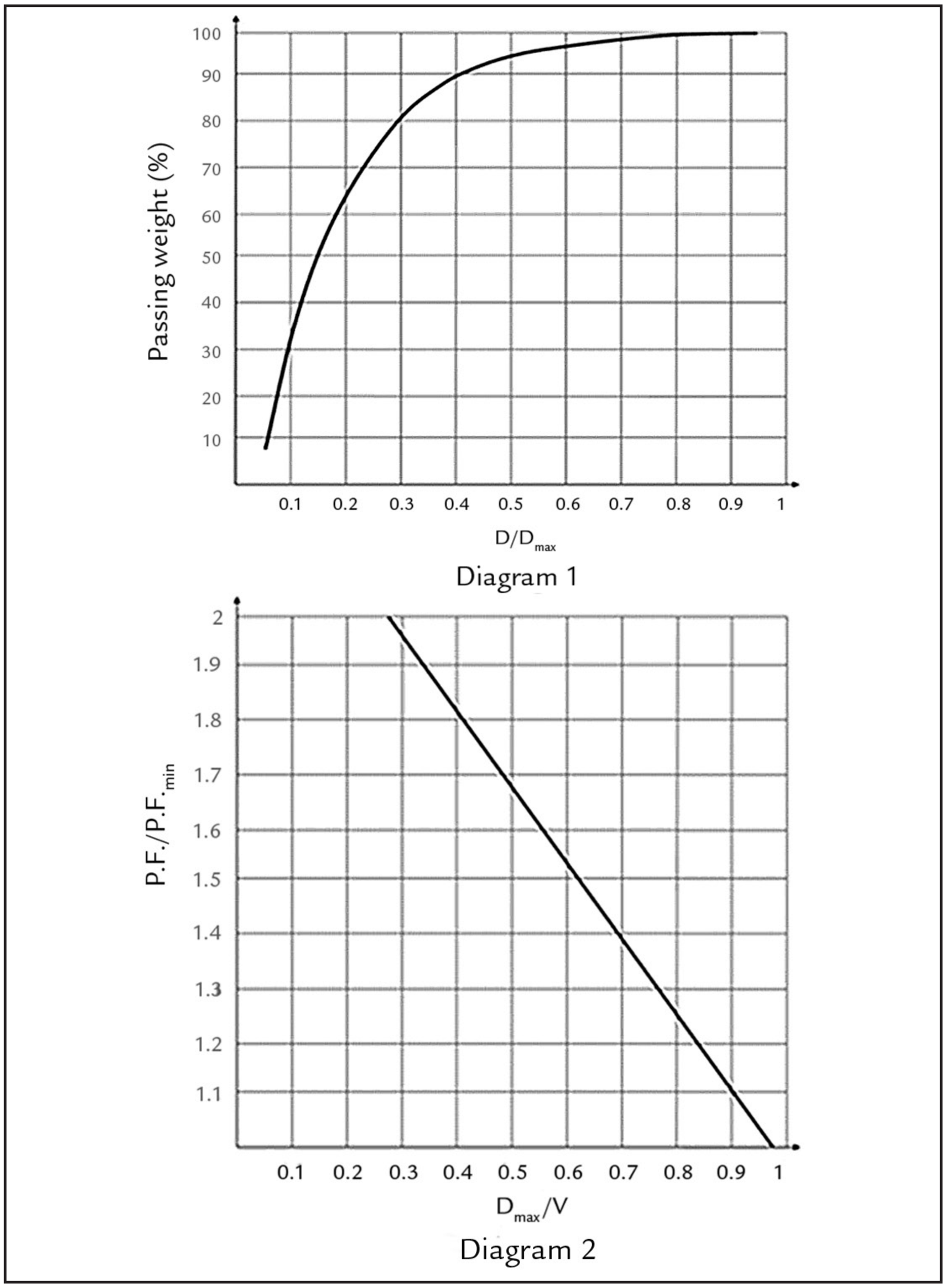

Figure 1
Graphs employed to project blasts of a given particle size distribution in limestone quarries. D[m]: Dimension of the desired size of blasted material, expressed as a percentage of the whole blast (ie, 90%<0.8m, means that only 10% of oversize is accepted, with D=0.8m); %: cumulative percentage of the blasted rock; Dmax[m]: maximum block size obtained; PF_{min}[kg/m³]: the minimum effective powder factor; V: Average value for the burden. Adapted after Clerici *et al*., 1974.

Normally, the choice of some of the aforementioned parameters, as PFmin and V, depends on the rock strength; however, being the distribution of this parameter unknown in the experimental quarry under study, it was assumed to resort to the calculation of the drilling speed to get information about the rock characteristics; in particular, drill rigs employed at the quarry have 3m length MF-rods: the operator was asked to record the time elapsed between junctions, corresponding to the time necessary to drill a 3 m length hole. Being both the operators and the machines always the same, it is legitimate to think that there are no changes in the performance of drilling. Having available a significant number of drilling speed data, it is possible to infer an empiric correlation between the rock strength and drilling speed. Being the drilling speed known in different areas of the quarry, resulting in higher or lower rock drillability, it can be decided whether, for a given bench, it is necessary to increase or decrease the P.F., either by means of reducing the charge per hole or by increasing the drill mesh size. This allows also changing the values of PFmin hypothesized in the initial stage, and then calculating a new PF.

Figure 2 shows an example of registration of drilling speed in a 10m high bench, in which 61 holes were performed in a 300m² surface.

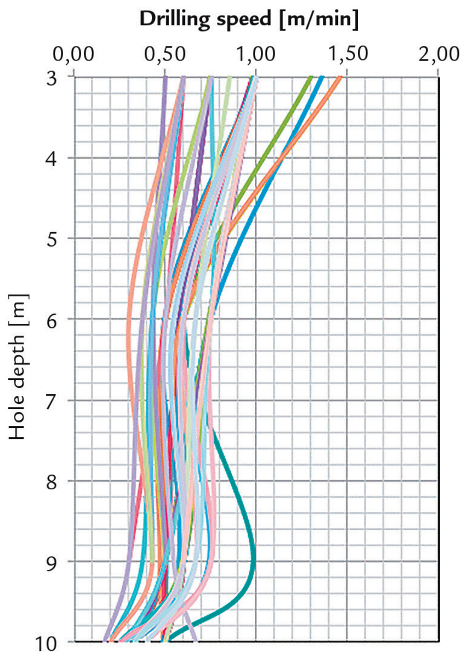

Figure2
Trend of the drilling speed in a number of blast-holes pertaining to a 10m high bench and a surface area of 300 m². To be noticed is the great speed variability (0.5-1.5 m/min)

3. Concepts for the choice of the initiation sequence

During this research, the initiation sequences adopted have always obeyed the following principles:

• Decomposition of the blast;

• Taking advantage of the free surfaces to favor the movement of the blasted material;

• Simultaneous holes as far away as possible, to avoid undesired cooperation of charges that may induce the explosive energy to work with shear effect instead of producing fragmentation.

The main limitation for the choice of the initiation sequence was the only availability of detonating cord and relays of the 17 ms and 42 ms series. The initiation sequences had to be adjusted varying the geometry of the web of inter-hole connections and the position of the relays along these connections.

The drilling density (holes/m²) is an indicator of how finely the explosive is distributed in the rock and, indirectly, of how large the monolith can be, which includes the volume to be excavated that is not affected by explosive (Langefors & Kihlström, 1967; Ash, 1968; Saharan ***et al.***, 2006); this is then correlated to the maximum size of the fragments obtained from the blast. The distinction based on the number of free surfaces available before the blast is important, but refers only to the early situation: the blast must be analyzed in its evolution (decomposition), according to the sequence of explosions, which must be established with the aim of having the maximum number of blastholes that can operate under favorable conditions. The decomposition is intended in a temporal sense, and should consist of showing the geometry of the bench after each explosion, erasing the already fragmented rock. It is actually impossible to reach this goal on a regular blast (also an ultra-fast camera takes only the external aspect of the blast under its evolution) but a theoretical reconstruction is possible, by assigning to each blast-hole a reasonable volume, and reshaping the face for every explosion, erasing what would have to be removed. It is therefore an idealized reconstruction of what should happen, i.e. a means to control whether a project is reasonable or not.

The objective of a production blast is to transform into fragments of a predetermined size a predetermined volume of rock (Lownds, 1997). The least one can expect is that the blast reduces to a transportable size, with a tolerable percentage of oversize, a given volume of rock; the maximum to be expected (the "perfection") is that the blast detaches only the desired volume of rock and reduces it into fragments of a specified particle size distribution, leaving regular and undamaged walls corresponding to the geometry of the project (Mancini &Cardu, 2001). This perfection is almost never reached, but it can be used as an instrument to judge the quality of the result: the closer it gets to perfection, the better it is. It will be necessary, of course, to use quantitative indicators that take into account the performance of the result. Also, criteria must be established to distinguish which part of the imperfection is due to the rock characteristics from that which is due to defects in the design or execution of the blast, and therefore can be improved by the operator.

4. Concluding remarks for Part I

The primary aim of this research is to depict a way to improve the rational utilization of the explosive energy for the benefits of the quarrying process. An extensive literature review shows how good fragmentation by blasting favorably influences the profitability of the whole mining process. Many methods allowing the prediction and estimation of fragmentation are available today. If these methods are carefully and reasonably used, they can be very helpful to obtain an optimal fragment distribution which will lower the total cost of the whole production process and not only that of the drilling and blasting. The blast design process must represent an effort to reduce oversize fragments and to minimize the amount of fines in the rock pile. In this first part is described a method to design cost-effective and reliable solutions that can ensure compliance with the productivity target without drastically modifying the geometry of drilling or the specific consumption of explosive. This method has been applied in field tests at the Experimental Mine of the Research Center for Responsible Mining of the University of São Paulo. The experimental methods, examples of application and the results obtained will be presented and discussed in the second part of this article.

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