THE MUSIC OF BLASTING

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THE MUSIC OF BLASTING

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ABSTRACT

A common adage in the Explosives Industry goes by saying that "Blasting is not bombing". One of the key differences between the two employs of explosive energy lays in the same gap existing between the application of acoustic energy that differentiates noise from music: timing and the distribution of energization in time. While timing in blasting is widely accepted to influence blast-induced vibrations, it is still not completely investigated when related to rock fragmentation and downstream benefits. This paper shows a research about this topic, developedon two phases: 1)test blasts at the Experimental Mine of the Research Center of Responsible Mining of the University of São Paulo; 2) development project for large-scale production blasts in an open-cast mine. The first phase of the research was performed attempting to increase the productivity of the experimental mine, by lowering production costs and improving the quality of the product. Some Key Performance Indicators (KPIs) were established to monitor the results. A new blast design method and a more appropriate initiation sequence were designed according to the principles of: i) decomposition of the blast; ii) taking advantage of the free surfaces to favor the movement of the blasted material; iii) simultaneous holes firing 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 results show that the proper selection of delay timing leads to significant benefitsfor rock fragmentation, downstream processes and the quality of final walls. The second phase of the study was a research and development (R&D) project in an open-cast mine with the goal to achieve an average P_{80} of 300 mm (11,8”) in the run-of-mine (ROM) product without altering the existing budget. The project included several variables in the blast design that were not previously taken into account, such as the orientation of natural joint sets in the rock mass, specific energy of the explosive and firing sequence. The new blast design method considered the directions of natural joint sets and determined the drilling pattern and the firing sequence accordingly to favor the movement of the blasted rock along its preferential direction, to reduce its confinement. At the end of the project, it was achieved an average P_{80} of 304mm(12”) in the ROM, 50% lower than the one at the beginning of the project. The final blast of the project showed a reduction of 3% of the drill and blast cost, employing the same powder factor and the same drill pattern size used at the beginning of the project. The results of this study show how blast performance is related to variables that are not contemplated in the most common design methods or fragmentation models: the firing sequence, the degree of freedom and the direction of movement in the blast.

INTRODUCTION

Blasting is not bombing. Vorand and Gonzales (1998) report the case of a misconception of blasting activities amongst the population of a urban area close to a tunnel construction site: the public perceived that "blasting was a bombing campaign using massive amounts of dynamite". The reason for this not being the case is due the control of the application of the explosive energy in space and time. The application of explosive energy in a blast is controlled through:

i. Geometry (position of charges in space)
ii. Timing (energization of charges along time)
iii. The combination of these two aspects: the initiation sequence (sequence of detonation along time of charges distributed in space).

The proper management of the initation sequence allows to control:

- the energy distribution;
- the shockwave interference;
- the muckpile movement;
- the creation of new free surfaces forthe holes of inner rows.

The influence of timing to control vibrations is well known and widely accepted (Dowding 1985, Wu et al. 1998, Khandelwal and Singh2007, Aldas and Ecevitoglu 2008, ISEE 2011). The most common control parameter is the charge per delay (CPD): by delaying the charges it is reduced the energy release per instant, therefore "diluting" the effect of the total charge employed along time. Furthermore, as shown by Rosenhaim et al. (2013), the initiation sequence can influence ground vibrations by allowing a greater freedom of movement of the blast towards free surfaces, and therefore employing a greater amount of energy for the displacement of the blasted material and reducing the amount of energy transferred to the rock mass left in place.

Nonetheless, the influence of timing on rock fragmentation and downstream operations is not thoroughly investigated yet. The concept of charge per delay does not have much sense when dealing with rock fragmentation: a didactic example is shown in Figure 1.

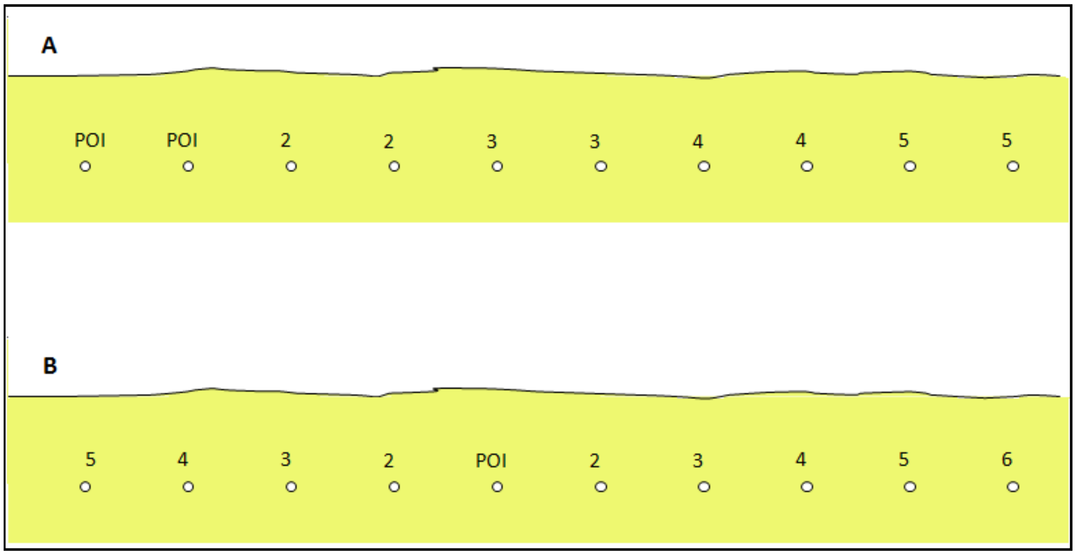

Figure 1 - Example of two bench blasts with same geology, same drilling geometry and same CPD_{max} but different initiation sequences and therefore different outputs in terms of fragmentation

The the most common fragmentation models adopted today are the KUZ-RAM (Cunningham, 1983) and its modern version the SWEBREC (Ouchterlony et al., 2006). These models allow to predict the fragmentation output of a bench blast, with reasonable reliability, based on inputs regarding:

i. The properties of the explosive employed;
ii. The geometrical features of the drilling pattern;
iii. The column charge in a single blast-hole;
iv. The properties of the rock mass.

Amongst the variables considered in these models, none refers to timing.

The main research on the effects of timing on rock fragmentation is based on small-scale tests blasts(Stagg 1987,Cho & Kaneko, 2004, Katsabanis et al. 2006, 2008, Kim 2010). Stagg (1987) performed small-scale tests in dolomite benches, using 0 to 45 ms delay intervals, equivalentto 0 to 118 ms/m of burden. The finest fragmentation occurred at blast-hole delay intervals of 3 to 56 ms/m of burden; coarse fragmentation resulted from short delays (<3 ms/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 (>57 ms/m), with explosive charges acting independently. Cho & Kaneko (2004) came to the conclusion that the optimal fragmentation with respect to delay time depends strongly on the gas flow through the fractures caused by the stress wave. Katsabanis et al.(2008), performing small-scale blasts in igneous rock,show 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 fragmentation models investigate the geometry of explosive distribution in the rock mass. Experimental research focuses on delay timing of charges. The combination of these two aspects, i.e. the initiation sequence, has had little investigation so far. This paper shows some experimental results regarding this subject.

RESEARCH AT THE EXPERIMENTAL MINE

This phase of the research has been performed at the Experimental Mine of the Research Center for Responsible Mining of the University of São Paulo, Brazil. This is an open-pit marble quarry which operates under normal production conditions, and at the same time collaborates with experimental research conducted within its premises.

Influence of the initiation sequence on particle size distribution

The detailed description of the experiments of this section is reported in NAP.Mineração (2015a, 2015b) and the comparative study of the results is contained in NAP. Mineração (2015c). This phase of the research considers special blasts conducted at the Experimental mine outside the standard working system: charging with bulk emulsion and initiation by electronic detonators. Two experimental blasts were analyzed here, Blast A and Blast B. Both blasts possessed the same geometry and the same charges per hole, as reported in Tables 1 and 2. The geology was exactly the same, asone bench was detonated right next to the other.

Table 1 - Drilling Parameters

Parameter	Unit	Both Blast A and Blast B
Hole diameter	Φ [m]	0,0762
Bench height	H [m]	13,00
Burden	V [m]	2,50
Spacing	S [m]	2,80
Stemming	B [m]	2,00
Underdrilling	U [m]	0,50
Hole inclination	α [°]	75

Table 2 - Charging parameters

Parameter	Unit	Both Blast A and Blast B
Loading density of the emulsion	ρ [kg/m³]	1,08
Charge per hole	Q [kg]	71,00
Volume of rock per hole	V [m³]	91,00
Powder Factor	P.F. [kg/m³]	0,78

What varied was merely the initiation sequence:

- Blast A: details described in NAP.Mineração (2015a). The initiation sequence of this blast was determined empirically by the blasters on field, without any technical or scientific criterion. It was merely determined by adapting a standards sequence to the geometry of the bench and of the drilling pattern
- Blast B: details described in NAP.Mineração (2015b).The initiation sequence of this blast was based on the following criteria: i) 14 ms between rows (5.6 ms / m burden); ii) 17 ms between holes of the same row (5.7 ms / m spacing); iii) take advantage of the presence of two vertical free faces and the initiation sequence should be designed so that each hole of the internal rows should always find two

free surfaces generated by the detonation of previous holes; iv) each row is fired independently, the first hole of the next row only detonates upon the detonation of the last hole in the previous row. The first two criteria adapting the theory Bergmann et al. (1974), cited in Cunningham (2005) to determine the maximum delay between holes in the same row for which it has maximum fragmentation: t_{max} = 15.6 Vp-1B where Vp is the velocity of compressional waves in the rock mass, B is the distance (Burden) and 15.6 is a scale coefficient that normalizes the calculation with the speed of the waves in the rock mass where Bergmann et al. made their trials (a hard granite). The velocity of compressional waves in the portion of the Experimental Mine rock mass where the blast was executed was estimated at 3 km / s.

The initiation sequences are reported in Figures 3 and 4. The result is shown in Figure 4.

It appears evident how two blasts performed in the same geology and with the same characteristics can give different results simply by varying the detonation sequence. In particular, it appears that taking advantage of free surfaces and favoring the movement of the blasted material can significantly meliorate the output of the blast.

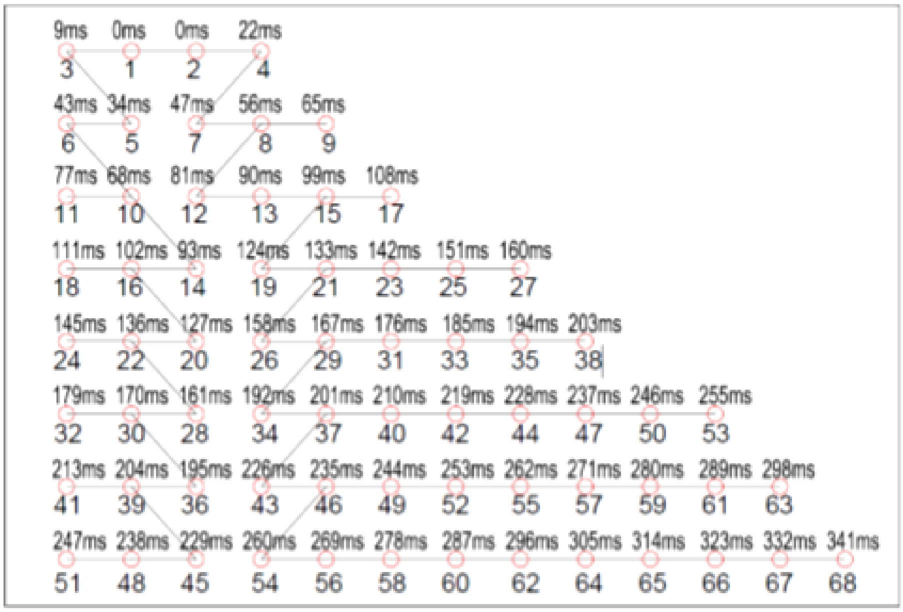

Figure 2 - Initiation sequence of Blast A

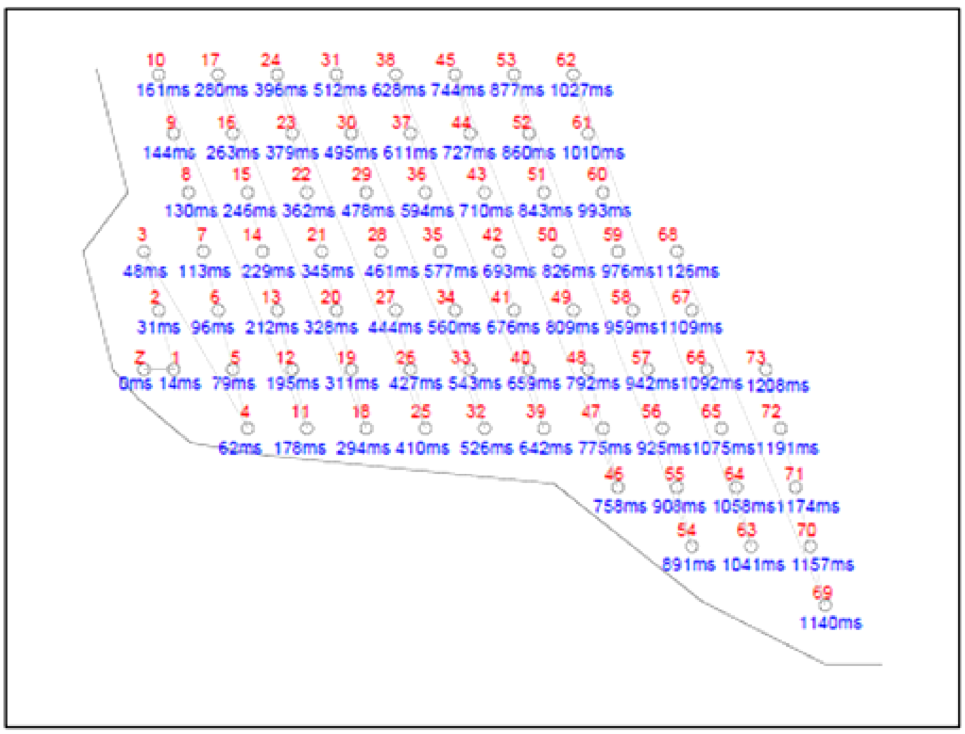

Figure 3 - Initiation sequence of Blast B

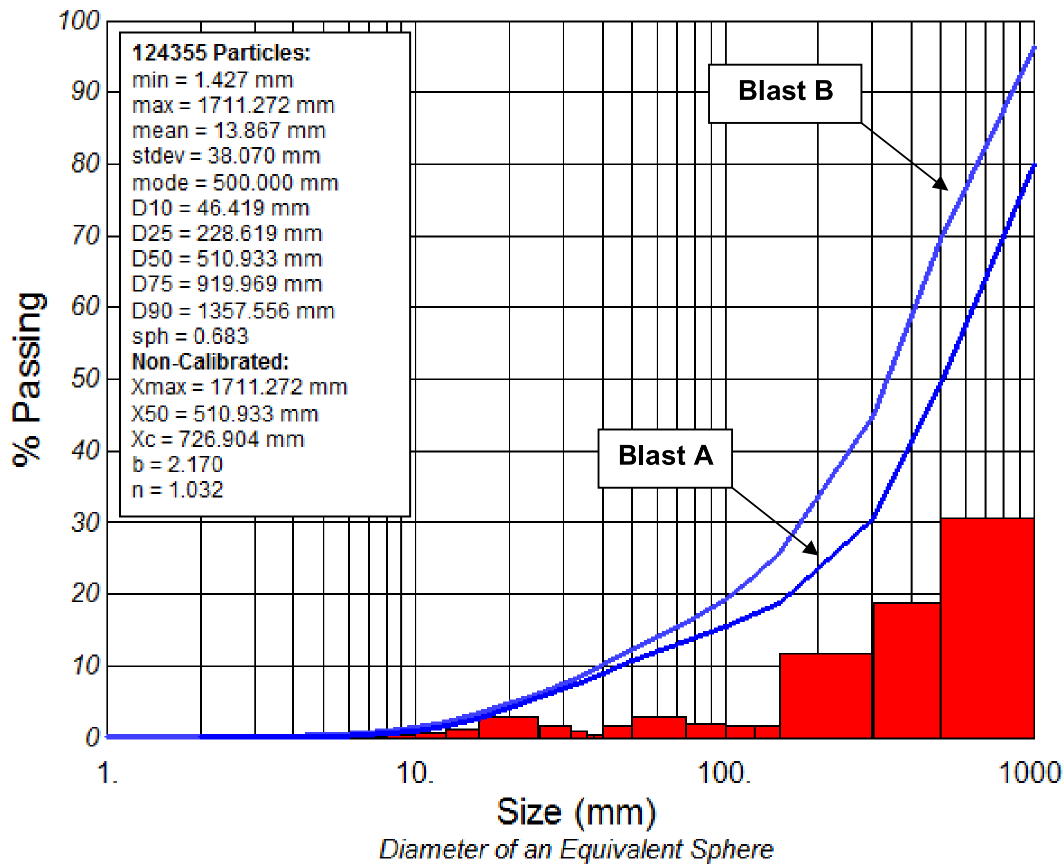

Figure 4 - Comparative results in term of particle size distribution of the two blasts

Influence of the initiation sequence on downstream operations

The detailed description of the experiments of this section is reported in Vaudagna (2014). Cardu et al. (2015a, 2015b) provide a thorough discussion of the results. The main aspects reported here are cited from Cardu et al.'s work. This phase of the research was performed using the standard working system adopted in the experimental mine: charging with cartridged explosive and initiation by detonating cord and delays.In these blasts the aim was varying merely theinitiation sequences in bench blasts on benches 6m high. All the blasts analyzed had approximately the same powder factor, ranging between 0,40 kg/m^3 and 0,45 kg/m^3. All the blasts had the same bench height and the same drilling pattern (2 m x 2 m on squared pattern).What varied was the initiation sequence: it shifted from an empirical method adopted by the quarry operators (first blasts of the research) towards a scientific method (final blasts of the research) that obeyed to the following principles:

i. *Decomposition of the blast*. The blast must be analyzed in its evolution (decomposition), according to the sequence of explosions. The decomposition is intended in a temporal sense, and consistsin considering the new geometry of the bench after each explosion, erasing the already fragmented rock.

ii. *Taking advantage of the free surfaces.* This is done to favor the movement of the blasted material and therefore employ the explosive energy for fragmentation and movement instead of damage and vibration in the rock mass left in place.

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

In order to understand the influence of the blasting sequence on blasting performance, it has been considered the distance of holes detonating at the same nominal delay. 3 classes of distance where evaluated:

1. D = 2 m, when two simultaneous holes are along the spacing or burden lines of the square drilling mesh;

2. D = $2^{1.5}$ m when two simultaneous holes are along the diagonal of the square drilling mesh;

3. D > 3 m, when two simultaneous holes do not belong to the same square of the drilling mesh

For each class of distance, it was analyzed the ratio between the number of holes falling in the given class over the total number f holes of the blast. It has been noticed that this parameter has a direct influence on two KPIs that control the outcome of the influence of the blast: secondary breaking (Figure 5) and total cost of the blast (Figure 6).The complete list of KPIs adopted during the research is defined and described in Vaudagna (2014) and Cardu et al. (2015b).

It is noted that:

- increasingthe distance betweenthe holes that detonatesimultaneously the volume of oversize blocks that need secondary breaking is reduced
- increasingthe distance betweenthe holes that detonatesimultaneously the cost of excavationis reduced
- even a slight variation of the distance D between the first two graphs of Figure 2 leads to a variation of the trend line

The reduction of oversize blocks is a consequence of the phenomenon by which if more adjacent blast-holes detonate simultaneously (see Figure 5A) the result is the rock detachment, and if, instead, detonate with different delay or simultaneous but effectively spaced (see Figure 5B), the result is fragmentation. The reduction in term of total costcan be attributedto a greater homogeneityof the muck-pileobtained and to the reduction of secondary breaking.

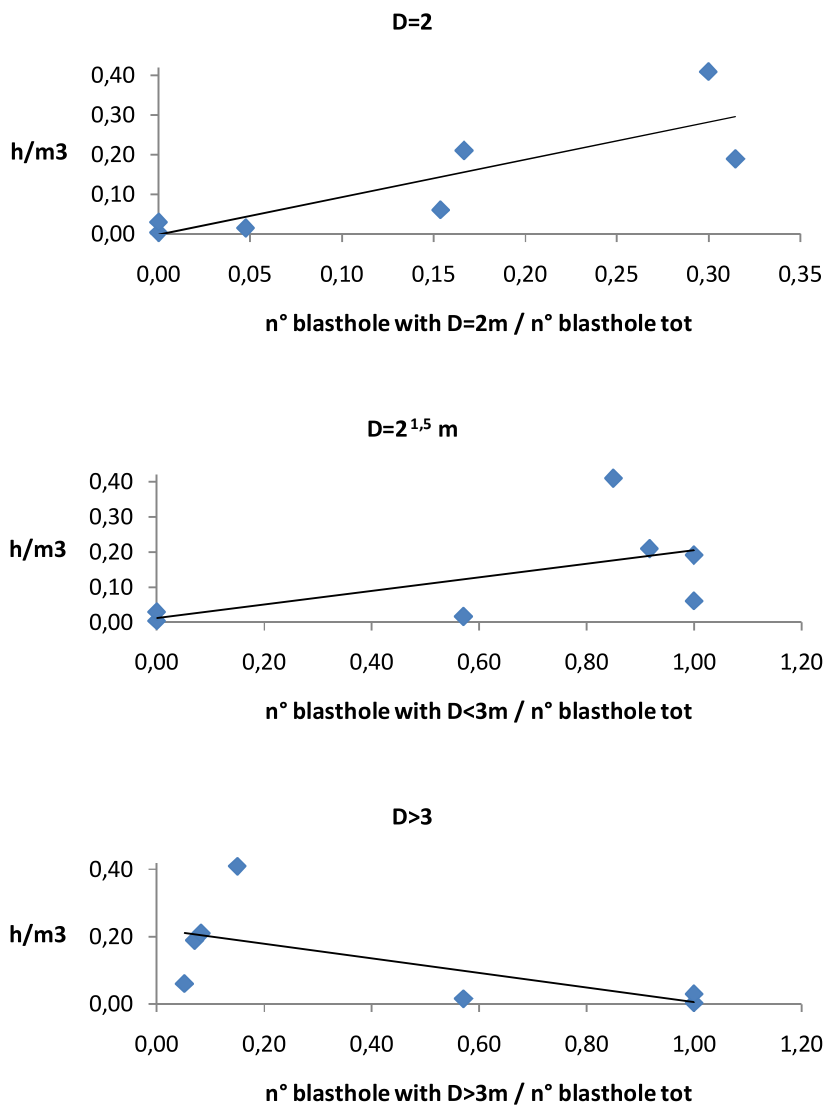

Figure 5: Relation between the blasting distance and the secondary breaking. The lines shown in the graphs are mere trends and not statistical regression lines, since the population of data is too scarce and the records too scattered to give any regression statistical significance. (Cardu et al., 2015b)

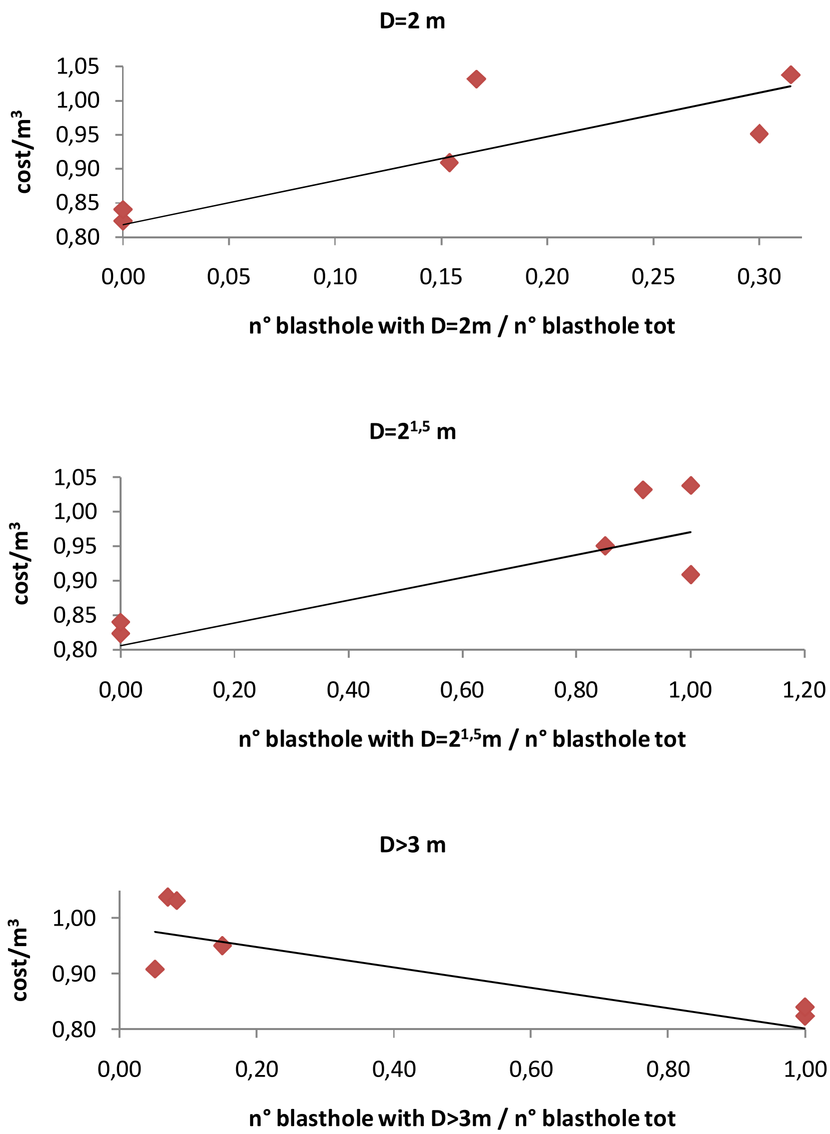

Figure 6: Correlation between the blasting distance and the cost of blasting. The lines shown in the graphs are mere trends and not statistical regression lines, since the population of data is too scarce and the records too scattered to give any regression statistical significance. (Cardu et al., 2015b)

RESEARCH ON FIELD

This phase of the research has been carried on in an open-cast mine, where the predominant geology is granite rock, mined by drilling and blasting on 10 m benches, with sub-vertical holes. The details of this phase of the research are reported in Pinto e Moura et al. (2014, 2015). During this researchit was taken into account the orientation of natural joint sets in the rock mass, and the firing sequence was adopted to favour the detachment of the rock along its natyral planes of weakness. The main characteristic of the new blast design method was to favor the movement of the blasted rock along its preferential direction, to reduce its confinement. This was achieved using the direction of the joint sets as the main preferential direction of movement, and designing the drilling pattern and firing sequence accordingly. As it is widely accepted that, in terms of first approximation, the movement of the rock during the blast can be assumed as perpendicular to the direction of the isochrone lines of the firing sequence (Lopez Jimeno et al., 1995, ISEE, 2011),the firing sequence was therefore designed according to this principle to achieve the desired direction of movement. The results are shown in Figure 7:it was achieved a reduction of 50% of the average P_{80} employing the same Powder Factor, the same drill pattern size and without increasing the cost of the blast. This result could not be explained without taking into account the choice of the firing sequence and its consequences in terms of feedom of movement. Also Rosenhaim et al. (2013) came to the same conclusion: in a blast the best results are obtained with the lowest confinement coefficient.

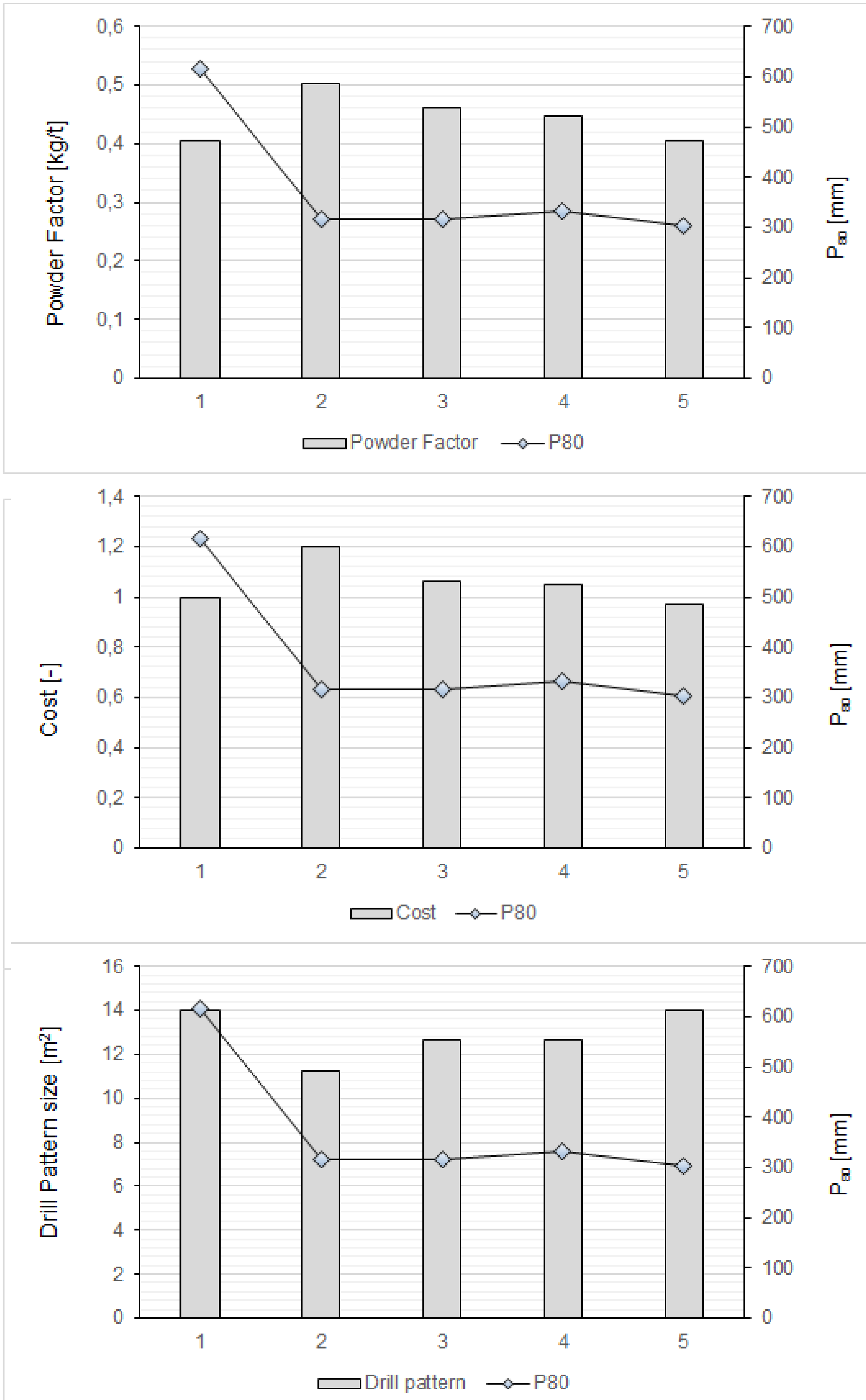

Figure 7 – Evolution of the Powder Factor, Cost and Drill Pattern Size during the project, always compared to the evolution of the average P_{80} of the pile.Cost refers only to the cost of drilling, explosives and accessories. (Moura et al, 2014, 2015)

DISCUSSION

If the KUZ-RAM or the SWEBREC models were to be brutally applied, two blasts in the same rock mass and wih the same drill pattern and explosives characteristics but with two drastically different firing sequences would be modelled to give the same results in terms of fragmentation. This is not what happens, and the experimental results showed above demonstrate this. Such a bias is due to the fact that fragmentation models consider geometrical variables (position of charges in space) but still do not consider timing (energization of charges along time) nor the combination of the two (firing sequence in space along time). These are difficult variables to be quantified, and it is natural that they tend to be neglected in numerical models. Their authors are, of course, well aware of that: Ouchterlony et al. (2006) recognize the limit of their model and warn the reader about it. The Extended KUZ-RAM (Cunningham 2005) is, so far, the most advanced attempt to integrate timing in a fragmentation model: it considers the inter-hole delay, but still does not consider the firing sequence and its direction.It is evident that future research will have to focus on the inclusion of the following aspects in fragmentation models:

- The firing sequence;
- The confinement of the blast;
- The influence between geological and geostructural features and the direction of movement of the blast.

CONCLUSIONS

Music is often defined as "organized sound" (Goldman, 1961). Blasting is no less an "organized explosion". Once the energy levels (musical notes or explosive charges) are set, their organization makes all the difference to achieve the desired results.This work intended to consider the effects of timing (that can be seen as the rhythm) and of the initiation sequence (that can be seen as the melody) on the output of a blast. We carried on test blasts in the field, in different geologies. Results show that blasts with identical geometrical parameters, that vary only in their initiation sequence, give very different results in term of fragmentation and downstream effects.We show how:

- two blasts performed in the same geology and with the same characteristics can give different results simply by varying the detonation sequence;
- increasingthe distance betweenthe holes that detonate simultaneously decreases secondary breaking and costs;
- designing a detonation sequence that accompanies the natural fracturing of the rock mass and favors the freedom of movement of the blasted material can decrease particle size by the half without varying any other blast parameter or the cost of drilling and blasting.

These results show that conceiving, designing and analyzing a rock blast under a static point of view (considering the three spatial dimensions without taking into account the temporal fourth) can result in heavy drawbacks in terms of quality of the results.

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