New convincing results in the reduction of fines obtained thanks to digital simulation

A case study in an open-pit mine

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ABSTRACT : The chief aim in rock blasting is fragmentation. A reduction in the maximum size of rock fragments to facilitate the use of a crusher is an ongoing aim. Frequently, a large quantity of very fine particles are produced. These are removed during the crushing-screening stage but a considerable percentage of the deposit is thus wasted. This paper describes the method used in an open-pit mine to limit the production of fines, whilst maintaining a maximum acceptable rock size.

1. THE ECONOMIC CONTEXT OF EUROPEAN QUARRIES

Despite the hundreds of thousands of direct and indirect jobs it represents on a continental level, and its strategic nature in terms of development and supplies for the building industry, the European aggregate industry is "being monitored" *(Bernard et al., 2012).* This is in particular due to growing spatial, regulatory and societal constraints. The Anglo-Saxon acronym NIMBY – “Not In My Back Yard”, to quote the most famous, shows that the rejection phenomena reach far beyond the frontiers of Europe and are indeed a daily preoccupation for Canadian and American quarriers.

The recession has also meant that quarries and mines have had to face up to drastic budget cuts, and cost reduction objectives, the success of which is sometimes purely and simply the governing factor in the continuation of their business. Quarry engineers and blasters are in the front line trying to make each blast, a tricky and often paradoxical balance, of maximising (and homogenising) fragmentation whilst minimising the quantity of fines.

2. THE CHALLENGE OF REDUCING FINES

Each year in Europe, the aggregate and ore industries produce approximately 1.35 billion tonnes of blasted rock. This results in the production of about 270 million tonnes of rock with a fragmentation distribution of 10 to 20 millimetres *(Moser, 2003).* This represents approximately 20% of the overall production and is too fine to be used. Therefore, it is rejected and becomes waste.

The definition of a fine varies from one site to another, but generally speaking, a fine is a particle whose size means it is of negligible economic value, and/or whose presence can have a detrimental effect on the smooth operation of the crushing process, in particular due to agglomeration. Limestone quarries are particularly prone to this phenomenon, all the more so because the heterogeneity and the specific features of their geology (limestone veins, cavities, etc.), often create additional complications when it comes to optimising blasting.

The launching of the European programme, "*Less Fines*", reveals the size of the phenomenon and the inherent industrial and financial challenges of this question. Dozens of partners in the mining sector, suppliers, and research centres, have set themselves the task of reducing what is considered as the wastage of a non renewable resource by 50% in the long term.

Having said that, the mining industry has to meet these challenges on a daily basis. Pragmatic and efficient solutions have to be provided "here and now". In this technically, politically and economically tense context, TBT is a major actor in the definition and implementation of exemplary mining procedures, from a technical, economic, social and environmental standpoint. The internal development of the I-Blast software, that is integrated within an *ad hoc* protocol of measurements and on-site engineering, helps improve the acceptation, safety and productivity of present blasting techniques, via the design and digital simulation of blasting.

3. A REDUCTION OF FINES, A CASE STUDY

Around the French Riviera and the Principality of Monaco, the aggregate quarries are chiefly owned by industrial groups working on a national or international basis. The sites are average in size, but are strategically located throughout these two regions that are leaders in the building industry.

These sites create nearly 4,400 direct jobs regionally and are the first link in the building chain, upstream of the building industry and civil engineering. The annual turnover is over €1 billion, and they produce 32.5 million tonnes of aggregates.

The quarries in the hinterland of Nice (Alpes-Maritimes, France) mine limestone rock and have their own crushing or processing centres, thus enabling sand, gravel, concrete mixes or clay-based sealants to be produced locally.

TBT was assigned an ambitious objective to reduce fines at one of the sites in the region that produces aggregates. The operator subcontracts drilling and mining, and entrusted blasting engineering to TBT on a long-term basis.

3.1. A quarry monitored for several months

The quarry operator contracted TBT for blasting design and vibration control, air blast, fly rock and fragmentation over a year ago. It was a question of adhering to the limits defined by prefectural authorisation and the vibration and noise pollution regulations. The permissible acoustic and vibration thresholds on the edge of the mine are respectively 125 dB and 10mm/s.

In terms of fragmentation, the average distribution desired is 450mm, whilst the 800mm passing size must be adhered to for 95% of the muck pile.

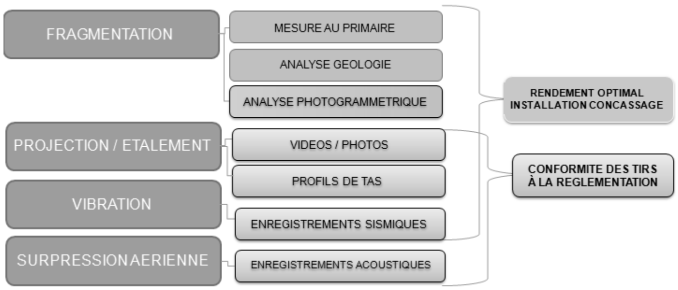


Figure 1 Logic diagram of TBT's measurement protocol

A complete iterative protocol of measurements for each blast (Figure 1) enabled digital simulations of blasting sequences to be established on a firm basis, whilst a series of measurements after blasting (spread, fragmentation) authorised a continuous improvement cycle (Figure 2). The aim with regard to 800mm could thus be reached for all 30 blasts of the first part of the study.

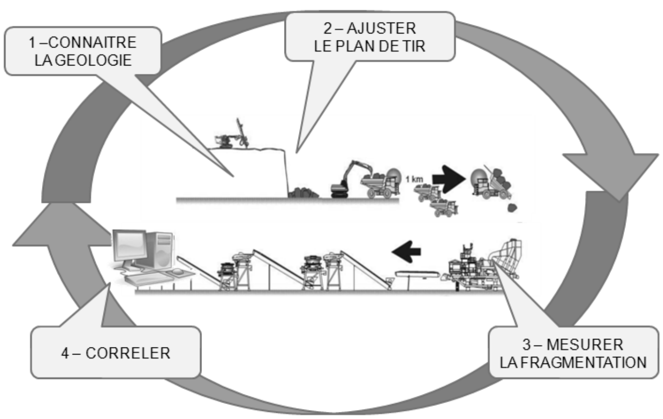


Figure 2 Improvement cycle in an open-pit mine

This protocol enabled the creation of a very detailed database including seismic, and acoustic recordings, and the fragmentation curves of each blast, as well as providing access to accurate knowledge about the deposit per area. After 30 blasts, statistically representative regression lines began to appear for 3 then 4 measurement points, located in and at the perimeter of the mine. The use of one single explosive and detonator supplier also makes the analysis more reliable, thanks to accurate documentation on the influence of the weight of the explosive on the different blasting parameters.

3.2. The apparition of the fines issue

The issue of fines firstly appeared when operations reached a particularly poor part of the deposit. The installation of a new secondary crushing line also helped add an objective regarding the lower end of the fragmentation distribution. This very substantial investment necessitated fast and significant gains in productivity.

After several stoppages of the crushing line, due to a percentage of fines that was too high, a reduction of the latter became a major challenge in the optimisation of the installation, and cost reduction strategy on the scale of the site, although this was not among the original objectives.

So a further objective was added to that of minimising the number of blocks of more than 800mm (less than 5%), i.e. also minimising the number of fragments below 150mm (less than 5%).

The present case study concerns sixty blasts, i.e. a comparison with the 30 blasts already mentioned, and the following 30. Each group of blasts is for a comparable volume for a total equivalent to approximately 18 months' operations.

3.3. Problematical fines: findings

The wealth of the database created for the site, to optimise its blasts via the digital simulation of the effects of the explosive, was very responsive when the critical objective of reducing fines was added.

The first thirty blasts were therefore analysed, by area, bearing in mind this new criterion. A base line was rapidly visible, i.e. on average the percentage of 150mm passing size was 27.87%. Figure 3 shows that, only 35% of the blasts would have been satisfactory with regard to the customer's new objective of a maximum of 5% of 150 mm.

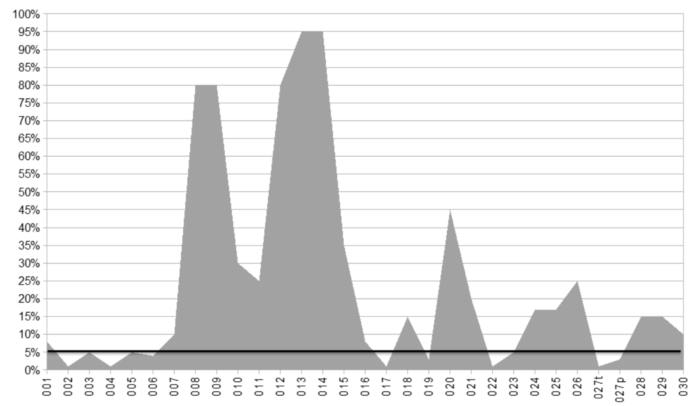


Figure 3 Percentage of 150mm passing size_Blasts 1 to 30. The 5% objective is highlighted.

The comparative analysis of the lower 10% of the size spectrum showed an average size of 114mm, decreasing by 100% over the period (Figure 4). The 5% passing size was well below 114mm, thus confirming the observations made on the crushing line.

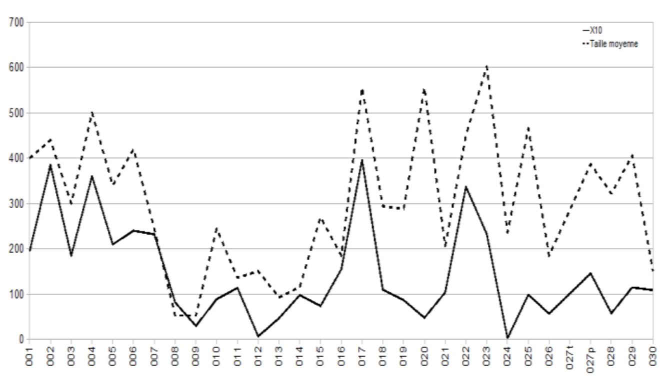


Figure 4 Average fragmentation and the lower 10% of the fragmentation distribution of blasts 1 to 30

The analysis of the whole size spectrum, in addition shows a growing dispersion of the distribution of the fragmentation of the blasts (Figure 5).

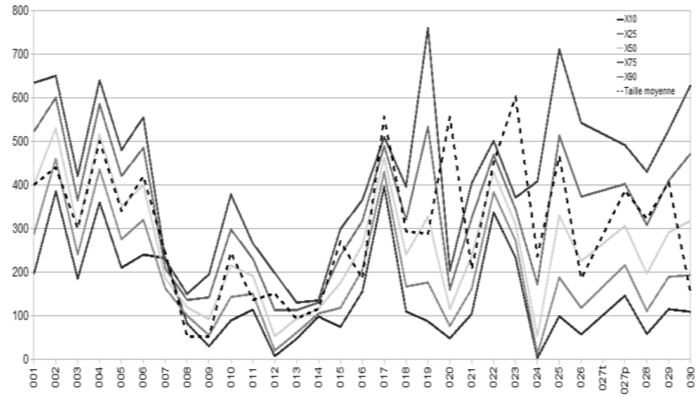


Figure 5 Size spectrum of blasts 1 to 30

3.4. Technical options available

The issue of reducing the production of fines in a blast, can be confined to decreasing the fines around the holes (10 diameters), and first and foremost requires a decrease in the bore hole pressure (shock pressure). Considering the fragmentation mechanisms as described by Bernard *(Bernard, 2010)*, the technical options, in order of priority, without one being exclusive of the others, focus on the use of the following:-

1. A less powerful explosive (creating less shock)
2. Air columns
3. Intermediate stemming
4. A high decoupling of the charges
5. The practice of destructive interference between holes

Therefore, it is a question of gradually moving down to less powerful explosives (for example from an emulsion to a low density emulsion, then to ANFO). The next alternative is to replace part of the explosive with air, then by intermediate stemming (one or more), if the percentage of fines is still too high, and then finally, apply the principle of a high decoupling of the charges. Then, the only solution left is to have recourse to destructive interferences, which requires the use of very accurate initiation systems that have a very low dispersion of the firing time (electronic detonators).

3.5. The dilemma of the quantity or the size of the fines

The use of less powerful explosives, or even air in the column, will nevertheless continue to split the rock. The same percentage of fines will be obtained, but they will be "bigger".

The use of intermediate stemming leads us to use less explosives. Proportionally there will be less fines, due to the fact that the explosive is not present throughout the whole height of the column, but it will have little or no effect on the respective size of the fines.

The technique whereby the charge is decoupled permits the explosive to be packed in the whole of the column. Thanks to the reduction in the bore hole pressure, the respective size of the fines will increase, but their proportion will not decrease in the muck pile.

The introduction of destructive interferences provides similar advantages. The explosive shock energy is minimised (less fines) and the explosive gas energy remains constant (same displacement). This specialised technique requires the use of electronic detonators, which, as such, like the decked charges method, fails to enable the proportion of fines to be reduced.

Ideally, a combination of a decked charge (intermediate stemming and air) with the use of destructive interferences, enables us to make the most of the advantages, whilst reducing the proportion of fines and increasing their average size. This alternative is presented as a matter of interest, since it was not implemented within the scope of the case study presented.

3.6. Geometry of the blast, gas thrust, toe displacement: a balance to be found

It has been proved that for an area equivalent to approximately 10 times the diameter of the hole, fragmentation takes place chiefly thanks to the explosive shock energy which creates cracks by exceeding the compression limit of the rock *(Bernard, 2010)*. This is where most of the fines are produced.

Decreasing or lessening the explosive shock energy to limit the production of fines, is unavoidably accompanied by a reduction in the explosive gas energy, hence the thrust on the materials, which is not desirable with regard to digging.

Considered separately, the reduction of the drilling pattern to maintain a constant weight for decked or very decoupled charges, will firstly proportionally increase the production of fines, but it will also increase the wave energy after its reflexion on the free faces. These very powerful tensile waves will lead to a surplus splitting of the material, due to the tensile strength being exceeded, hence creating ...... fines.

Regarding the thrust, undeniably the decoupling techniques or those using air, contribute to decreasing the gas pressure (as well as the quantity of explosive for a constant drilling pattern), hence affecting the thrust and thus the displacement of the whole blast. Widening the drilling pattern has the same consequence, since it leads to mechanically decreasing the weight of explosive and the percentage of fines.

Simultaneously, you have to safeguard a good displacement of the blast in general and the toe in particular. Unless, you work on the sequence (destructive waves) and not on the loading, a sufficient quantity of energy must therefore be kept to move the blast, which, *de facto*, limits us to simply decreasing the energy quality and the quantity of explosive in the column.

If we assume that the height of the toe can be defined as being equivalent to approximately 30 times the diameter of the hole and that, on the other hand, we maintain a stemming height equivalent to 20 times this diameter, in order to limit fly rock, it can be noted that the area where a fines reduction strategy can be applied is relatively limited. For a constant diameter, it is obviously, all the more so, if the bench height is low. The aim of not producing blocks (95% 800mm passing size in our case), must also be taken into account both for the minimum quantity of energy to be injected into the rock, as well as for the definition of the intermediate and final stemming.

Only the technique of destructive waves, mentioned here as a matter of interest, enables us to maintain a comparable thrust whilst decreasing the explosive shock energy.

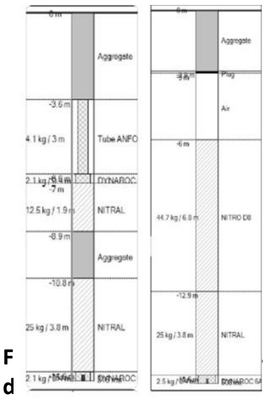
3.7. Methodological and technical choices

The strategy chosen in our case is based on loading whilst maintaining the possibility of changing the sequence, later, if the first option is not completely satisfactory, or if it became necessary to reduce fines further.

The decrease in the bore hole pressure (shock) was therefore achieved by introducing:-

- Intermediate stemming
- Air columns
- Decoupling the charge per tube as and when necessary (poor deposit area)

After the digital simulations, different techniques (see Figure 6 for the examples) were selected to be applied to the three different areas of the deposit identified during the first period *(see 3.1)*. This necessary differentiation of techniques per area, corroborates Moser et al.'s empirical and statistical conclusions (Moser, 2003).



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- Healthy area of the deposit: decked loading with an air column
- Mixed area: tubing + decked loading with an air column (every alternate row)
- Poor or very poor area: tubing all the holes limited to three rows

In the mixed areas, and from three rows onwards, the loading was designed to have sufficient explosive in order to guarantee the gas thrust and in particular the displacement of the toe *(see 3.7)*. The loading was therefore imposed alternately with traditional non-tubed charges.

3.8. The choice of the decoupling diameter: a major advantage of digital simulation

TBT developed software to help with decision making for design, simulation and optimising blasting, both above and below ground: the I-Blast software. One of the characteristics of this model is that it is chiefly based on laws of physics and not empirical laws or statistics, like most of the rival models. The fact that this software integrates all the blasting parameters, including the firing sequence, in the simulation routines, enables multiple configurations to be tested; an exercise that would be impossible to undertake in a traditional manner, because the quantity of combinations possible is vast. All the types and characteristics of the explosives, the stemming, their height, the diameters associated with the diameters of the holes, and the pattern, amongst others have to be taken into consideration simultaneously. Therefore, there is an almost infinite number of solutions.

I-Blast is capable of calculating, among other things, the pressure field, according to loading and decoupling *(Bernard, 2010)*. The simulations carried out take into account the different types of explosives available on the site, with their individual characteristics, as well as the influence of the introduction of decked loading, with or without an air column. I-Blast also enables all the decoupling diameters possible to be simulated with loose charges.

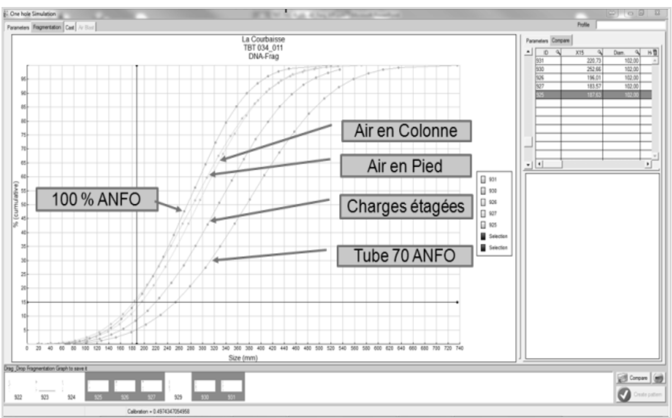

Figure 7 Comparison of the simulation of different loading in terms of fragmentation distribution

A tube with a 70mm diameter for a 102mm hole came to light, after the iterative simulation process. It appeared to provide the ideal decoupling, together with the geometry and simultaneously optimised loading. In passing, note the advantage of the tubing compared with decked solutions (Figure 7).

3.9. Results in terms of fragmentation

As with the previous simulations, the graph in Figure 8 clearly shows the influence of the presence in the same area (mixed, in the case of our example), of the location of an air column and/or its interaction with traditional charges. The fragmentation distribution curves measured are presented, respectively for blasts 28 (traditional loading without an air column), 32 (air column at the toe of the column) and 33 (air column at the top, alternately with decked loading, without an air column).

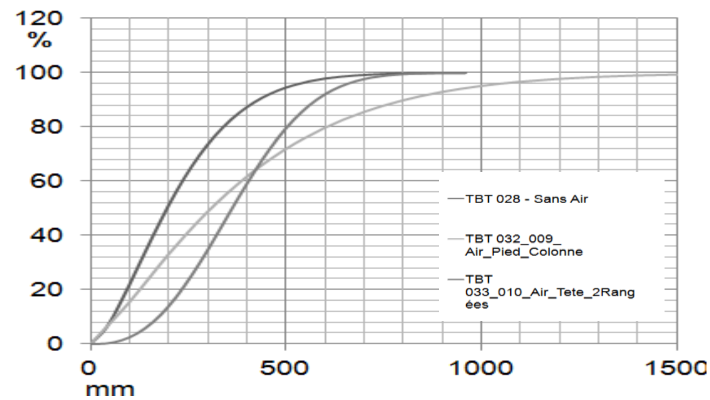

Figure 8 Fragmentation distribution measurements compared for three types of loading

The comparative analysis of the lower 10% of the size spectrum of blasts 31 to 60 (Figure 9) produces an average size of 156mm, compared with 114mm for blasts 1 to 30, i.e. an increase of over 36%. The average fragmentation between blasts 31 and 60 rose by 88%.

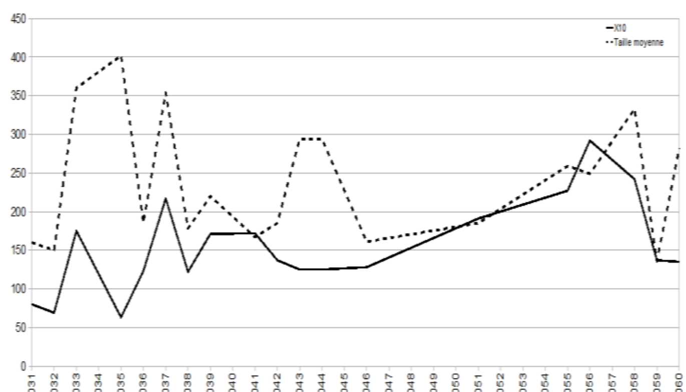

Figure 9 Average fragmentation and the lower 10% of the fragmentation distribution of blasts 31 to 60

The analysis of the whole size spectrum (Figure 10) in addition shows a significant narrowing of the distribution of the fragmentation of the blasts.

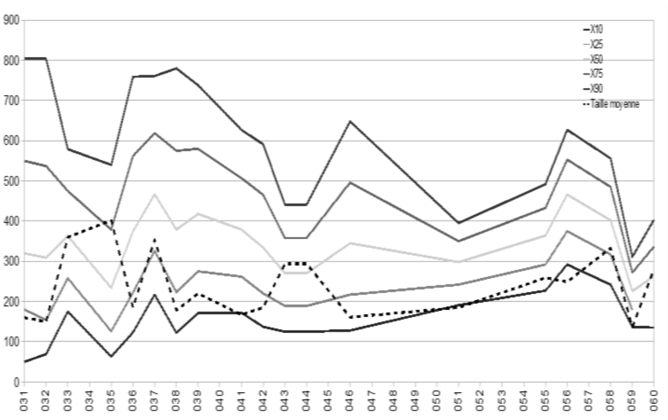

Figure 10 Size spectrum of the fragmentation of blasts 31 to 60

For blasts 31 to 60, the average percentage of the 150mm passing size was 2.73%, compared with 27.87% for blasts 1 to 30, i.e. -90%

As can be seen in Figure 11, the customer's objective aiming at a maximum of 5% of fragments of less than 150 mm is satisfied in 90% of the blasts (27 out of 30). 100% of the blasts were less than 10% <150 mm.

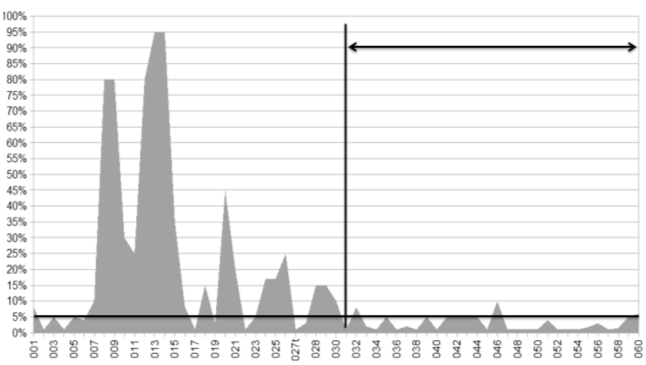

Figure 11 Percentage of the 150mm passing size _Blasts 1 to 60. The aim of 5% is achieved as well as the period to be optimised (Blasts 31 to 60).

The advantage of decked loading with an air column and/or tubing, was highlighted thanks to a comparison of its influence per area of the deposit, on the percentage of the 150mm passing size (fines).

Diagrammatically, the present area being worked can be divided into two major areas that we will call "healthy" and "poor" for clarity's sake (Figure 12). The area on the edge of these two areas will be called the "mixed" area. It concerns both the blasts that are precisely in this area and those partially in the healthy area and partially in the "poor" area.

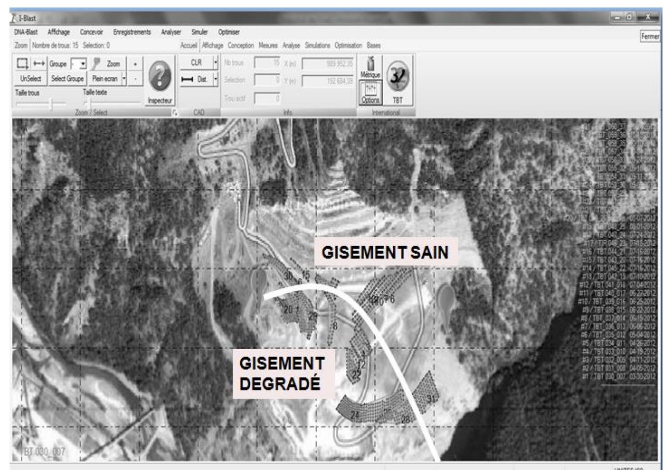

Figure 12 Diagrammatic and qualitative boundary of the deposit

As previously mentioned, the poor deposit area was only dealt with in the final blasts of the first period *(see 3.2).* Nevertheless, it should be noted *a posteriori* that the blasts in the healthy area created a substantial percentage of fines.

Figure 13 shows that significant reductions in the percentage of fines in the loosened rock are found both in the poor part of the deposit (-51.7%), as well as in the geologically healthy part (-88.7%), and in the so-called mixed area (-47.2%).

ZONE	% moyen passant à 150mm		
	Tir 001 à 030	Tir 031-060	Variation %
SAINE	29,67%	3,35%	-88,7%
MIXTE	5,75%	3,04%	-47,2%
DÉGRADÉE	6,67%	3,22%	-51,7%

Figure 13 Table summarising the percentage of the 150mm passing size according to the quality of the deposit

These figures also demonstrate the stabilisation of the percentage of fines, whatever the quality of the deposit, thanks to the application of a specific and differentiated technique per geological area.

3.10. Absence of impact in terms of nuisance

All the techniques available *(see 3.4)* also help in the reduction of vibrations, either by lowering the unit charge, or by the use of destructive waves (here for the record).

At this stage, it is important to stress the dominating role of vibrations, both in the fragmentation process and in the generation of nuisance, so that controlling one, leads to a better control of the other. The same applies to the distance fly rock is projected and the spreading of the muck pile.

The technique chosen, that is the object of the present case study, was undertaken according to a holistic approach, enabling the best balance possible to be attained, for each blast, between fragmentation and vibration.
The I-Blast digital simulation software was decisive in this respect.

Following upon the loading modifications, no regulatory levels were exceeded for vibration or noise pollution. Although the blast-sensor distance fluctuated from one blast to another, there were comparable maximum levels between the two periods. The average of the maximum seismic levels increased by 4.9%, whilst the average maximum level of decibels decreased by 0.5%.

A slight drop in the average spreading ratio was noted, i.e. from 1.8 to 1.3 times the bench height. This slight settling is undoubtedly caused by a lower gas thrust, due to the presence of air columns and intermediate stemming *(see 3.6).*

CONCLUSION

The measurement, analysis and simulation protocol, as well as TBT's recommendations have enabled the percentage of fines in loosened rock to be stabilised on a lasting basis, within the scope of the objective defined by the operator, without having to abandon other objectives (safety, the top part of fragmentation distribution, environmental nuisance). This approach that is both scientific and pragmatic has also led to a significant narrowing of the average size spectrum around an increasing average size of the fragments.

This protocol, that is compatible with the production cycle of open-pit mines and quarries, whatever the materials mined or their geographic location, has been very reactive when satisfying a new objective whose financial challenges were crucial.

Le I-Blast design, simulation, and optimisation software developed by TBT has demonstrated its capability to our customers working open-pit mines, of rapidly and reliably simulating a multitude of configurations, whilst taking into account the data measured on site, as well as the individual characteristics of each blast. The optimisation of the decoupling diameter according to all the blast parameters could not have been carried out successfully without this unique simulation capability.

The results measured a posteriori, that are presented within the scope of this case study, show that the simulations undertaken, and the protocol followed, have enabled us to adapt to new objectives and achieve them very rapidly, without needing to interrupt or slow down the production of the site.

REFERENCES

Bernard, T. et al. 2012, Le Contrôle Total des Tirs de Mine en Carrière - Exemples de Conception, Simulation et Optimisation des Tirs de Mine sur des Exploitations à Ciel Ouvert, Revue de la Société d'Energie Explosive du Québec (SEEQ), vol.20 – N°2, Octobre 2012, pp.8-26

Bernard, T. 2010. New blasting simulation approach. *Proc. Fragblast, 9th International Symposium on Rock Fragmentation by Blasting*, Granada, Spain, 13-17 September 2009, Sanchidrián (Ed.), Taylor & Francis Group, 2010, pp. 437-446

Bernard, T. 2009. Explain to me why? *Proc. 5th EFEE Conf. on Explosives and Blasting*, Budapest, Hungary, 26-28 April. European Federation of Explosives Engineers.

Bernard, T. 1995. Control of Explosive Energy : Action of the explosive on the surrounding area. Thesis, Institut de Geodynamique URA-CNRS, Nice, France.

Chapot, P. 1980. Study of the vibrations caused by the explosives in the rock solid masses. Laboratoire Central des Ponts et Chaussées, Paris

Ho Cho S. et al. 2004. Rock Fragmentation Control in Blasting, The Mining and Materials Processing Institute of Japan, in *Materials Transactions*, Vol. 45, No. 5, pp. 1722 to 1730

Holsapple, K.A. 1987. Impact crater scaling laws. NASA Tech. Memo., NASA TM-89810, pp. 392-393, May.

Liard, J.J. 1993. Efficacité du bourrage dans le collet des trous de mine. Abattage des roches à l'explosif. *Une école d'été internationale*, Alès, France, 6-10 Sept 1993, pp.439-455. Ecole des Mines d'Alès.

Moser, P. 2003. Less fines production in aggregate and industrial minerals industry. *In Explosives and Blasting Techniques*, Holmberg Edition, 2003, pp. 335-343.

Simon R. 2002. Étude de l'effet du sautage adouci sur la fracturation des parois d'une excavation souterraine, Institut de recherche Robert-Sauvé en santé et en sécurité du travail, Rapport R-310.

Tosello, R. 2005-2006. Shock Waves & Detonation Waves. *Cours de détonique.* Institut des Sciences de l'Ingénieur Toulon Var (ISITV), La Valette du Var.