BLASTING VIBRATIONS CONTROL : THE SHORTCOMINGS OF TRADITIONAL METHODS.

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SUMMARY.

In the context of its studies for the french ministry of the environment and for the French national coal board, INERIS (the French institute for the industrial environment and hazards, formerly CERCHAR) has made a complete critical survey of the methods generally used to reduce the levels of blasting vibrations.

It is generally acknowledged that the main parameter to control vibrations is the so-called “instantaneous charge”, or charge per delay. This should be reduced as much as possible in order to diminish vibration levels.

On account of this, the use of a new generation of blasting devices, such as non-electric detonators or electronic sequential timers has been developped since the seventies.

INERIS has collected data from about 900 blasts in 2 quarries and 3 open pit mines. These data include “input” parameters such as borehole diameter, burden, spacing, charge per hole, charge per delay, total fired charge, etc . . . They also include “output” measurements, such as vibration peak particle velocities, and main frequencies. These data have been analysed with the help of multi variable statistical tools.

Decreasing the charge per delay with the help of priming devices such as non electric detonators or electronic sequential timers improves the levels of vibrations, but only to a certain point. After this point, the phenomena are far less well controlled than in traditional pyrotechnic timing and the perturbations seems more erratic. The total fired charge, the accuracy of pyrotechnic delays and the adjustment of the timer also have a strong influence on vibration levels.

Blasting tests were undertaken to evaluate new methods of vibrations control, such as the superposition of vibration signals. These methods appear to be accurate in many critical cases, but certainly would be highly improved with a better accuracy of firing delays. The development of electronic detonators seems to be the way of the future for a better blasting control.

The numbers between square brackets refer to the bibliography list.

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INTRODUCTION.

In the context of its studies for the french ministry of the environment and for the French National Coal Board, INERIS (French institute for the industrial environment and hazards, formerly CERCHAR) has made a complete survey of usual methods to reduce the levels of blasting vibrations, in order to advise field managers and environment inspectors.

Data from about 900 open pit blasts in 2 quarries and 3 mines have been collected and analysed with the help of multi variable statistical tools, in order to understand the mechanisms of developping or controlling vibrations, according to the blasting technique used.

Blasting tests were undertaken to evaluate new methods of vibrations limitation, such as vibration signals superposition.

CONTEXT OF THE STUDY.

Within the last two decades, blasting has evolved in Europe, with the increase of drilling diameters and the more frequent use of large blasts, in order to supply material to larger loading and hauling equipments. The research for better quality control of blasting results was also a factor of development.

In the meantime, regulations concerning blasting vibrations limitation have been drawn up and published, on account of the increase in general concern about environment. These regulations are generally more severe than those of countries like the USA or Canada, since the density of urbanization is higher on the old continent, In addition, in Europe, masonry is the most frequent structure of buildings, including numerous historical monuments. But this masonry is much more sensitive to vibrations than the concrete of industrial buildings or the wooden housing structure, that is very frequent in Northern America or Scandinavia.

For all these reasons, electric or non electric sequential firing techniques are nowadays very successful, in order to diminish the so-called “instantaneous charge”, that is considered as the main parameter for controlling vibration levels.

The practice of such techniques must be controlled with the help of a certain number of rules, in order to avoid misfires, as well as vibration superposition. For instance, one rule is that all the electric firing circuit or non electric shock tube network must be initiated before the detonation of the first charge. The second rule is that the difference in time between any two detonations of all the charges must be greater than 8 ms, in order to avoid vibration superposition due to the scattering of pyrotechnic delays [1].

Nevertheless, since millisecond detonators starting at long delay times are not common in Europe, some new rules have been adopted in order to keep these firing techniques possible with only a few number of pyrotechnic delays. For instance, the first rule previously mentioned has become that all the electric firing circuit or non electric shock tube network must be initiated in a certain radius around the current detonating charge.

The experience shows that, thanks to the use of sequential blasting, vibrations levels have been generally reduced, but remain unsuitable for the neiborhoood and are erratically above the authorized limitations. As it is rather difficult to directly analyse these phenomena, for instance with the help of in-situ measurements, a large scale data collection has been undertaken and a multi variable statistical analysis has been set up.

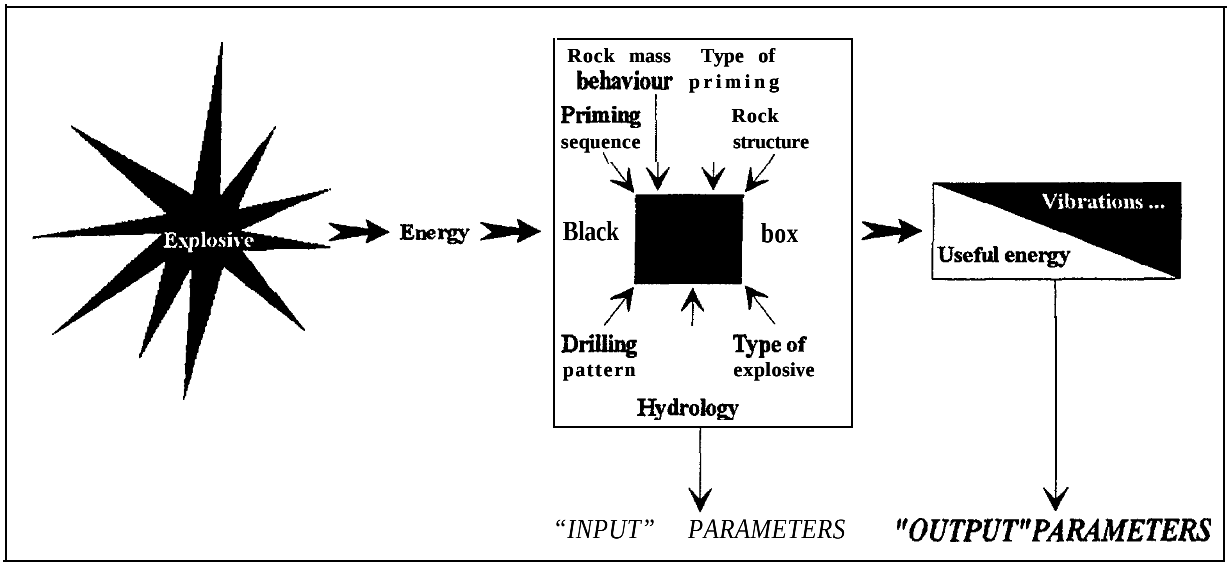
For the most critical cases, the technique of superposition of vibrations signals has been more recently developped. This technique has also been analysed.

MULTI VARIABLE STATISTICAL ANALYSIS.

Description of the data base.

As a general principle of study, it is admitted that blasting is a tool for transforming the energy release of the explosive into mechanical energy. This may be positively used, for instance in the fragmentation or the adaptation of the muckpile shape. But it may also have negative effects, like noise, flyrocks and vibrations.

FIGURE 1: TEE "BLACK BOX" OF BLASTING.



So, let's consider the blast as a "black box" that controls the distribution between positive and negative effects of mechanical energy (figure 1). The effect of this "black box" depends on "input" parameters, that may be classified as "natural" parameters (existing geological and geographical conditions, hydrology, etc ...) and "exploitation" parameters (drilling pattern, explosive energy, charge per hole, charge per delay, charge per period of firing time, total fired charge, etc . ..).

"Output" parameters are fragmentation, shape of the muckpile, environment injuries, etc . . . In this particular study, the work was focused on vibrations : longitudinal, transversal and vertical maximum peak particle velocities, as well as corresponding main frequencies.

The aim of this study is to bring to the fore the influence of input parameters (natural and exploitation parameters) on output parameters (vibrations) in open pit jobsites.

Finally, data were recorded for several hundreds of blasts, each of them being a recording, as shown in table 1.

TABLE 1: STRUCTURE OF DATA BASE.

	"INPUT" PARAMETERS		"OUTPUT" PARAMETERS	
	Natural parameters	Exploitation parameters	3 peak particle velocities	3 frequencies
Recordings				
⇩				
⇩				
	....	....	.............................*	. . . .*....................
a				
⇩				
⇩				
⇩				
a				

Table 2 shows the origin of data (3 mines and 2 quarries), the period of collection, the type of blasting technique used, the number of recorded parameters and the number of recordings for each site. All in all, 865 recordings have been collected.

TABLE 2 : DESCRIPTION OF THE DATA BASE.

	Mines				Quarries	
Jobsite	**A**		**B**	**C**	**D**	**E**
Number of recorded parameters	**25**	**31**	**19**	**29**	**20**	**21**
Date of beginning	**05.93**	**01.95**	**01.93**	**04.91**	**01.91**	**01.91**
Date of end	**02.94**	**03.95**	**11.93**	**08.94**	**04.91**	**06.94**
Type of sequential timing	**Electric**	**Electric**	**Non electric**	**Electric**	**Electric**	**Electric**
Number of recordings	**132**	**187**	**206**	**113**	**96**	**131**

What is multi variable statistical analysis ?

Each site’s data constitute a huge matrix of 19 to 31 columns and 96 to 206 lines. Of course it is an impossible task to immediately deduce the correlations between the parameters. Therefore, multi variable statistical analysis means were used, such as principal component analysis (PCA), factorial discriminant analysis (FDA) or multiple regression.

As many readers are certainly not specialists in multi variable statistical analysis, we will try to give a simplified example in order to explain the global methodology.

If we want to examine the correlation between 20 or 30 parameter, we would have to imagine data points within a space of "n" dimensions. But it is virtually impossible to visualize "n" dimensions if n is greater than 3. It is easily understood that, even in a "n" dimension space, the scattered group of points is approximately ovoid-shaped. This ovoid has a length, a width and a thickness, that is to say so-called principal axes. In an "n" dimension space, there are "n" principal axes. For instance, the principle of principal component analysis (PCA) is to calculate the direction of these axes with the help of the least square method. The principal components are more or less correlated with the original parameters, so that only a few of them are significant. The points are projected onto the most significant planes (2 components). The correlations between parameters become more perceptible immediately.

Results.

Some strong specific correlations have been detected for one site and may be the opposite on another. For instance, the presence of water in the boreholes may provoke an increase or a decrease in the levels of peak particle velocities. If they diminish, it may be that the matter is infiltrated rain water. In this case, it is obvious that infiltrations mainly occur in naturally fragmented rock masses, that will tend to attenuate the shock wave. If the peak particle velocities increase with the presence of water, the matter is more probably the presence of a water layer, which, on the contrary, may ensure a better transmission of shock waves.

It must be remembered that the aim of the study is to bring to the fore the most general correlations that may be useful for the entire blasters community. Therfore, we do not want to publish specific quantitative relationships between parameters, which would be appropriate for a unique jobsite, nor general quantitative relationships, which would not be appropriate for any particular site.

We prefer to show the general trends that were oberved at all jobsites. These are shown in table 3. In this table, the arrows show the direction of the effect and their size shows the quality of the correlation.

Some well known former results are successfully confirmed :

- the peak particle velocities are logically decreasing functions of the distance from the blast ;
- the peak particle velocities are increasing functions of the so-called “instantaneous charge” ;
- the frequencies are decreasing functions of the distance from the blast.

TABLE 3 : RESULTS OF THE ANALYSIS.

	INFLUENCE ON :	
INCREASING **PARAMETER**	PEAK PARTICLE VELOCITIES	FREQUENCIES
Distance **from blast**	↘	Y
"Instantaneous charge"	↗	**↗ or Y**
Drilling diameter	↗	Y
Surface of drilling pattern	↗	Y
Number of boreholes	↗	↗
Number of rows	↗	↗
Total blasted charge	↗	↗
Charge per 8 ms period of blasting time	↗	↗
Charge per 16 ms period of blasting time	↗	↗
Delay between **charges**	Y	↗

In the same way, less known results are also confirmed and generalized [2] : the peak particle velocities are increasing functions of the total fired charge.

It is shown that most of the correlations with frequencies are poorer than those obtained with peak particle velocities. Hence, the frequencies seem more difficult to control.

Concerning the peak particle velocities, some few significant correlations are obtained with input parameters like the borehole diameter and drilling pattern surface. Some other input parameters are well correlated with the velocities, such as the number of fired boreholes or the number of rows, but they have a direct or indirect link with the total fired charge.

The correlations observed between the velocities and the charges fired per period of 8 or 16 ms are of more interest : the higher the charge fired within a short period, the worse the vibrations control So, it seems that peak particle velocities are less well controlled when the timing technique is electronic.

Of course, this must be due to the scattering of pyrotechnic delays, since it is clearly demonstrated that the velocities decrease when the delay between charges increases. That is the reason why we deliberately maintain "instantaneous charge" beween quotation marks.

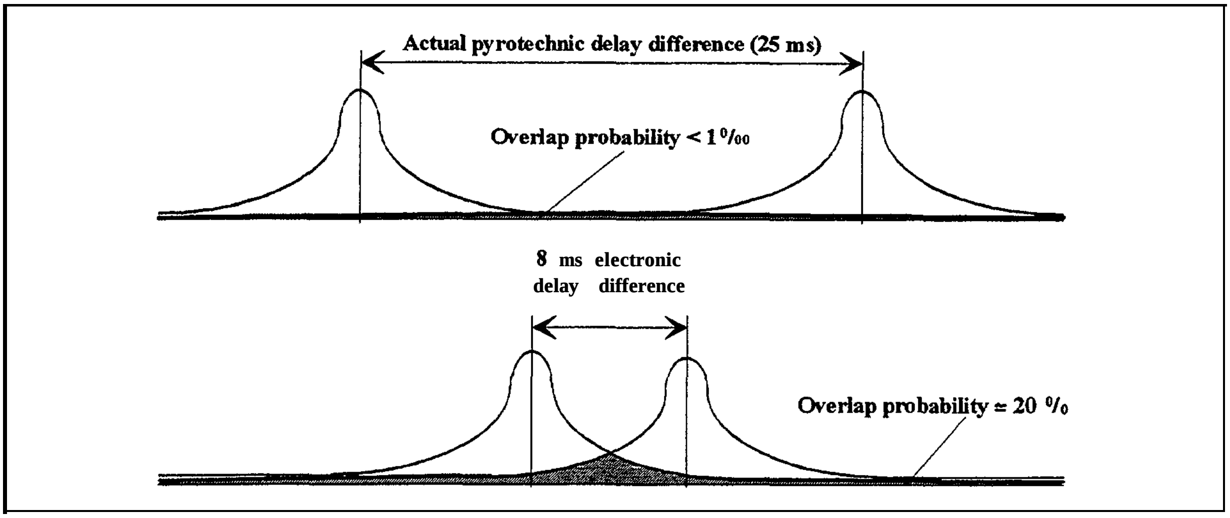
What is the meaning of *‘instantaneous charge” ?

The “instantaneous charge” is well defined when the delay between charges is constant and relatively great (usually 25 ms in non electric timing and greater than 30 ms in electronic timing).

It is well known that the delays of detonators are normal-distributed and that their scattering increases when the detonation time increases. For instance, in the case of 25 ms delays detonators, the most common in France, the standard deviation of detonation times may go up to 7 ms, within a total range of 500 ms (20 available delays).

If we consider an average standard deviation of 4 ms, it is easily shown that the overlap probability, which must be less than 1 ‰ in France with the normal pyrotechnic delay difference of 25 ms, may increase up to approximately 20 % if an electronic timer reduces to 8 ms the actual detonation times difference (figure 2).

FIGURE 2 : OVERLAP PROBABILITY WITH ELECTRONIC SEQUENTIAL TIMERS.



This figure is given as an example in the case of two single detonators. For a large number of charges, the overlap probabilities of all detonators may be cumulative and it is not surprising to observe some erratic surpassings of the authorized peak particle velocities values for blasts that are usually well controlled.

For these reasons, we think that “instantaneous charge” should preferably be defined as “near instantaneous charge”, that is to say : the maximum charge fired within a short period of time. Apart from changing the sequential firing technique, the prediction of blasting vibrations could be made on the basis of this new concept.

Thus, the "8 ms rule" should be reconsidered. However, in this case, all of the advantages of sequential firing are to be reconsidered.

SUPERPOSITION OF THE VIBRATIONS SIGNALS.

Principle.

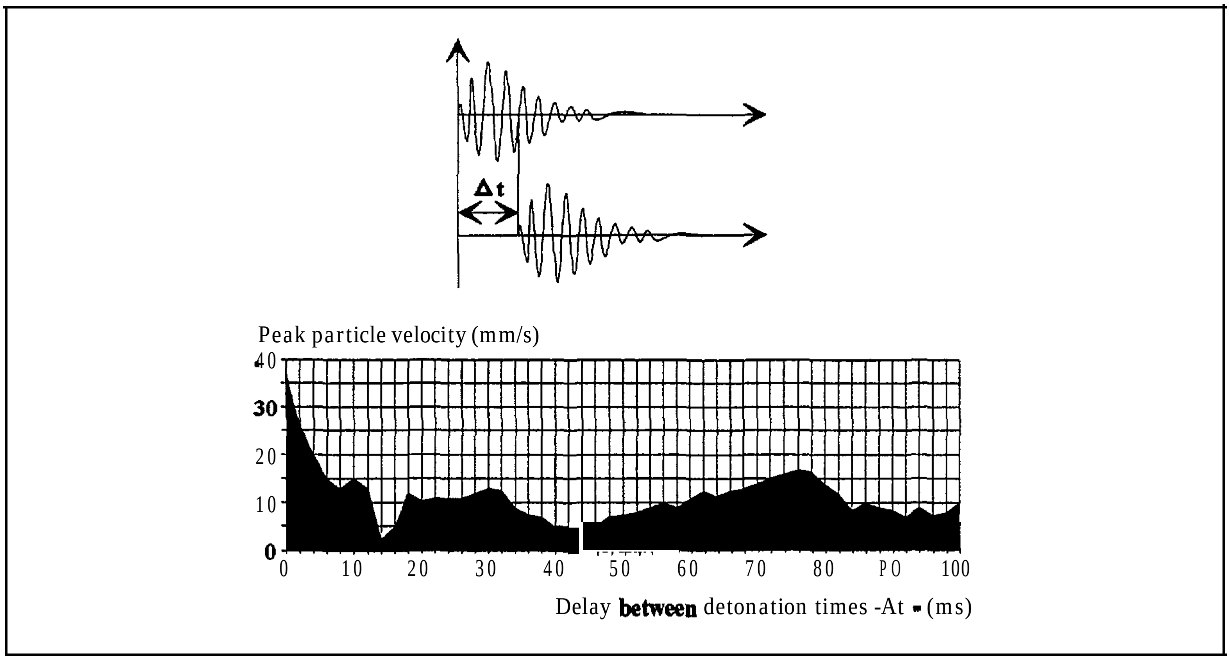
The aim of this technique is to fire the charges at adequate detonation times, so that the emitted vibration signals reach a place needing protection in phase opposition. So one may hope that particle velocities cancel each other out.

There are several methods to obtain this result in practice. The one we choose for testing seems to be most pragmatic [3]. Several series of tests have been undertaken in two quarries and one mine.

The basic hypothesis of the method is that a charge that is fired in a certain area of the jobsite produces a reproductible signal at the monitoring point.

As blasting vibrations are not perfect sine waves, and as the behaviour of the rock mass is heterogeneous, it is practically impossible that particle velocities perfectly cancel each other out.

FIGURE 3 : PRINCIPLE OF SUPERPOSITION OF THE VIBRATIONS SIGNALS.



One or several single charges are fired in the area and the corresponding signals are monitored at different places, including the one to be protected (notice that it is also possible, but more complicated, to deduce the elementary signals from a complete production blast). Then, a full scale blast is simulated, involving as many charges as the normal blast of the quarry, with different detonation times. The geometry of the whole blast and the velocity of transmission of the shock waves on the site are taken into account. For instance, figure 3 shows the way of calculating the superposition of two charges with a detonation times difference of At.

Results.

One representative test was undertaken with a shot of 10 single column boreholes fired with the same pyrotechnic delay at the bottom, while a constant detonation times difference At between boreholes was given with the help of a sequential timer.

Figure 3 also shows the computerized peak particle velocity in one of these test, versus the detonation times difference At. The graph gives the expected peak particle velocity for optimum detonation times differences : optimization is possible for values of At of 14 or 44 ms.

We observed a constant reduction by about 40 % of peak particle velocity, when comparing it with the normal pyrotechnically delayed blast, involving the same drilling pattern and the same charges per borehole. This result was quite reproductible with a 44 ms detonation times difference.

We decided that a test with a 14 ms detonation times difference was not suitable, since the overlap probability of charges detonations, due to pyrotechnic delays scattering, would have reached the value of 5 %. Looking at the shape of the graph in figure 3, it is easily understood that a shift of 2 or 3 ms on both sides of the optimum of 14 ms would largely change the results. The risk of surpassing the legal limitation of peak particle velocities would have been unacceptable at this particular site.

More generally, the superposition method of blasting signals is effective. But, when the optimum range of delay differences between the charges is too narrow, the benefits of the method may be outweighed by the scattering of pyrotechnic delays.

Moreover, some tests undertaken show that the method is less beneficial when there is a great number of boreholes. Again, this is due to the scattering of pyrotechnic delays, which can accumulate if the number of detonators is greater. But it is also due to the enlargement of the total blasting surface, which introduces scattering in rock mass behaviour.

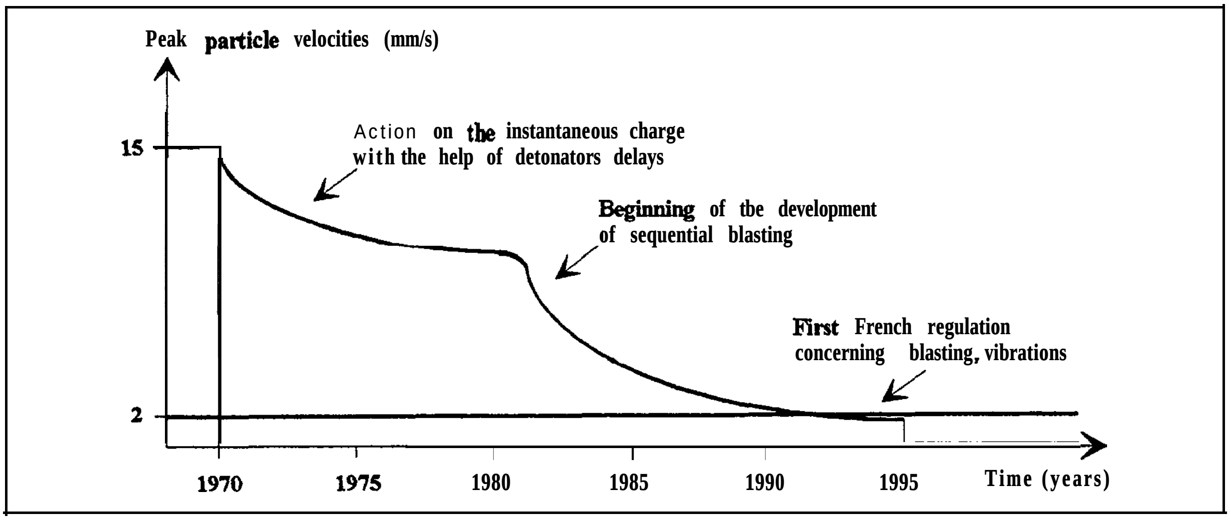
The development of electronic detonators should improve the accuracy of the method [4].

CONCLUSIONS.

It is obvious that non electric or electronic technologies of sequential timing have largely improved blasting results from the point of view of the production, while they also have made it possible to reduce the levels of blasting vibrations (figure 4).

In France, the most severe limitation of peak particle velocities is 2 mm/s for the lowest frequency taken into account (1 Hz). Thanks to these technologies, this limitation is seldomly surpassed in the most critical cases.

FIGURE 4 : SCHEMATIC HISTORY OF BLASTING VIBRATIONS (IN FRANCE).



But this study shows that these technologies make it impossible to prevent erratic phenomena, that may be unacceptable for surrounding residents. The limits of the methods are particularly reached in the case of large blasts, since sequential blasting still requires the use of pyrotechnic delay detonators. The scattering of their delays provokes a loss in the control of undesirable blasting effects. Some common rules of sequential blasting - such as the famous “8 ms rule” - should be reconsidered. However, in this case, all of the advantages of sequential firing are to be reconsidered.

The superposition method of blasting signals is effective, but it is also limited by the actual accuracy of pyrotechnic detonators.

The development of electronic detonators, having an improved accuracy, will consitute a new step in the control of vibrations.

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