Instituto Superior Técnico, 2020

Comparison of vibration amplitudes with non-electrical and electronic initiation systems

José Manso Urbano (1)

(1) Masters in Geological and Mining Engineering student nº. 76814

Abstract

Mining industry is continuously demanded to provide answers to mankind's diverse raw materials needs. In order to have access to the mineral goods that societies require, excavation works using explosives are a common practice, namely due to lower costs and shorter production cycles and, in the proximity between exploration zones and residential areas, it can cause negative environmental impacts, as well discomfort over populations.

The respect for the legislation that allows coexistence between people and industry in the same area, obliges mining and earthmoving companies to use the best practices and to use the most advanced techniques, so that the legal limits that guarantee the quality of life in the surroundings of the excavation areas are complied with. In this context, a comparison is established between non-electrical and electronic initiation systems, analyzing the feasibility of using each of these systems, in different application situations, in a limestone quarry, used in the production of cement, located in the vicinity of a population center, aiming to control the vibrations produced by the detonations.

The performance evaluation criterion of the initiation systems results from the dynamic characterization of the rock mass, under the action of explosive detonations. In the present work, statistical correlations (multiple linear regression) are used, considering the weighting of the explosive charges used, the distances and the delay timing between contiguous holes, to carry out the referred dynamic characterization, resulting the information used in this analysis from data field, on the application of explosives, obtained in three monitoring campaigns: one related to the non-electric initiation system and two related to the electronic initiation system, balanced from the point of view of the amount of data that characterize them.

The main objective is to create a model for predicting the amplitudes of vibration resulting from detonations, which presents greater reliability compared to the models currently used in geotechnical activity.

Key-words: Non-Electric detonators, Electronic detonators, Environmental impacts; Vibrations.

1. Introduction

Constraints in the use of explosive substances derived from possible environmental impacts arising on the population and on structures located in the vicinity of where the projects are implemented, namely by the production and propagation of vibrations to existing structures (which can cause damage), by the projection of blocks, by the propagation of aerial waves and also by the production of significant volumes of dust that can generate discomfort in people. The mitigation of undesirable environmental effects, inevitably almost always poorly received by public opinion, which sometimes disturbs the normal course of mining works, has led to the emergence of specific environmental protection policies capable of regulating the industry, establishing legal limits and contemplating the protection of populations as well as the preservation of existing structures in the vicinity of blasting sites. Following the establishment of these limits, there was a need to create predictive models of the vibratory amplitudes generated by the detonations that related this parameter to the instantaneous explosive charge and the distance to the points where the sensitive receivers are located. This modeling has allowed to predict the vibrational amplitudes generated and to adjust the fire diagrams, legally framing the mining operation, according to the applicable norm, mitigating the environmental impacts, with objective criteria of operation control and correcting any dimensioning errors related to loads or inadequate timings.

Invariably, detonations in rock masses result in temporary and permanent effects, which result from the propagation of dynamic stresses and the rapid expansion of gases.

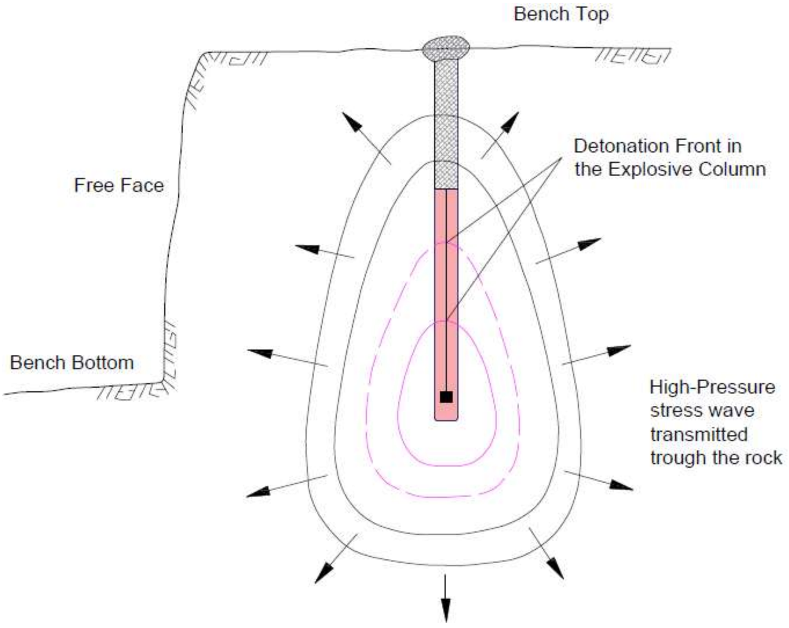

Figure 1 – Propagation of stress waves (Adapted from ESSEEM, 2010)

This sudden release of energy on the ground causes the propagation of volumetric and surface waves, which will affect people and nearby structures. The amplitudes of vibration depend on several factors, including the amount of energy released in the phenomenon that originated them, the distance between the origin and the registration point, the transmitting and dissipating properties of the terrains involved and the dynamic resistance of the structures and their most fragile components (Dinis da Gama, 2003).

2. Vibration

Bernardo (2004), defines vibration as an oscillatory movement of a material, solid or fluid, which has been removed from its equilibrium position. In this context, the elastic response of terrains, whose constitution is soil or rocks, to the passage of a tension wave, with direct or indirect origin in a dynamic request, is defined as vibration and the main parameters that characterize the waves are:

- Amplitude (m). Magnitude of a particle's affectation from its resting position
- Displacement (m). Space covered by a particle when excited by the wave
- Vibration speed (m/s). Displacement of particles per unit of time, caused by the passage of a wave
- Acceleration (m/s^2). Variation in particle speed per unit time
- Period (s). Time required to complete a cycle
- Wavelength (m). Full cycle length
- Frequency (Hz). Number of cycles per second

The maximum vibration speed, during the propagation of tension waves, is called the peak vibration speed (v_L), usually recorded in mm/s (or cm/s) and the most relevant variables for its characterization are the maximum charge detonated at the same moment, the distance traveled by the waves, the geological conditions, the confinement of the rock mass, the physical properties of rocks, the coupling of the explosive, the dispersion of detonator timings and the type of explosive.

Monitoring of vibrations and peak vibration speeds is carried out by engineering seismographs, equipped with triortogonal geophones (recording the longitudinal, transversal and vertical components of the waves), whose function is to receive and record seismic impulses. Usually is recorded the peak vibration speed, the frequencies measured in the instant of time when the maximum amplitudes are verified and the resulting vector (PVS - peak velocity sum), the latter being used as the maximum value of the vibratory speed that reached the monitoring location (Bernardo, 2004).

As with all force fields, seismic waves decay or disappear with distance, and an inverse proportionality relationship between this factor and the vibration speed is expected. This phenomenon is called attenuation. Sarsby (2000) pointed the geometric expansion of the waves and the presence of discontinuities in the rock mass, as well the progressive separation of the three components (which derives from the different propagation speeds) and the dynamic internal friction characteristic of the rocks as the factors whose contribution affects the decrease in vibrations with distance.

The law of attenuation of vibrations in the terrains, originated by detonation of explosive charges, more used is due to Johnson (1971) with the following general formulation (Dinis da Gama & Bernardo, 2001):

$$\mathrm{v} = \mathrm{a}\mathrm{Q}^{\mathrm{b}}\mathrm{D}^{\mathrm{c}} \qquad \text{(Equation 1)}$$

Q is the maximum charge per delay, D is the distance and a, b and c are empirical constants (calculated regression parameters)

3. Monitoring campaigns

Between July 31 and October 24, 2006, a campaign with non-electric detonators (NED) took place, aiming at the dynamic characterization of the terrains and the assessment of the environmental impacts produced by detonations to dismantle the rock mass, either in the quarry area, either in the vicinity of the Maceira Production Center.

On November 22, 2012 began a first monitoring campaign in which the charges were initiated with electronic detonators (EBS1) which lasted until May 13, 2013. In this campaign, detonations were concentrated in two areas of the quarry and the registration points coincided with structures close to the areas where the dismantling took place.

During 2014, between March 14th and June 26th, due to the better performance of electronic detonators, a new campaign appeared with the application of electronic detonators (EBS2), in an area of the quarry very close to the limits of the exploitation, in order to try to control the vibrations produced and transmitted to the surrounding populations. On this campaign, to reduce the maximum charge per delay, holes were loaded with deck charges.

Table 1: Campaigns Summary

Bank Detonations		**Global average values**				
Reference	Number of Elements	PVS (mm/s)	Maximum Charge per Delay (kg)	Distance (m)	N.º of Holes	Total charge (kg)
NED	63	1,88	84,3	531,1	8,9	544,5
EBS1	49	0,77	42,8	554,1	11,3	503,6
EBS2	18	1,92	29,8	269,9	20,8	941,7

Note: To ensure equivalence in the NED campaign, only detonations carried out in the same way as EBS1 and EBS2 were considered for study purposes

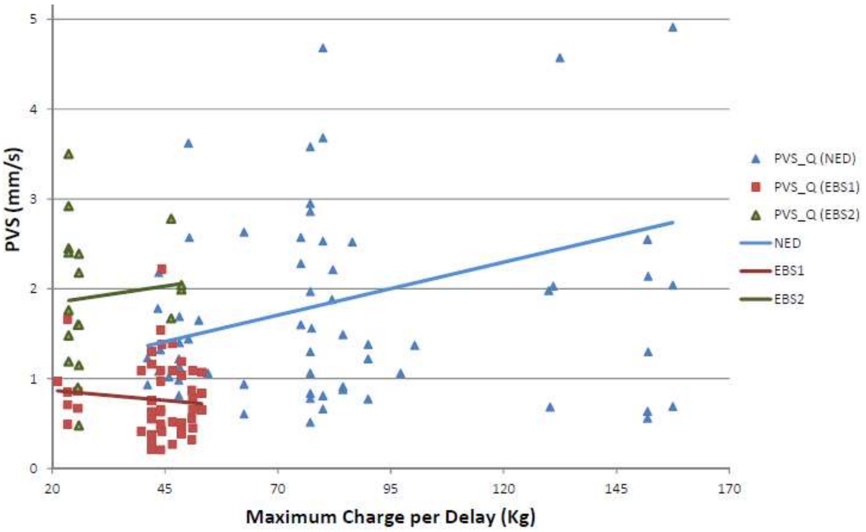

Figure 2 – Vibrations produced in the 3 campaigns

Observing the adjustment lines in the case of EBS1, the behavior that appears to be contrary to expectations stands out due to smaller amplitudes of vibration with higher loads per delay unit. This phenomenon is due to the presence of anomalous elements "outliers" and it is necessary an approach that filters the information collected in order to suppress the effect of these elements on the behavior of the campaign data.

The criterion used to remove outliers was to represent graphically, by load classes per delay, the values of the vibrations produced as a function of the distance and to identify, in the graph produced, which elements are the most distant from the correlation lines, removing a total number of elements close to 10%.

The withdrawal of outlier elements solved the EBS1 problem but caused some constraints in EBS2, due to the relatively small number of elements in this campaign

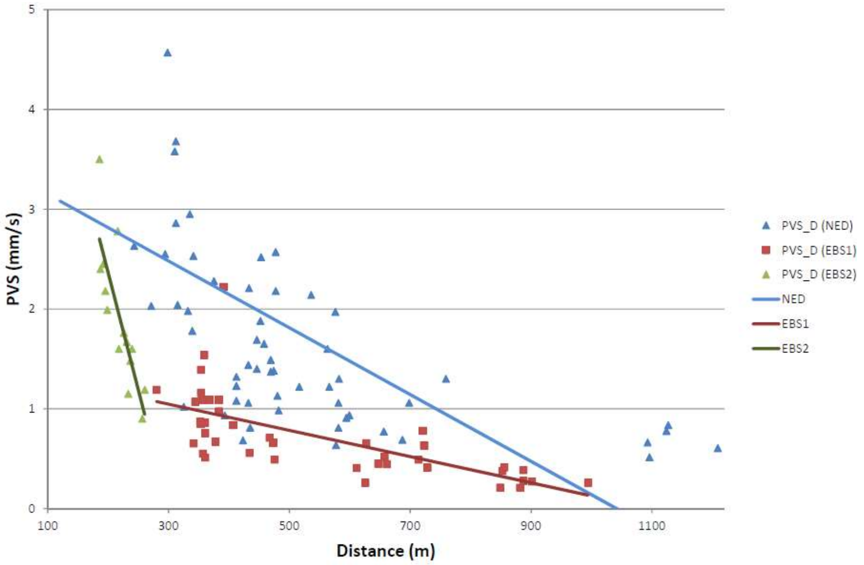

Figure 3 – Vibrations versus distance in the 3 campaigns without outlier elements

This fact was also observed and confirmed with the use of linear regressions to calculate the empirical constants in Equation 1 (Table 2).

In order to enable the determination of the non-linear function, $v = f(Q, D)$, due to the presence of the parameters in the exponents of the Equation 1, a logarithmic transformation was carried out where $\mathrm{y} = \log_{10} \mathrm{v}$; $\mathrm{x}_1 = \log_{10} \mathrm{Q}$ and $\mathrm{x}_2 = \log_{10} \mathrm{D}$

$$\mathrm{y} = \mathrm{b}_0 + \mathrm{b}_1\mathrm{x}_1 + \mathrm{b}_2\mathrm{x}_2 \qquad \text{(Equation 2)}$$

Obtaining a linear relationship between v, Q e D. Finally, to determine the empirical constants of the rock mass, we have $\mathrm{a} = 10^{\mathrm{b}_0}$; $\mathrm{b} = \mathrm{b}_1$ and $\mathrm{c} = \mathrm{b}_2$

Table 2: Rock mass parameters in the different campaigns and correlation factors obtained

Campaign	Number of Elements	Correlation Coefficient, R	a	b	c
NED (Original)	63	0,68	168	0,27	-0,95
NED without outliers	56	0,79	398	0,23	-1,07
EBS1 (Originais)	49	0,61	386	-0,16	-0,92
EBS1 without outliers	43	0,81	430	0,23	-1,19
EBS2 Originais	18	0,78	198	0,18	-0,97
EBS2 without outliers	16	0,70	21348	0,34	-1,94
Literature D. Gama *1	-	-	580	0,6	-1,4
Literature Visa Cons.*2	-	-	500	0,42	-1,22

*1 – Dinis da Gama (1997) *2 – Visa Consultores (1999) - Source: (Bernardo, 2005)

In the case of the NED and EBS1 campaigns without outliers, values with very good adherence to the literary references are obtained, justifying the statistical treatment of the data. In the case of EBS2 it is preferable to use the original data.

4. Estimation of maximum explosive charge values according to NP 2074, 2015

The dominant frequencies in the 56 elements of the NED campaign (without outliers) vary between 2 Hz and 37.5 Hz, with 25 elements below 10 Hz and 31 elements between 10 Hz and 40 Hz. Although the average values are 11.42 Hz, it seems prudent, in view of NP2074, 2015, to limit the maximum permissible vibration speed to 3 mm/s, for current structures (class in which dwellings located in the vicinity of exploration are inserted).

Equation 1 can be written in order to the maximum load per delay:

$$Q = \left(\frac{v}{aD^c}\right)^{\frac{1}{b}}$$ Equation 3

For a given speed of vibration, v, knowing the parameters of the rock mass, (a, b, c), it is possible to obtain a relationship between the maximum load Q that can be used as a function of a distance, D, between the source and sensitive receivers, allowing to evaluate the performance of the different scenarios considered in the campaigns carried out. This analysis allows the construction of bilogarithmic graphs of comparative isovalues of the different campaigns and to evaluate the performance in the different scenarios (Figure 4).

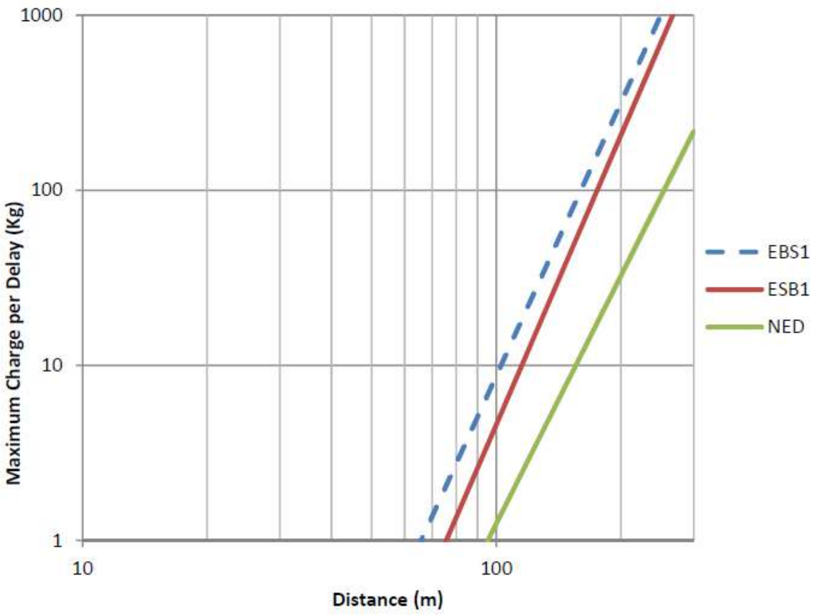

Figure 4 – Isovalues of velocity for v= 3 mm/s (current structures)

Looking at the Figure 4, there is a high degree of parallelism between the various campaigns. Given the strictly equal nature of the explosives used and of the rock mass, this fact is of particular relevance as it demonstrates the better performance of electronic detonators compared to non-electric ones, meaning that, for a given distance (D), more charge of explosives can be used per delay when using electronic detonators, for the same vibration speed limit.

Propagation laws with slightly higher correlation factors should be obtained, when a more detailed approach is used, considering the relative weight of the explosive charges (that reflects the dependence on the nature of explosive products) and the weight of timing between delays used.

$$\mathrm{v = aW^bD^c} \qquad \text{(Equation 4)}$$

$$\mathrm{v = aW^bD^cT^d} \qquad \text{(Equation 5)}$$

Parameters a, b, c and D are similar to those in Equation 1. W is the weight of bottom and column charge through detonation pressure and T is the weight of timing in the connections between adjacent holes. Equation 5 cannot be used for NED campaign, due to the (relative) lack of precision of this system.

$$\mathrm{W = \left(\frac{Pd_{CC}}{Pd_{CC}} * \frac{QC}{QT} + \frac{Pd_{CF}}{Pd_{CC}} * \frac{QF}{QT}\right) * QT} \quad \text{[kg]} \qquad \text{(Equation 6)}$$

$\mathrm{Pd_{CF}}$ is the detonation pressure of bottom charge and $\mathrm{Pd_{CC}}$ is the detonation pressure of column charge, whose values were obtained from the respective product catalogs. QC is the column charge, QF is the bottom charge and QT is the total charge

Adding the load weights, W and timing weights, T, applying linear regressions according to the principles previously considered to the data sets generated and according to equations 3, 4 and 5 the results are shown in Table 3, and, as mentioned, the elements of the NED and EBS1 campaigns resulted from the elimination of "outliers" values and in the EBS2 campaign all elements were considered.

Table 3: Rock mass parameters in the different campaigns and correlation factors obtained with and without weights of charge and timing

	Campaign	**Number of elements**	**a**	**b**	**c**	**d**	**R**
Without weights	NED	56	397,54	0,23	-1,07	-	0,79
	EBS1	43	430,38	0,23	-1,19	-	0,81
	EBS2	18	197,72	0,18	-0,97	-	0,78
Weight W	NED	56	418,51	0,21	-1,07	-	0,79
	EBS1	43	381,57	0,26	-1,19	-	0,81
	EBS2	18	153,94	0,24	-0,97	-	0,78
Weight W and T	NED	-	-	-	-	-	-
	EBS1	43	916,95	0,27	-1,22	-0,21	0,81
	EBS2	18	187,91	0,46	-0,95	-0,40	0,81

From the observation of Table 3, it can be seen that, regarding the rock mass parameters, the EBS2 campaign always presents results that are far from the average, mainly in parameter a, compared to the values of the NED and EBS1 campaigns. This happened because during the EBS2 campaign there were very different conditions in terms of water saturation of the rock masses and in only 8 trials, there were days of clean sun and dry weather, days of intense rain and flooded holes and days of dry weather but still with residual water in the massif.

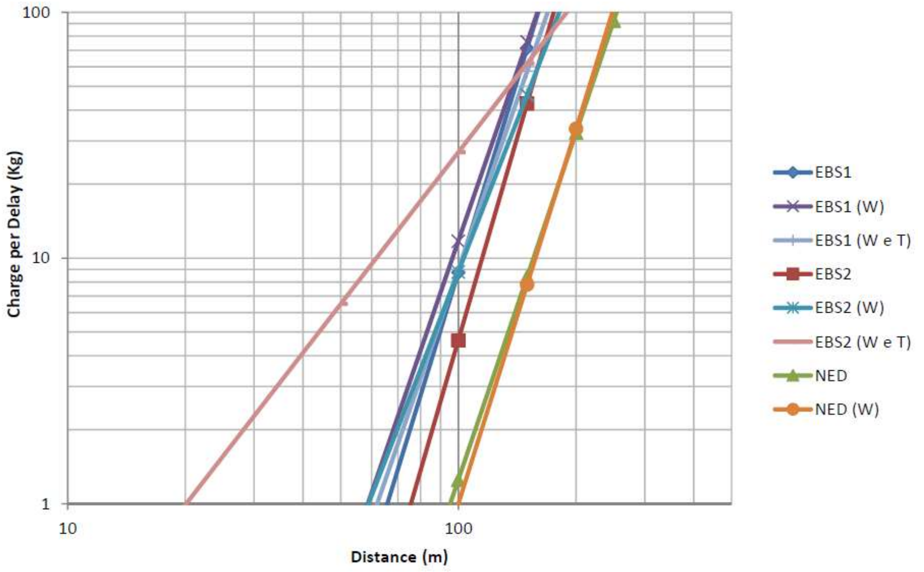

Figure 5 – Isovalues of velocity for v= 3 mm/s, without weights, with weights W and T (25 ms)

From the observation of the graph in the Figure 5 the better performance of electronic initiation systems is highlighted in comparison to non-electric systems. The similar behavior of all linearizations can be seen, expressed by the relative parallelism of the lines corresponding to the different situations under study, except for the EBS2 campaign using weights for charge and timing (25 ms). It should also be noted that this behavior appears only when the timing parameter is introduced in the EBS2 campaign. Apparently, in the EBS2 campaign, the use of the timing weight does not improve the system, on the contrary, since the behavior of the linearization departs from other situations and the slope and positioning of the straight line leads to a sudden decrease in the maximum charge per delay from 70 m away, compared to other simulations. It follows that the timing scheme used in the tests performed does not produce the best results. In terms of delays between holes, in the EBS2 campaign, were used 20 ms, 30 ms and 40 ms. In situations where decks were used, there was a difference of 15 ms between upper and lower charges (opening through the upper deck).

From several simulations it was found that higher timings produce better results, particularly in the 40 ms range, to the detriment of lower timings, although due to the way in which the linearization equations were obtained, it is not possible to establish the optimal timing limit.

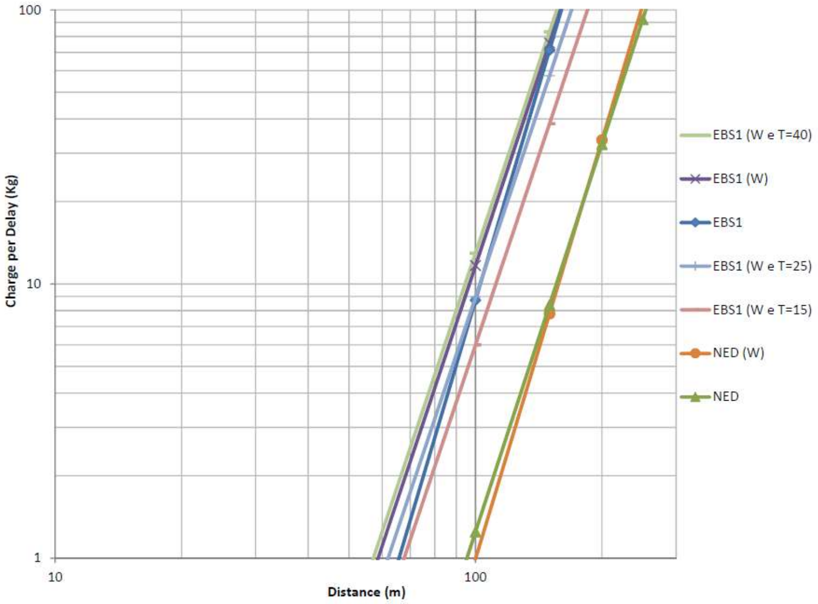

Figure 6 – Isovalues of velocity for v= 3 mm/s, NED and EBS1 campaigns, without weights, with weights W, and with weights W and T (15 ms, 25 ms and 25 ms)

From the observation of Figure 6, the best behavior of the EBS1 campaign can be seen, compared to the NED campaign, being especially relevant to point out that for a distance of less than 200 m, respecting the legislation, it is very complicated to blast rock in this quarry with the non- electrical system, with a maximum allowable of 33 kg per delay (at holes in 10 m high benches, at least 40% more explosive mass is required), with the possibility of continuing to use the electronic system. The parallelism of the linearizations, for both systems, translates even better the behavior of the electronic system regardless of the distance considered.

3 Conclusions

With this work it is concluded that, regardless of the limit amplitude for the peak vibration speed considered, electronic detonators always present better environmental performance compared to non-electric detonators. It was also demonstrated that when the area to be blasted approaches to populations or structures that must be protected, in compliance with the legislation in force, it is necessary to take special care with the vibrations produced during the blast, with the non-electrical system having greater limitations in use, compared to the electronic initiation system. The latter system presents less restrictions regarding the charge detonated per delay and due to its greater precision, it also allows the possibility of increasing the size of the blast and reducing the number of events that disturb the populations in the vicinity of the quarry.

For a peak vibration speed of 3 mm/s there are clear advantages in using the electronic initiation system, particularly for distances less than 250 m and with maximum charges per delay of up to 60 kg, as the non-electrical system will not present, under these conditions, values below this limit and with the electronic system it is still possible to continue to blast.

As a final suggestion, it is also indicated the possibility of scheduling the blasts taking into account the levels of water saturation in the rock mass. After intense periods of rainfall it is not advisable to perform blasts, because the presence of water facilitates the propagation of vibrations produced by detonations, being much more likely to occur unwanted values.

In view of the nature of the blasted material, which does not change in physical and chemical properties due to exposure to atmospheric elements, when the rock mass is dry, stocks of material that can be used during rainy periods must be produced.

References

Bernardo, P. A. M. (2004). *Impactes Ambientais do Uso de Explosivos na Escavação de Rochas, com Ênfase nas Vibrações*. Dissertação para obtenção do grau de Doutor em Engenharia de Minas. I. S. T. – U. T. L.. Lisboa

Bernardo, P. A. M. (2005). *Metodologia para a prevenção de danos e controle ambiental de vibrações causadas por detonações em maciços rochosos*. Publicado no XV Encontro Nacional do Colégio de Engenharia Geológica e de Minas da Ordem dos Engenheiros, realizado em Ponta Delgada, 26 a 29 de Maio de 2005

Dinis da Gama, C. (2003). *Elementos de Dinâmica das Rochas: 1º Curso Sobre Explosivos para Responsáveis Técnicos de Pedreiras e Obras de Escavação*. Organizado pelo CEGEO (Centro de Geotecnia do I. S. T.), no I. S. T., em Março de 2003

Dinis da Gama, C & Bernardo, P. M. (2001). *Condições Técnicas para Uso de Explosivos na Escavação de Túneis Urbanos em Maciços Rochosos.* Curso sobre Túneis em Meios Urbanos (Organizado por SPG e FCT-UC) – Coimbra, 5 e 6 de Abril

ESSEEM (2010). *European Shotfirer Standard Education For Enhanced Mobility*. ESSEEM Work Package 6 Blasting theory

Norma Portuguesa NP 2074 (015). *Avaliação da influência de vibrações impulsivas em estruturas*. Instituto Português da Qualidade (IPQ), Lisboa

Sarsby, R. (2000). *Environmental Geotechnics.* Thomas Telford, Londres. Reino Unido