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Analysis of Blasting Vibrations Produced In a Gold Mine Using the Damage Prevention Abacus

Rafael Rodríguez[a], Patricia Fernández[a], Cristóbal Lombardía[b], Marc Bascompta[c]
[a] Department of Mining Exploitation and Prospecting, School of Mining, Energy and Materials Engineering, University of Oviedo, Independencia 13, Oviedo, 33004, Spain
rrodrifer@uniovi.es
[b] Perforaciones Noroeste S.A, Longoria
Carbajal No. 3, Oviedo, 33004, Spain
[c] Department of Mining, Industrial and ICT Engineering, Polytechnic University of Catalonia (UPC), Manresa, Av. Bases de Manresa, 61-73, Barcelona, 08242, Spain

Abstract **-** Ground vibrations due to blasting can cause damage to nearby structures. Damage prevention criteria have been developed to avoid this potential risk, demonstrating a limit value for the peak particle velocity (PPV) as a function of ground natural frequency and type of structure to protect. In addition, several empirical attenuation laws to estimate PPV and frequency as a function of distance and the amount of explosive used were also developed. These models can be used to predict, separately, PPV and frequency, obtaining the representative point in the damage prevention abacus of the designed blast and decide if a potential damage could exist or not. In a previous work, the authors have proposed a procedure to define not a point but an area representative of the risk in the abacus of damage criteria. The procedure was developed for blasting in limestone quarries working simultaneously with the PPV and frequency attenuation laws. The present work demonstrates that the method can be used for other types of limestone blasts. Thus, several blasting operations were monitored on limestone materials in an open-pit gold mine. Verifying the goodness of the new method proposed.

Keywords**:** Blasting, Ground vibrations, Vibration attenuation law, Frequency attenuation law, Damage prevention criterion

1. PPV and Frequency Attenuation Laws and Damage Prevention Criteria

Blasting is a well-known technique widely used in mining and civil works because of the operational low costs compared to mechanical excavations. Thus, the correct management of the whole blasting process and the potential impacts that could cause is crucial for the viability of its usage. Vibrations are usually the main concern when applying blasting techniques and, therefore, it is necessary to control and predict the vibrations induced, as well as analyse them and take the required actions, if needed. It is especially important when there are nearby constructions.

The threshold limit values of ground vibrations are based on the damage that could cause and the type of construction affected, being a topic extensively studied over time and mainly governed by the velocity and frequency of the waves. The first attempt is proposed in [1] and from it, the first criterion was proposed by the U.S. Bureau of Mines RI 8507 (1980), in which a limit value of the PPV was established as a function of the ground vibration frequency.

Other standards were subsequently developed, [2] – [4], such as the British Standard BS 7385, the Spanish Standard UNE 22-381-93 or the German standard DIN 4150. Since the risk of damage to structures increases as the magnitude of the vibration increases and the frequency of vibration decreases, all prevention criteria were established as a function of peak particle velocity (PPV) and frequency. In general, all standards propose the use of an abacus with the damage prevention criterion limiting the PPV as a function of vibration frequency.

Given its importance, more than twenty empirical models have been developed for the prediction of PPV as it is summarized in [5]; a physical and mathematical justification for these empirical models was proposed in [6]. However, and despite being also important, there are not so many works focused on the frequency and its prediction. Since Sadovskij's first proposal [7], only half a dozen models have been proposed, [8] and [9].

One of the most important things to design the blast is to define the maximum charge per delay Q, and Some standards give some rules to do it. For example, the Spanish standard UNE 22-381 establishes that an equivalent explosive charge Q_{eq} is calculated by means of Eq. 1.

$$Q_{eq} = F_R \, F_S \, Q \qquad (1)$$

F_R depends on the type of rock, being F_R= 0.4 – 1 – 2.52 for a strong, medium strength or weak rock respectively (for limestone F_R=1); F_S is defined based on the type of structure, F_S= 0.28 – 1 – 3.57, for structures of a high, medium or low sensitivity to the vibrations (for buildings F_S=1). With the equivalent charge Q_{eq} and the minimum distance D_{min}, from blasting to nearest house or structure, the requirements with respect to blasting are determined from abacus of Figure 1A. If the point is below the lower line, it is considered that there is no risk, and the blasting can be carried out without prior actions, it can be justified by a theoretical Standard Study. If the point falls above the upper line, it is considered that there is a clear risk of causing damage and then a Preliminary Study is required, where trial blasting will have to be done to locally determine the behaviour of the rock mass with respect to vibrations and to be able to make an adequate design. If the point is placed between the two straight lines, the blasting can be carried out, but a Vibration Control or vibration monitoring procedure is required.

On the other hand, the standard defines a damage prevention criterion represented in Figure 1B. Once the frequency, *f*, of the vibration has been defined, the maximum velocity of the particle, *PPV*, must be less than the limit curves depending on whether the sensitive of the structure to the vibration is low (Group III), medium (Group II) or high (Group I). Residential buildings are considered Group II structures.

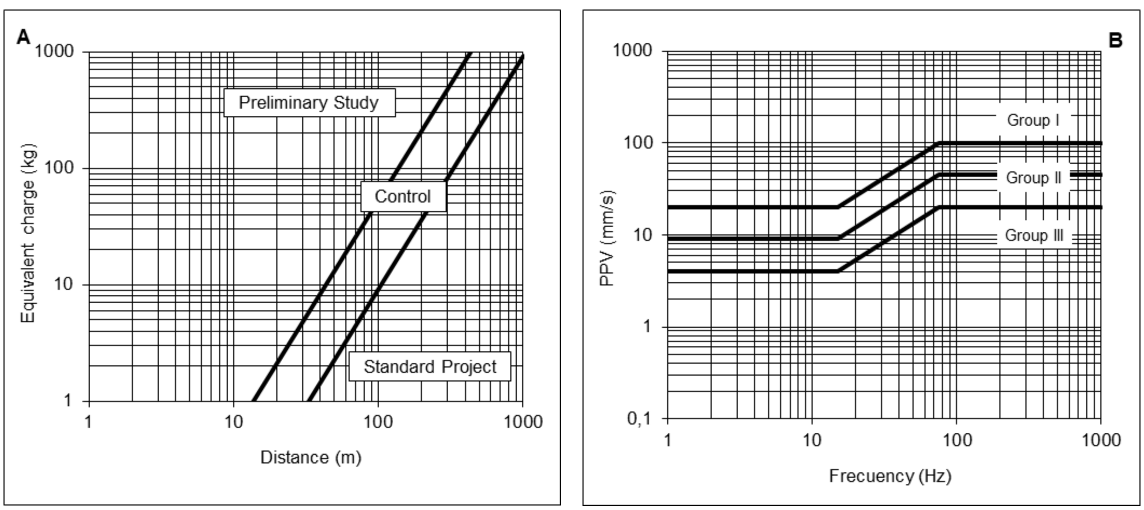

Figure 1. Abacus to determine the type of study and abacus with damage prevention criterion after Spanish Standards.

The proposed procedure to analyse the potential damage of blasting vibrations is described more in detail in [10]. The necessary parameters are the average value for the maximum charge per delay Q_{med} and the minimum and maximum distances from blasting to structures D_{min} and D_{max}. In the case of designing a blast in Spain, the abacus of Figure 1A can be used to determine Q_{med}.

Otherwise, he procedure to analyse the potential damage of blasting vibrations proposes to calculate Q_{med} as follows. First, the following *PPV* attenuation law for limestone is used:

$$PPV = c_v \; K_v \, Q^{\alpha} \, D^{-\beta} \qquad (2)$$

Q is the maximum charge per delay, D is the distance from blasting to monitoring point. K_v, α and β are empirical parameters, which values for limestone after [11] are K_v= 3085; α= 0.757; β= 1.651. The coefficient c_v is introduced to take in to account the variability in the results. The curve corresponding to c_v=1.0 is the average value for *PPV* for different scaled distances. The maximum *PPV* value for different scaled distances is established by a parallel line

(c_{vmax}=2.5). The lower limit, for low velocities, is defined by a parallel line (c_{vmin}=0.25). After our own experience, more than 95% of the data will be between these two limits.

The frequency attenuation used is the one proposed by [7]:

$$f = c_f \ \frac{K_f}{log_{10} D} \tag{3}$$

In the case of limestone, K_f= 77.4 is proposed for any limestone rock mass. The average frequency for a given distance D is given by the curve with c_f=1.0. The lower and upper limits are two parallel lines defined by the coefficients c_{fmin}= 0.35 and c_{fmax}= 2.2, respectively. After our own experience, more than 95% of data are within the range.

The procedure to define the representative area in the damage prevention abacus is the following:

1. D_{min} and D_{max} are the distance from buildings to the closest and farthest projected blasting for any given period. It is assumed that it is known because it can be determined from quarry planning.

2. The mean frequency f_{med} is determined from experimental data whenever possible. If f_{med} is not known, we must suppose a given behaviour of the rock mass assuming a value of K_f, and then estimate f_{med} as follows:

$$f_{med} = \frac{1}{2}\left(\frac{K_f}{\log_{10} D_{max}} + \frac{K_f}{\log_{10} D_{min}}\right) \tag{4}$$

3. The most unfavourable frequency is determined, which will be the minimum f_{min} detailed in Eq. (5).

$$f_{min} = c_{fmin} \ f_{med} \tag{5}$$

4. The maximum allowable PPV for the protection of structures from Group II for that frequency, v_{GII}, is determined from the prevention criterion of the UNE 22381 standard, Eq. (6). In addition, a reduction coefficient, c_s, could be applied on the safety side or within quality standards, if it is considered necessary.

$$v_{lim} = c_S \ v_{GII} \tag{6}$$

5. The maximum and minimum charge per delay, Q_{max} and Q_{min}, that can be used are determined, so that v_{lim} is not exceeded at distances D_{max} and D_{min}. Thus, the attenuation vibration law is used, considering that PPV can be c_{vmax} times the value estimated by the formula, Eq. (7-9); the charge per delay to be used in the calculations will be the average value Q_{med}:

$$\frac{v_{lim}}{c_{vmax}} = 3085 \ Q^{0.757} \ D^{-1.651} \tag{7}$$

$$Q_{max} = \left(\frac{v_{lim}}{3085 \ c_{vmax} \ D_{max}^{-1.651}}\right)^{1/0.757} \tag{8}$$

$$Q_{min} = \left(\frac{v_{lim}}{3085 \ c_{vmax} \ D_{min}^{-1.651}}\right)^{1/0.757} \tag{9}$$

$$Q_{med} = \frac{Q_{max} + Q_{min}}{2} \tag{10}$$

Finally, the representative area of the blasting results in the damage prevention criterion is drawn with six points calculated from Q_{med}, D_{min} and D_{max} following the calculations from Table 1. If we will compare the estimated results with the actual ones, the real locations of the seismographs must be considered. If f any seismograph is located nearer than the nearest house or further than the furthest house, we should use $D'_{min} \neq D_{min}$ and/or $D'_{max} \neq D_{max}$.

Table 1. Values of f and PPV of the representative points of the envelope.

Point	Q (kg)	D(m)	c_v	c_f	f (Hz)	PPV (mm/s)
1	Q_{med}	D_{max}	c_{vmin}	c_{fmin}	$c_{fmin}\ (\frac{K_f}{log_{10}D_{max}})$	$c_{vmin}\ (K_v\ Q^\alpha\ D_{max}^{-\beta})$
2	Q_{med}	D_{max}	c_{vmax}	c_{fmin}	$c_{fmin}\ (\frac{K_f}{log_{10}D_{max}})$	$c_{vmax}\ (K_v\ Q^\alpha\ D_{max}^{-\beta})$
3	Q_{med}	D_{min}	c_{vmax}	$c_f = 1$	$1 \times (\frac{K_f}{log_{10}D_{max}})$	$c_{vmax}\ (K_v\ Q^\alpha\ D_{min}^{-\beta})$
4	Q_{med}	D_{min}	c_{vmax}	c_{fmax}	$c_{fmax}\ (\frac{K_f}{log_{10}D_{min}})$	$c_{vmax}\ (K_v\ Q^\alpha\ D_{min}^{-\beta})$
5	Q_{med}	D_{min}	c_{vmin}	c_{fmax}	$c_{fmax}\ (\frac{K_f}{log_{10}D_{min}})$	$c_{vmin}\ (K_v\ Q^\alpha\ D_{min}^{-\beta})$
6	Q_{med}	D_{max}	c_{vmin}	$c_f = 1$	$1 \times (\frac{K_f}{log_{10}D_{max}})$	$c_{vmin}\ (K_v\ Q^\alpha\ D_{max}^{-\beta})$

2. Description of the blasts and data acquisition

To extend the use of the described procedure to blasting in limestone under different conditions, we are going to apply it to analyse the potential risk due to vibrations in the case of the blasting in a gold mine in Asturias.

As it is described in [12], the Río Narcea Gold Belt (RNGB) has received special attention over the past years due to its important economic potential. Detailed geological mapping and mining works have permitted to identify five main intrusive stocks (namely La Ortosa-Godán, Carlés, La Brueva-Pando, Villaverde-Pontigo and Boinás) located along a NE-SW trend with characters typical for Au and Au-Cu skarns. Most of the RNGB skarns with economic interest are exoskarns. Various carbonate lithologies exercise a firm control over the type of exoskarns. In the case of study, calcic skarns (garnet-pyroxene-wollastonite-scapolite) are formed along the contact with limestone units of lower Devonian [13].

The exploitation under study is an open pit mine with blasting benches between 3 to 15 meters high (Figure 2). In the blasting zones, the mineralization consists of granodiorites while the host rock is basically limestone; the compressive strength is 120 and 65 MPa respectively. A typical blast consists of 30 to 40 holes with a drilling diameter of 51-89 mm and an inclination of 15º-25º. The charge per hole ranges between 3 and 50 kg of explosive. The difficulty in this case lies in the proximity of several single-family houses (in the present study from 90 m to 200 m) which made to use lower maximum charges per delay.

The equipment used for the data acquisition were three seismographs of the Spanish manufacturer Vibracord with three seismic channels (vertical, longitudinal and transversal) and the following operational range of velocity, 0–150 mm/s, and frequency, 2–250 Hz. The attachment of the equipment to the ground was done following the criteria stablished by the UNE 22-381. The trigger value for PPV was fixed at 1 mm/s.

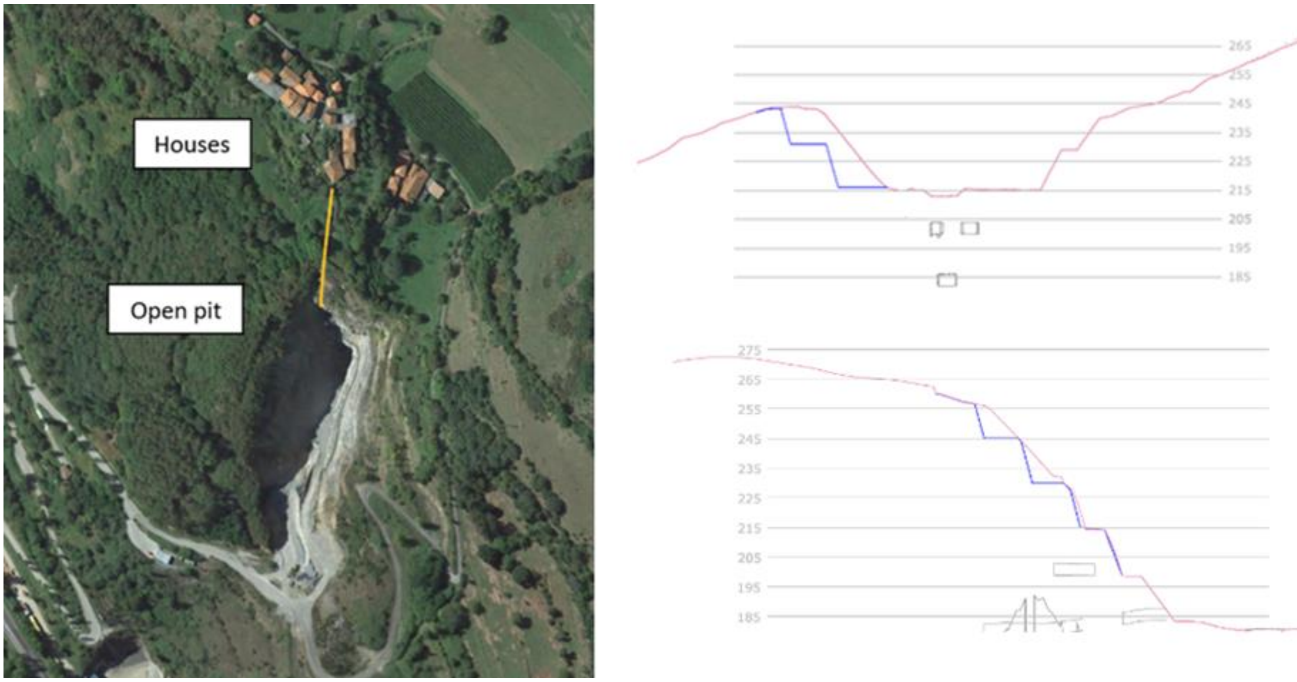

Figure 2: Layout of open pit and two cross sections with the blasting benches.

The results of the five vibration monitoring campaigns are summarized in Table 2. Q is the maximum charge per delay and D is the distance. The maximum PPV (mm/s) and mean frequency, f_{med} (Hz) from the vertical, longitudinal and transversal components are chosen as representative vibration characteristics.

Figure 3: Photographs of blasting benches and the seismograph installed near a house.

Table 2. Values of f_{med} and *PPV* of the representative points of the envelope.

Blast	*D* (m)	*Q* (kg)	f_{med} (Hz)	*PPV* (mm/s)
1	95	17.3	26	25.59
1	161	17.3	26	11.67
2	88	17.3	25	8.65
2	156	17.3	12	3.96
2	185	17.3	20	3.15
3	83	20.8	38	12.28
3	184	20.8	23	15.96
4	99	19.3	53	19.29
4	110	19.3	28	7.31
5	110	28.9	21	3.13
5	105	28.9	22	5.76
5	200	28.9	39	2.1

3. Evaluation of the procedure performance

As mentioned before, except for the mineralized intrusions, the rock mass is composed by limestone. The objective is to demonstrate that the general procedure for the analysis of blasting vibrations, developed in limestone quarries, could have predicted the result of blasting in the gold mine.

In the first place, it is necessary to establish the hypothesis of about the natural vibration frequencies. The field characterization of the rock mass can give us a first idea. The frequency in the first blast was f_{med}=26 Hz. By using the Eq. (3) with K_f=77.4, the average frequency to use is f_{med}= 37 Hz. Although they are significantly different, both initial values of f_{med} lead to the same results.

The distances from blasts to monitoring points near the houses varied between D_{min}= 83 m and D_{max}= 200 m. Following the procedure to predict the results described above the estimated average charge per delay is Q_{med} = 8.0 kg.

With the data Q_{med}= 8 kg, D_{min}= 83 m and D_{max}= 200 m and following the calculations synthetised in Table 1, we can draw the representative area of the risks related to blasting vibrations in the damage prevention abacus of the Spanish Standard UNE 22-381 (Figure 4A). This defined area allows to make a more realistic analysis. Indeed, if this procedure were used, engineers in charge of blasting could verify that the most probable would be the blasting being under the *PPV* limits established by the standard for houses (structures of Group II), but with a small probability that the vibrations could overpass these limits. The blasts must be carefully designed to avoid any damage to structure or complaint problems with the neighbours. It is shown that the procedure proposed for limestone is valid since practically 11 of the 12 representative points, 92% of the cases, are within the defined area. One of the blasts does not meet the criteria, however, it must be said that the seismograph was several meters apart from the house and the actual vibration that would reach the house was significantly lower fitting the criterion.

In the reality, the blasting project was elaborated following the Spanish Standard UNE 22-381. Then the maximum charge per delay was chosen by using the abacus of Figure 1A. As the minimum distance in this study was D_{min} = 90 m, the equivalent charge could be Q_{eq}= 7.5 kg (Standard Project) or Q_{eq}= 43.2 kg (if a Vibration Control campaign is carried out). The rock and structure factors are F_R= F_S= 1, and then the maximum charge per delay also varies from Q_{min}= 7.5 kg to Q_{max}= 43.2 kg, being the average value Q_{med}= 25.3 kg. In the present case, the fact that ground vibrations were monitored, allowed to use a bigger charge per delay. Figure 4B shows the estimated representative area defined, along with the representative points of the actual monitoring blasts (Table 2). The result is better because 100% of the estimated

PPV (12 of 12 points) are within the defined area. As the value of Q_{med} is more similar to the real explosive charge, the highest vibration level is also more similar to the actual one.

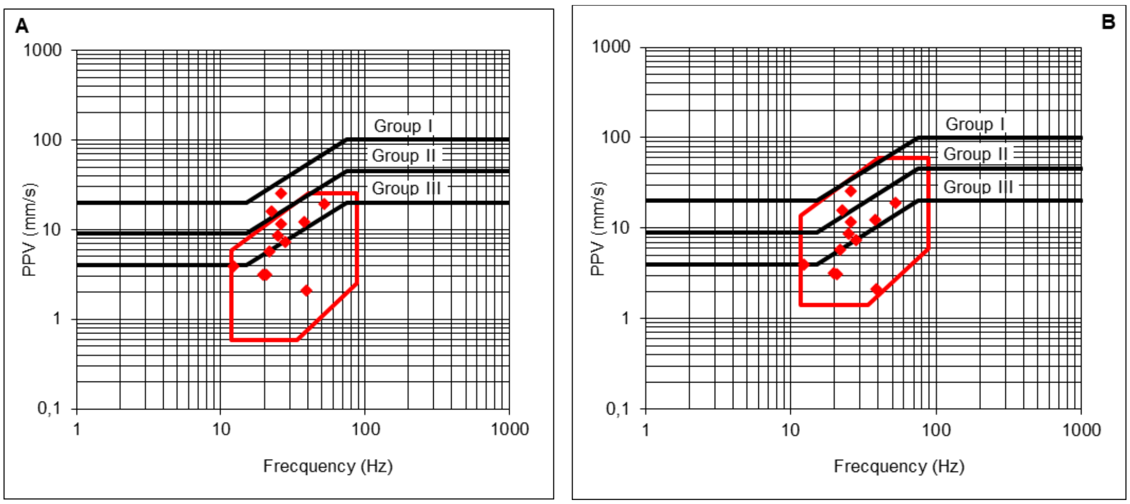

Figure 4: Representative areas predicted and actual data from real blasts in the damage prevention abacus.

Once there is enough data from the vibration monitoring campaigns, a second analysis can be done to check if the rock mass behaviour is like limestone with a low vibration frequency.

Figure 5A represents the *PPV* attenuation law for limestone that corresponds to Eq. (1), taking c_v= 1. The upper and lower curves are obtained, c_{vmax}=2.5 and c_{vmin}=0.25 respectively, according to [10]. It is verified that 92% of the points of the real blasts are within the established range, showing that the *PPV* attenuation law for limestone seems to be useful in this case.

On the other hand, Figure 5B represents the frequency attenuation law for limestone that corresponds to Eq. (2) taking K_f=77.4 and c_f= 1. The upper and lower curves are obtained with c_{fmax}=2.2 and c_{fmin}=0.35 respectively, according to [10]. It is verified that 100% of the points of the real blasts are within the established range, showing that the frequency attenuation law for limestone seems to be also useful in this case.

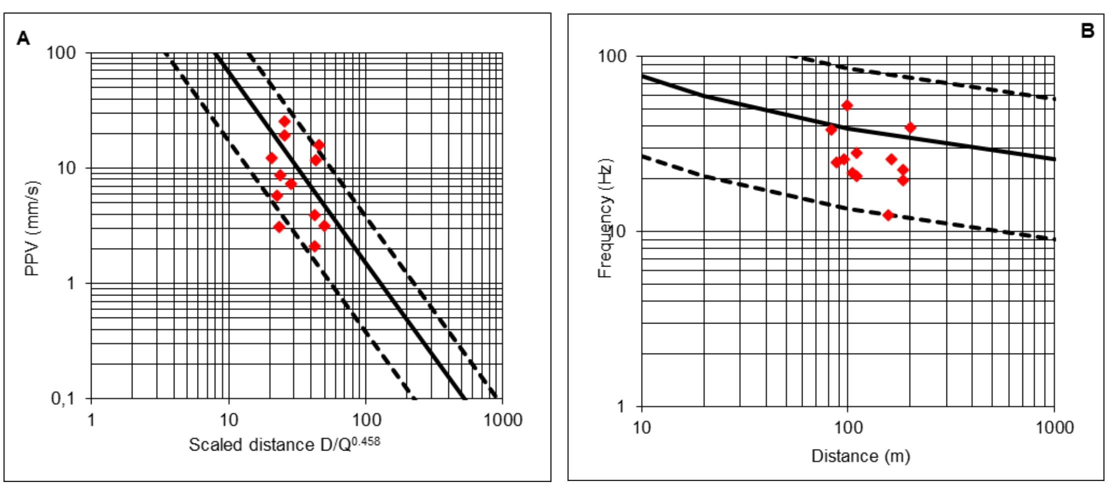

Figure 5: Limestone attenuation laws for PPV and frequency and recorded values from the real blasts.

4. Conclusion

The method proposed in [10] improves the management of vibration generated by blasting compared to the current approach used. Having more detailed information about the behaviour of vibrations in a user-friendly system. Besides, it is based on the classical damage prevention criterion abacus, so it is well-known and calibrated system.

The new approach has been developed by means of results from limestone quarries and it is extended to different in limestone rock masses in the present study. Hence, the actual representative 12 points of 5 blasts in an open-pit gold mine fit perfectly within the representative area predicted by the procedure. Further research should be done to apply the system in other conditions, such as civil works or mining on other rock masses different to limestone rock masses.

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