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Representative-Area Approach to Define Blast-Induced Ground Vibrations—Damage Prevention Criterion Abacus

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Abstract: Ground vibrations due to blasting can cause damage to nearby structures. In this context, a damage prevention criterion was developed to avoid this potential risk, establishing 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 the PPV and frequency as a function of the distance and amount of explosive were also developed. These models can be used to separately predict PPV and frequency, obtaining the representative point of the designed blast and decide if a potential damage could exist or not. The proposed approach allows one to simultaneously work with an attenuation law for the PPV and another one for the frequency, defining an area in the damage criterion abacus instead of a single representative point. The system was applied using data from 75 blasts in different limestone quarries in the north of Spain.

Keywords: blasting; vibrations; frequency; prevention criterion

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Citation: Rodríguez, R.; Bascompta, M.; Fernández, P.; Fernández, P.R. Representative-Area Approach to Define Blast-Induced Ground Vibrations—Damage Prevention Criterion Abacus. *Minerals* **2022**, *12*, 691. https://doi.org/10.3390/min12060691

Academic Editor: Abbas Taheri

Received: 23 April 2022
Accepted: 25 May 2022
Published: 30 May 2022

1. Introduction

Blasting is a well-known technique in mining and civil works [1]. As the rock is stronger and more abrasive, the drilling and blasting method becomes more competitive because the performance remains practically constant. Under some specific conditions, it is the best method to break the rock economically. Thus, the correct management of the whole blasting process and the potential impacts that it could cause are crucial for the viability of its usage [2]. A proportion of the energy released by the explosive, around 30%, is used for the rock-mass fragmentation and displacement, while the remaining part is transformed into ground vibrations or air blast or it damages the remaining rock mass [3,4].

The vibration intensity mainly depends on the rock-mass conditions, blast design and explosive features [5,6], as well as the presence of natural or artificial barriers such as trenches [7]. In the case of soils, its density and intrinsic composition are crucial for the vibration transmissivity [8].

Pal [9] analyzed in detail the design characteristics of rock blasting, which are the main variables that can be handled in order to reduce the blast-induced adverse effects. Vibrations are usually the main concern when applying blasting techniques [10]; therefore, it is necessary to control and predict the vibrations induced [11], as well as analyzing them and taking the required actions if needed. This fact is especially important when there are nearby constructions [12,13] that are likely to be affected, requiring vibration monitoring [14]. Hence, there is plenty of past and ongoing research to predict vibrations and their associated effects, such as analyzing the different attenuation laws [15], combining predictive and probabilistic models [16], the response determination of a structure to a blast [17] or the study of the propagation velocity in fault zones [18]; existing studies are mainly based on the Peak Particle Velocity (PPV) approach.

A topic that has been extensively studied over time [19–21] regards the threshold limit values of ground vibrations, which are based on the damage that they could cause, and the type of construction affected and are mainly governed by the velocity and frequency of the waves, with both variables being defined by the rock-mass and blast characteristics [22]. Thus, PPV is a well-established characteristic to study blast-induced vibrations based on the maximum explosive charge per delay and distances between the point measured and the blasting point [23–25], either for deep tunnels [26], shallow underground excavations [27] or surface blasts [28]. However, less research has focused on frequency and its prediction [29] from a classical perspective, despite its importance and the potential damage it causes in structures if it produces a resonance effect [29–31].

The frequency characteristics and behavior in blasting have been defined by [32,33]; the frequency-value variation is determined depending on the distance from the blast [34,35]. However, it is very difficult to quantify the influence of the different factors involved.

Some research studies applying artificial neural network (ANN) models have been conducted to determine PPV and frequency values [3,35,36], either for mining or civil works [37], while other approaches such as support vector machine [38], Harris Hawks optimization algorithms [39] or finite element methods (FEM) [40] have also been proposed. However, it is very common to use empirical attenuation laws among the technicians of the administration and mine site managers for the design and assessment of blasts because of its simplicity and link to the national standard regulations. Usually, the pair of points, PPV–frequency, is entered in the damage prevention criterion abacus to analyze the risk of the blasts.

The objective of this study is to develop a new method to better predict the impact generated by blast-induced vibrations, by improving the use of the abacus damage prevention criterion, moving from a point analysis to the analysis of a representative area of the blast. The method proposed was designed to be useful and easy to understand for any type of engineer or technician. It is relevant because sometimes the technicians of the institutions in charge of assessing the environmental impact of the project that requires authorization do not have experience in blasting and/or vibrations.

2. Classical Analysis of a Blast Using the Damage Prevention Criteria

2.1. Damage Prevention Criteria

Damage caused by vibrations is an important issue, and its analysis and management are regulated by means of national legislation. Vibrations generated by construction activities are unlikely to damage building elements, except in the case of sensitive buildings. On the other hand, vibrations caused by blasts are totally different, having a major potential impact on the environment and constructions [6].

The first attempt to assess and tackle damage created by blasting was proposed by Duvall and Fogelson [41]. Nevertheless, [42] established a well-defined damage prevention criterion based on a correlation between horizontal peak particle velocity measured on the ground, close to a structure, and the threshold damage that it could bear, thus obtaining a simple and effective system to manage vibration damages.

Other standards have subsequently been developed by other countries (see Figure 1) following the same concept, such as British standard BS 7385 [43], Spanish standard UNE 22-381-93 [44] or German standard DIN 4150 [45]. Since the risk of damage to structures increases as the magnitude of the particle velocity rises, and the frequency of vibrations 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 the vibration frequency (see Figure 1). Thus, a point is obtained by the intersection of the abscissa and ordinate variables introduced to the abacus.

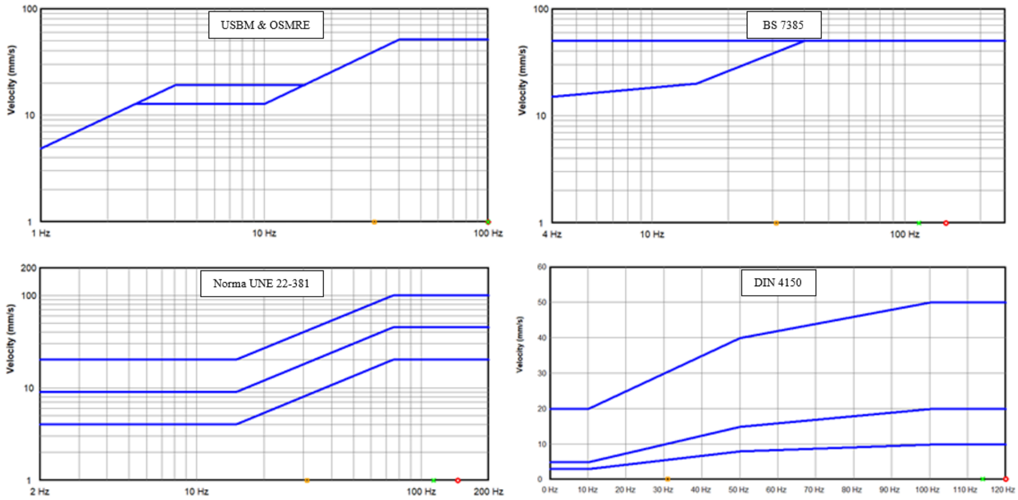

Figure 1. Abacus with damage prevention criterion according to different standards.

All criteria constrain particle displacement or particle velocity as a function of vibration frequency. On a logarithmic scale, constant-velocity borders are horizontal lines while constant-displacement borders are inclined lines.

In general, all criteria return higher displacements and higher particle speeds for higher frequencies. Likewise, all the criteria establish higher or lower limits depending on the different sensitivity of the structure to vibrations.

For example, the USBM criteria in the 3–15 Hz range establish a higher speed limit (0.75 in/s) for more modern structures with plasterboard (drywall) and a lower speed limit (0.50 in/s) for older houses with gypsum plaster. British standard BS 5228 [43] establishes a generic limitation of 50 mm/s independent of the frequency for reinforced or framed structures, industrial or heavy commercial buildings, while for the other cases (for example, residential or light type commercial buildings), it decreases below 40 Hz: to 20 mm/s at 15 Hz and up to 15 mm/s at 4 Hz. The German DIN 4150 [45] and Spanish UNE 22381 [44] standards are very similar and establish three curves that represent the speed limits for three types of buildings: structures with little sensitivity to vibrations (for example, industrial buildings), buildings with medium sensitivity (for example, residential buildings) or structures that are particularly sensitive to vibrations (such as hospitals or historical monuments). Below, the UNE 22381 standard [44] is explained in detail.

2.2. General Ground Vibration and Frequency Attenuation Laws

Many authors have proposed empirical expressions to estimate the blast vibrations based on operational parameters, such as [23,24,28,46–51]. On the other hand, frequency attenuation laws have also been developed by different authors using operational parameters, e.g., [52–57] or, more recently, [29].

Thus, there are calculation methods that, based on the blast parameters and the characteristics of the rock mass, allow the two variables to be estimated separately, PPV and frequency. With these values, the damage criterion abacus could be used, and the blast could be characterized from the point of view of possible damage to structures. However, only a single point is defined in the abacus, without any methodology or procedure established to define an area within which the representative point of the actual blast would be placed with an acceptable level of confidence, e.g., 90%.

2.3. Classical Analysis According to the 22381-93 UNE Standard

The actual operation of the abacus is described in this section, by means of a real example, to show the advantages of the model proposed.

A blast is to be performed in a weak limestone rock mass from a quarry in the north of Spain, having residential buildings at D = 150 m and a maximum charge per delay of

Q = 30 kg. Following Spanish standard UNE 22381-93 [44], the first thing to do is defining the type of study to be carried out according to the blasting conditions. The standard establishes that the modified load, known as equivalent load, is calculated by means of Equation (1).

$$Q_{eq} = F_R \times F_s \times Q \quad (1)$$

where F_R is the rock-type factor (for a medium rock such as limestone, it would be F_R = 1); factor F_S is defined based on the structure (for a building F_S = 1); and Q is the maximum charge per delay (Q = 30 kg). Therefore, Q_{eq} = 30 kg.

The point of the example (D, Q_{eq}) is plotted in the abacus of Figure 2A with a red dot, determining the requirements. If the point is below the lower line, it is considered that there is no risk, and the blast can be carried out without prior actions, justified by a simple theoretical study. If the point falls above the upper line, it is considered that there is a clear risk of causing damage; then, a preliminary study is required, where trial blasts have to be performed to determine the local behavior of the rock mass with respect to vibrations and adapt the design to its characteristics. If the point is placed between the two straight lines, the blast can be carried out, but a vibration control procedure is required. Since the example point is (150, 30), the latter situation is the assumption for the blast.

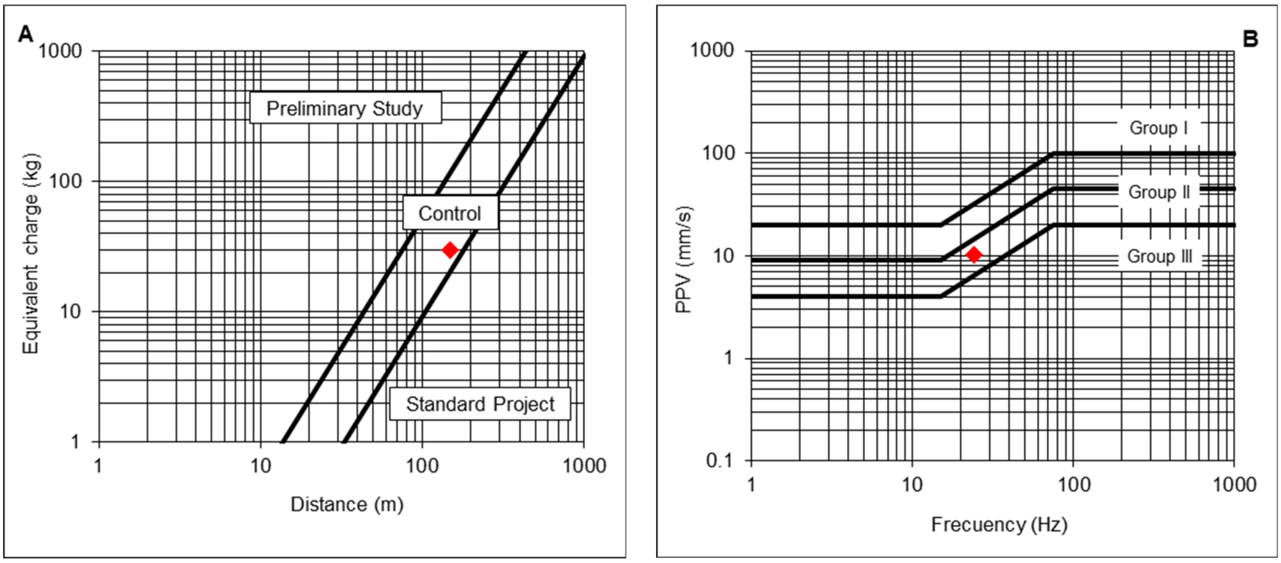

Figure 2. Type of study: (**A**) damage prevention criterion; (**B**) Spanish standard UNE22383 [44].

On the other hand, the standard defines a damage prevention criterion represented in Figure 2B. Once the frequency, f, of the vibrations has been defined, the maximum velocity of the particle, PPV, must be less than the limit curves, depending on whether the structure is very sensitive to vibrations (Group III), sensitive (Group II) or not very sensitive (Group I). Residential buildings are considered as Group II.

Hence, the blast design assessment requires to determine its PPV and frequency. The PPV can be estimated by Balsa's transmittivity law [58], Equation (2), initially proposed by Nicholls et al. [19], which is based on data from the explosive charge, distance, type of triggering and velocity:

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

where PPV is the peak particle velocity (mm/s); Q is the maximum load per time delay (kg); and D is the distance between the seismograph and the blasting point (m). Parameters K, α and β are constants to be obtained by empirical correlations and include all the other factors, which are mainly related to the characteristics of the excavated rock mass. Balsa [58] performed an thorough study in Spain to determine K_v, α, and β for different rock types based on hundreds of blasts, obtaining K_v = 3085, α = 0.757 and β = 1.651 for limestone rock masses and achieving the estimated PPV with a confidence level of 90%, Equation (3).

$$PPV = 3085 \times 30^{0.757} \times 150^{-1.651} = 10.3 \text{ mm/s} \quad (3)$$

According to the same author, a typical vibration frequency of limestone rock masses in Spain is f = 24 Hz. Subsequently, the values obtained are plotted on the abacus in Figure 2B (24 Hz, 10.3 mm/s), determining that the blast design is adequate since the point is below its corresponding limit curve (Group II). Hence, it is verified that the equivalent charge per delay proposed, 30 kg, is within the range allowed by the standard.

3. Conventional Quarry-Blasting Data

3.1. PPV–Frequency Data

The proposed procedure was developed considering that the limestone rock mass follows the general vibration attenuation law proposed by [58], which predicts the PPV with reasonable accuracy considering the natural dispersion in the results [59]. However, Balsa's [58] research study was only focused on the magnitude of the vibrations, not on the frequency.

The data used for the development of the proposed method were obtained by the authors; they are relative to 75 blasts from six limestone quarries in the north of Spain and are gathered in Tables 1 and 2. Many different types of blasting were included, from production blasts, with maximum charge per delay between 11 and 110 kg, to detonation tests, with small explosive loads of 10–33 kg. The large range of real data allowed us to achieve representative results from very different possible situations. The maximum PPV (mm/s) and mean frequency, f_{med}, (Hz) from the vertical, longitudinal, and transversal components are also included, being representative of the vibration characteristics from the different blasts.

Table 1. PPV and frequency data from production blasts.

Blast	Quarry	Region	Type of Blast	D (m)	Q (kg)	PPV (mm/s)	f_{med} (Hz)
1	1	Asturias	Production	97	30.0	9.16	88.7
2				144	30.0	3.39	70.7
3				125	33.0	22.80	41.7
4				240	33.0	4.85	33.0
5				164	50.0	8.20	36.0
6				350	50.0	2.77	35.7
7				213	17.3	7.06	55.3
8				322	17.3	2.27	42.3
9				125	79.5	12.21	56.3
10				60	29.1	28.28	40.7
11				300	76.1	4.64	54.3
12				30	35.7	151.99	37.0
13				105	35.7	16.94	36.0
14				30	16.8	37.19	40.0
15				105	16.8	7.51	35.3
16				75	23.3	82.12	49.7
17				75	46.6	19.89	41.7
18				347	46.6	3.19	39.7
19				167	58.3	29.79	49.3
20				128	58.3	31.09	47.7

Table 1. *Cont.*

Blast	Quarry	Region	Type of Blast	D (m)	Q (kg)	PPV (mm/s)	f_{med} (Hz)
21				30	34.6	65.41	34.7
22				15	11.1	30.70	54.7
23				104	68.6	14.19	28.3
24				104	14.0	2.85	53.3
25				329	89.2	5.72	42.7
26				329	89.2	8.08	45.7
27				218	63.0	11.05	53.0
28				218	63.0	13.16	51.0
29				278	51.4	9.06	73.0
30				278	51.4	5.01	34.0
31	2	Asturias	Production	100	109.1	36.29	52.0
32				180	109.1	10.64	43.3
33				240	109.1	6.50	30.7
34				100	108.3	25.27	28.7
35				200	108.3	5.08	46.0
36	3	Cantabria	Production	250	62.0	2.60	34.7
37				425	30.0	2.03	10.5
38				450	35.0	0.95	10.0
39				350	35.0	1.71	20.4
40	4	Cantabria	Production	168	85.0	10.30	14.7
41				210	85.0	3.42	18.3
42				168	92.0	18.12	17.3
43				225	92.0	16.05	23.7
44				149	42.0	10.53	16.7
45				314	42.0	5.67	18.0
46				264	42.0	8.20	15.0
47				535	42.0	1.40	12.4
48	5	Burgos	Production	180	15.0	7.11	51.4
49				180	12.0	6.60	61.3
50				190	14.0	2.54	44.2
51				200	12.0	1.97	42.1
52				180	12.0	1.97	37.0
53				75	15.0	11.07	39.7
54				110	15.0	4.38	32.7
55				80	15.0	3.15	33.3
56				145	15.0	3.00	41.7
57				515	35.0	2.31	51.3
58				90	15.0	3.87	78.3
59				125	15.0	2.77	48.7
60				110	15.0	1.89	34.7
61				90	15.0	17.00	56.7
62				50	15.0	27.80	67.0
63				40	15.0	4.38	29.7
64				110	15.0	2.52	20.7
65				90	15.0	3.87	24.0

Table 2. PPV and frequency data from test blasts.

Blast	Quarry	Region	Type of Blast	D (m)	Q (kg)	PPV (mm/s)	f_{med} (Hz)
66	6	Navarra	Test	190	9.6	1.71	14.5
67				240	9.6	0.95	14.6
68				180	7.2	1.40	17.1
69				230	7.2	0.89	15.3
70				160	12.0	1.46	13.4
71				210	12.0	0.95	12.1
72				150	33.6	3.56	17.3
73				200	33.5	1.65	12.4
74				120	16.8	4.64	20.8
75				170	16.8	1.52	14.2

3.2. PPV and Frequency Attenuation Laws in Limestone Rock Masses

As mentioned above, it is assumed that the general attenuation law of limestone rock masses is satisfied [58], defining the scaled distance (SD) as SD = $D/Q^{0.458}$; subsequently, the attenuation law takes the form of Equation (4):

$$PPV = 3085\ SD^{-1.651} \quad (4)$$

where D is the distance between the seismograph and the blasting point (m); Q is the maximum charge per time delay (kg); and SD is the scaled distance (m/kg).

Figure 3A shows the curve corresponding to Equation (4), represented by a solid line, together with the point cloud (SD, PPV) derived from the blasting data gathered in Tables 1 and 2. The experimental point cloud fits Equation (4) with a correlation coefficient r^2 = 0.60. However, it should be noted that during blast monitoring, the firing threshold is almost always set at 1 mm/s, which means that results giving low PPV values are not available in Tables 1 and 2.

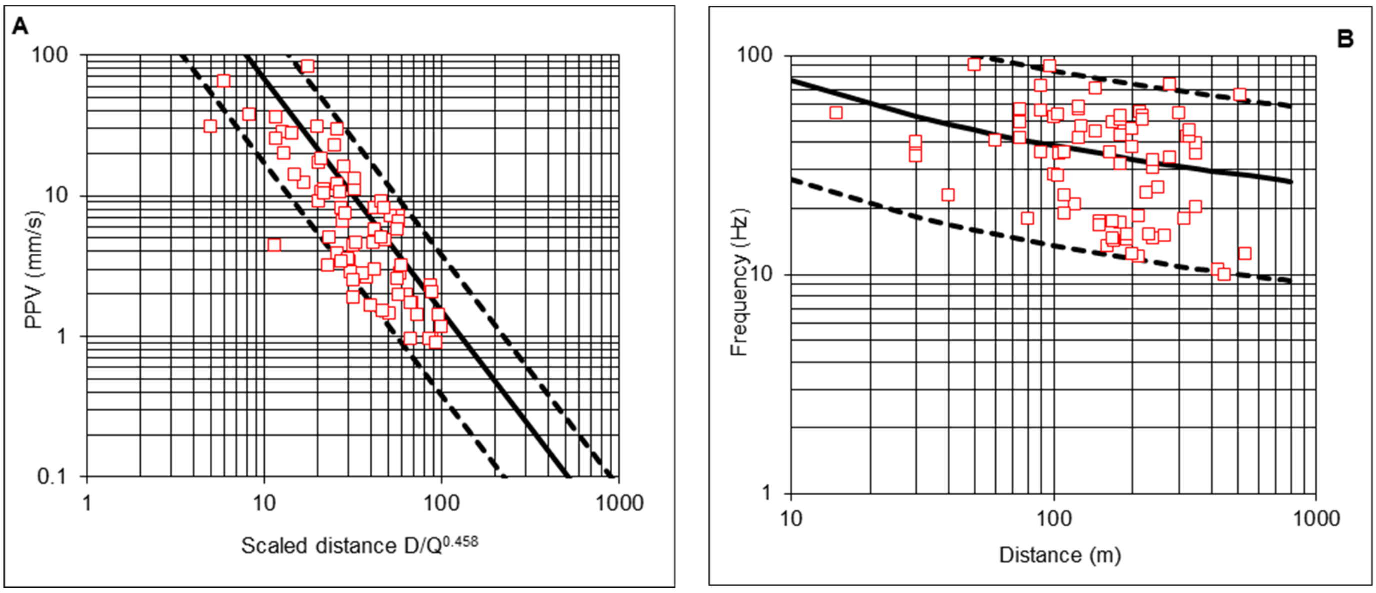

Figure 3. PPV (**A**) and frequency (**B**) attenuation laws derived from the empirical data set.

The most important fact is that experimental data with the attenuation law make it possible to empirically define, for a certain scaled distance, a range of variation in the PPV using two coefficients, c_{vmax} and c_{vmin}, as shown in Equations (5) and (6).

$$PPV_{max} = c_{vmax} 3085 \left(\frac{D}{Q^{0.458}}\right)^{-1.651} \quad (5)$$

$$PPV_{min} = c_{vmin} 3085 \left(\frac{D}{Q^{0.458}}\right)^{-1.651} \quad (6)$$

For a given c_{vmax} value, the line parallel to the attenuation law, represented by Equation (5), defines the upper limit with the maximum PPV values for different scaled distances. On the other hand, the lower limit is defined by a parallel line corresponding to a given value of c_{vmin} in Equation (6). Considering $c_{vmax} = 2.5$ and $c_{vmin} = 0.25$, 95% of the data are within the established limits, 71 out of 75. Hence, PPV is between these limit values in 95% of the blasts.

It should be noted that the choice of K = 3095, $\alpha = 0.757$, $\beta = 1.651$, $c_{vmin} = 0.25$ and $c_{vmax} = 2.5$ was made on the basis of the initial data. These parameters could be varied according to new available data to define the general model, modifying K, α, β, c_{vmin} and c_{vmax}.

The fundamental vibration frequency for each blast analyzed is represented in Figure 3, as a function of the distance from the measurement point to the blast. The average frequency value of the three components of movement is taken as a representative value for the fundamental frequency, obtained by means of the Fast Fourier Transformation (FFT).

The average frequency of all data is about 36.5 Hz, higher than the average frequency proposed by [58], which means that the frequency analysis can be improved. Hence, giving a single value to the vibration frequency of 24 Hz, for instance, as in a classical approach, is not realistic. Multiple factors, e.g., rock-mass strength, ground heterogeneity, topography, micro-delays used in blasting, etc., can produce a frequency dispersion as large as the PPV dispersion. Therefore, it seems more accurate to try to also define a variation interval for the frequency values.

It is also important to highlight that, according to the damage criteria of the Spanish standard, the velocity limit value has a large range, 15–75 Hz, since the admissible value is multiplied by 5 when going from 15 Hz to 75 Hz. This fact is operationally very important, because it verifies that the natural frequency is higher; therefore, a higher PPV can be reached, as well as a higher charge per delay. This is always appealing since the rock mass with the highest vibration is usually the strongest; therefore, a higher amount of explosive would be necessary.

The approach to predict the range of frequency variation is similar to that used to obtain the PPV. Firstly, a law is used to predict the average frequency as a function of distance. In this case, the law proposed by [52] and presented in [57,60,61] is here used, as shown in Equation (7):

$$f = \frac{K_f}{\log_{10} D} \quad (7)$$

where f is the frequency in Hz; D is the distance between the measurement point and the blast in meters; and K_f is an empirical parameter determined from real measurements.

In the case of limestone rock masses, the curve adjustment to the point set gives an empirical value of $K_f = 77.4$, gathered in Equation (8). Although there is a large dispersion, the correlation coefficient is quite high, $r^2 = 0.80$. Following the procedure from the previous subsection, two coefficients are also included, c_{fmin} and c_{fmax}, in Equations (9) and (10), respectively.

$$f = \frac{77.4}{\log_{10} D} \quad (8)$$

$$f_{min} = c_{fmin} \frac{77.4}{\log_{10} D} \quad (9)$$

$$f_{max} = c_{fmax} \frac{77.4}{\log_{10} D} \quad (10)$$

Figure 3B represents the law of variation of the average frequency (continuous line), together with the range of variation for a given distance (dashed lines) for limestone rock masses. Using c_{fmin} = 0.35 and c_{fmax} = 2.2, 96% of the data are within the range, i.e., 72 points of 75.

This is an empirical method and, consequently, the physical or mechanical fundamentals are not explicit. The variability in the results is derived from the range of variation in the PPV and frequency attenuation laws. After defining a range of variation for PPV and frequency we are integrating the variability in the procedure and in the results.

4. Definition of a Representative Area of Ground Vibrations Due to Blasting

4.1. Definition of the Representative Area Assuming That Q, D_{min} and D_{max} Are Known

The analysis of a blast using a single point (f, PPV) in the damage criterion abacus should not be considered as very realistic. First, it is well-known that there is dispersion in the results, both in PPV and frequency; subsequently, the possible effects of those results that deviate from the representative point are not evaluated. Moreover, the blasted area is usually not considered to be a precise area, so the distance to structures that may be affected varies.

On the other hand, if a point is used as a reference, it is expected to obtain similar points in control measurements. However, uncertainty can arise when this control gives other outcomes.

The facts mentioned can have important implications, especially if the person who must evaluate these results is a non-expert in blasting, which is the case in many situations, such as lawyers, environmental technicians or governmental staff. Therefore, it is crucial to define not a point but an area as representative of the ground vibrations due to blasts when using the damage criterion abacus. Hence, a new procedure is proposed to solve this problem.

Initially, it is assumed that the maximum charge per delay, Q, has been calculated and is, therefore, known. If it is also considered that the buildings to be protected are at a distance between D_{min} and D_{max}, two studies can be carried out, one for D_{min} and another for D_{max}. However, this approach is not completely realistic, since seismographs are placed many times at arbitrary points between those two distances during the vibration-monitoring campaign.

The first thing to note is that both velocity and frequency decrease with distance and Equations (11) and (12) are the representative curves of the mean values.

$$PPV = c_v \left(3085\, Q^{0.757}\, D^{-1.651}\right) \quad (11)$$

$$f = c_f \left(\frac{77.4}{\log_{10} D}\right) \quad (12)$$

Besides, we can define a point for a given Q and each distance for the corresponding frequency and PPV: f_1, PPV_1 and f_2, PPV_2, expressed in Equations (13)–(16).

$$PPV_1 = c_v \left(3085\, Q^{0.757}\, D_{min}^{-1.651}\right) \quad (13)$$

$$f_1 = c_f \left(\frac{77.4}{\log_{10} D_{min}}\right) \quad (14)$$

$$PPV_2 = c_f \left(3085\, Q^{0.757}\, D_{max}^{-1.651}\right) \quad (15)$$

$$f_2 = c_f \left(\frac{77.4}{\log_{10} D_{max}} \right) \quad (16)$$

Considering that there are three values for each coefficient ($c_v = 1$, $c_v = c_{vmax} = 2.5$ and $c_v = c_{vmin} = 0.25$; $c_f = 1$, $c_f = c_{fmax} = 2.2$ and $c_f = c_{fmin} = 0.35$), their combination allows us to represent eighteen points (f, PPV) in the abacus. The envelope of these points defines the representative area of the ground vibrations due to blasting.

However, there are also two highly unlikely combinations to mention. Since PPV and frequency decrease with the distance, the highest PPV and frequency are recorded at short distances. Therefore, it is unlikely to find results by combining PPV_{max} with f_{min}. Likewise, velocity and frequency decrease at long distances, so the combination of PPV_{min} with f_{max} is less probable. Thus, it is proposed not to consider these two combinations and to take the area within the envelope without these two points.

The proposed procedure is explained using the example from the above section. A limestone rock mass is going to be blasted using a charge per delay Q = 30 kg. The considered distance is not a unique value D, but it varies from $D_{min} = 125$ to $D_{max} = 175$ m due to the location of buildings. Table 3 gathers the calculation results of the 18 points. These points and the envelope are represented in the damage criterion abacus in Figure 4A. As mentioned, the extremes corresponding to combinations (12.9 Hz, 34.9 mm/s) and (75.9 Hz, 2.0 mm/s) are not considered to define the representative area.

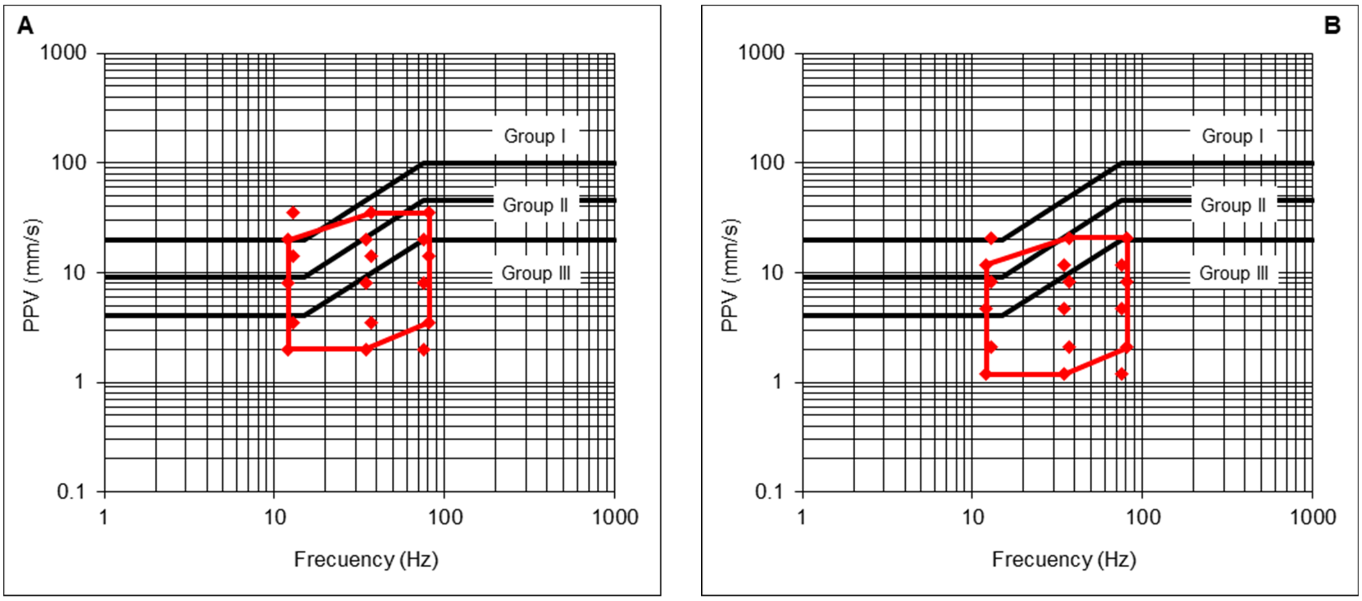

Figure 4. Representative areas of ground vibrations in the damage criterion abacus.

The area defined in the damage criterion abacus, Figure 4A, allows us to make a more realistic analysis. Indeed, it is verified that the blast may be within the Spanish standard, but it is also verified that it is probable that the vibrations could be well outside the limits established by the standard, and this fact could generate problems in the surrounding constructions.

If the charge per delay is limited to Q = 15 kg, the representative area would be lower (Figure 4B), with a high probability that the blast would not produce negative effects on buildings.

In a general case, the envelope can be drawn with only the six points given in Table 4.

Table 3. f and PPV values of the 18 representative points.

Point	Q (kg)	D (m)	c_v	c_f	f (Hz)	PPV (mm/s)
1	30	175	0.25	0.35	12.1	2.0
2	30	125	0.25	0.35	12.9	3.5
3	30	175	0.25	1	34.5	2.0
4	30	125	0.25	1	36.9	3.5
5	30	175	0.25	2.2	75.9	2.0
6	30	125	0.25	2.2	81.2	3.5
7	30	175	1	0.35	12.1	8.0
8	30	125	1	0.35	12.9	14.0
9	30	175	1	1	34.5	8.0
10	30	125	1	1	36.9	14.0
11	30	175	1	2.2	75.9	8.0
12	30	125	1	2.2	81.2	14.0
13	30	175	2.5	0.35	12.1	20.1
14	30	125	2.5	0.35	12.9	34.9
15	30	175	2.5	1	34.5	20.1
16	30	125	2.5	1	36.9	34.9
17	30	175	2.5	2.2	75.9	20.1
18	30	125	2.5	2.2	81.2	34.9

Table 4. 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	D_{max}	c_{vmin}	c_{fmin}	$c_{fmin}\left(\frac{K_f}{\log_{10} D_{max}}\right)$	$c_{vmin}\left(K_v\, Q^{\alpha}\, D_{max}^{-\beta}\right)$
2	Q	D_{max}	c_{vmax}	c_{fmin}	$c_{fmin}\left(\frac{K_f}{\log_{10} D_{max}}\right)$	$c_{vmax}\left(K_v\, Q^{\alpha}\, D_{max}^{-\beta}\right)$
3	Q	D_{min}	c_{vmax}	$c_f = 1$	$1 \times \left(\frac{K_f}{\log_{10} D_{max}}\right)$	$c_{vmax}\left(K_v\, Q^{\alpha}\, D_{min}^{-\beta}\right)$
4	Q	D_{min}	c_{vmax}	c_{fmax}	$c_{fmax}\left(\frac{K_f}{\log_{10} D_{min}}\right)$	$c_{vmax}\left(K_v\, Q^{\alpha}\, D_{min}^{-\beta}\right)$
5	Q	D_{min}	c_{vmin}	c_{fmax}	$c_{fmax}\left(\frac{K_f}{\log_{10} D_{min}}\right)$	$c_{vmin}\left(K_v\, Q^{\alpha}\, D_{min}^{-\beta}\right)$
6	Q	D_{max}	c_{vmin}	$c_f = 1$	$1 \times \left(\frac{K_f}{\log_{10} D_{max}}\right)$	$c_{vmin}\left(K_v\, Q^{\alpha}\, D_{max}^{-\beta}\right)$

The choice of the parameters c_{vmin}, c_{vmax}, c_{fmin} and c_{fmax} must be made in such a way that a high percentage of points are within the limits defined by these parameters (curves in Figure 3). However, it must also be considered that if very low values of c_{vmin} and c_{fmin} or very high values of c_{vmax} and c_{fmax} are used to increase this percentage, the defined area would be too large and would no longer be useful in the analysis.

The proposal made in this study, i.e., coefficients that include 95% of the PPV and 96% of the frequency, is reasonable and allows accurate predictions to be made, as it is shown in the subsections below. Assuming that PPV and frequency are independent variables, the probability that the blast is within the representative area is $0.95 \times 0.96 = 0.91$, i.e., higher than 90%.

Finally, the representative area of the blast results in the damage prevention criterion is drawn with six points calculated from Q, D_{min} and D_{max} following the expressions from Table 4; subsequently, f and PPV points can be introduced in the abacus. If seismographs are located near structures, D_{min} and D_{max} are the minimum and maximum distances to the nearest and furthest structures to protect. Nevertheless, if any seismograph is located closer than the nearest structure or farther than the last structure, the distances to the seismographs, D'_{min} and D'_{max}, should be used to carry out the comparison between the real points and predicted representative area.

In the event whereby the maximum charge per delay is known, the representative area is unique and only depends on the rock mass, as can be seen from Equation (11) to (16). That is to say, it is independent of the damage criterion and could be represented on the abacus of any criteria of damage. Once represented, the appropriate conclusions can be drawn and, if necessary, the blast redesigned (decreasing the maximum charge per delay). For example, as it can be seen in Figure 5A, this blast would fulfil the BS 5228 [43] standard since, based on the representative area, virtually 100% of the blast results are expected to be below the limits established by the standard for the protection of residential buildings. However, if we were in a region where German standard DIN 4150 [45] was applied, there would be a non-negligible probability that some results would be above the curve corresponding to residential buildings (Figure 5B). In this case, the maximum charge per delay would have to be reduced a little more.

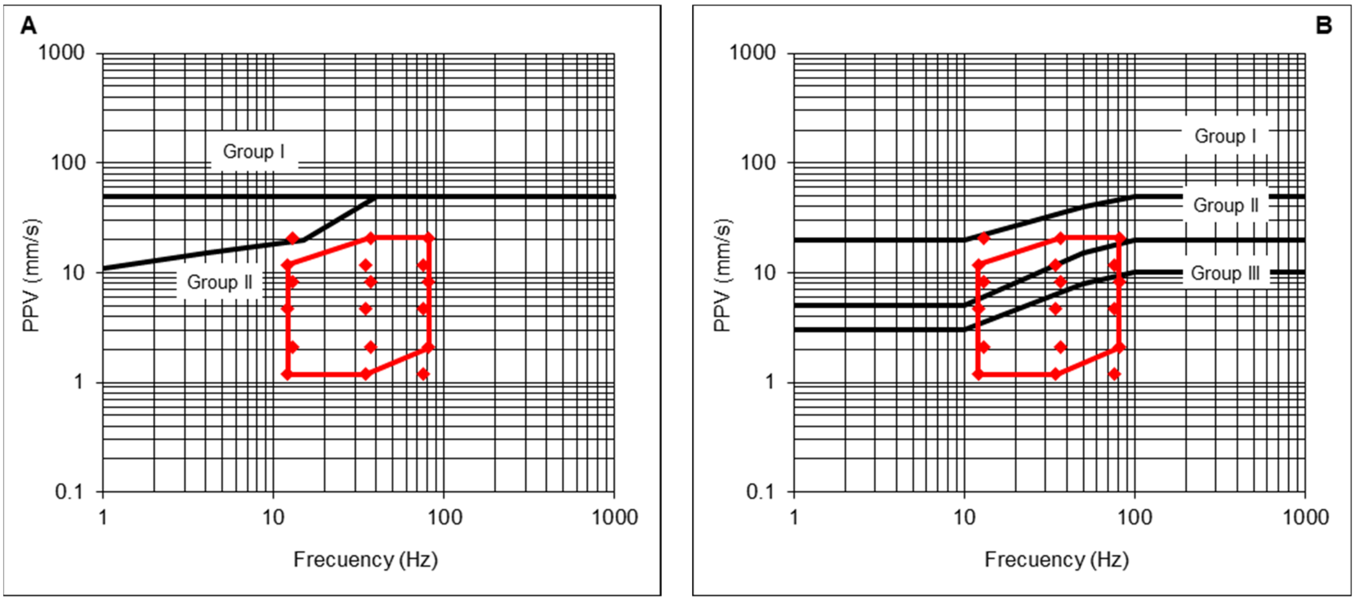

Figure 5. Representative areas of ground vibrations in damage criteria BS 5228 [43] and DIN 4150 [45].

To develop the procedure, a sufficiently large database must be available. This takes a while. However, the advantage is that once the database is available, implementing the calculation is an easy task:

(a) Firstly, the coordinates of the six points that define the border of the representative area are calculated (formulas in Table 4);
(b) Secondly, the envelope defined by those six points is represented in the graph of the damage prevention criterion;
(c) Finally, the result is analyzed from the relative position of the representative area with respect to the limit curves of the damage criterion.

4.2. Definition of the Representative Area When Charge per Delay Q Is Unknown

The representative blast area can be defined even if the maximum delay load to be used has not been previously calculated. The use of this procedure implies knowing the PPV and frequency attenuation laws, the minimum and maximum distances, D_{min} and D_{max}, and the damage prevention criterion (Figure 2B). This information is enough to estimate the maximum delay charge, Q_{med}, used in the definition of the representative area. The procedure is as follows:

1. D_{min} and D_{max} are the distances from the buildings to the closest and farthest projected blasts for any given year. It is always assumed that they are known because they can be determined from mine planning;
2. Mean frequency f_{med} is determined from experimental data. If f_{med} is unknown, a rock-mass behavior must be assumed, giving a value to K_f and then estimating f_{med} as shown in Equations (17)–(19);

$$f_{medmin} = \frac{K_f}{\log_{10} D_{max}} \tag{17}$$

$$f_{medmax} = \frac{K_f}{\log_{10} D_{min}} \tag{18}$$

$$f_{med} = \frac{f_{medmin} + f_{medmax}}{2} \tag{19}$$

3. The most unfavorable frequency is determined, which is the minimum f_{min} detailed in Equation (20);

$$f_{min} = c_{fmin}\, f_{med} \tag{20}$$

4. The maximum PPV admissible for the protection of Group II structures, with its corresponding frequency v_{GII}, is determined from the prevention criterion defined in the UNE 22381 [44] standard (Equation (21)). In addition, a reduction coefficient c_s could be applied as a more restrictive safety criterion, if needed;

$$v_{lim} = c_S\, v_{GII} \tag{21}$$

5. The maximum and minimum charges 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 Equations (22)–(24);

$$\frac{v_{lim}}{c_{vmax}} = 3085\, Q^{0.757}\, D^{-1.651} \tag{22}$$

$$Q_{max} = \left(\frac{v_{lim}}{3085\, c_{vmax}\, D_{max}^{-1.651}}\right)^{1/0.757} \tag{23}$$

$$Q_{min} = \left(\frac{v_{lim}}{3085\, c_{vmax}\, D_{min}^{-1.651}}\right)^{1/0.757} \tag{24}$$

6. The charge per delay is the average value obtained in the previous step (Equation (25));

$$Q_{med} = \frac{Q_{max} + Q_{min}}{2} \tag{25}$$

7. The representative area of the blast results is drawn in the damage prevention criterion abacus using Q_{med}, D_{min} and D_{max} values.

It should be emphasized that the analysis is conducted when there is a structure to be protected; therefore, the limit curve of the damage criterion must be taken into account. In this case, the proposal is to choose the operating load so that the upper limit of the representative area is below the damage criterion limit curve, in which case the blast meets that criterion approximately 90% of the time.

Steps from 1 to 7 can be used with different prevention criteria with nothing but v_G as in Equation (21), Step 4 (the one that establishes the criteria mentioned above), using $c_s = 1$.

In the previous case, the calculation gives that the minimum frequency to take into account is $f_{min} = 12$ Hz. If the BS 5228 [43] standard is used, the speed limit for the protection of residential buildings for that frequency is $v_G = 19$ mm/s. The proposed procedure leads to a max charge per delay to be used to define the area of $Q_{med} = 20.7$ kg. In view of the representative area in the damage criterion (Figure 6A), it is concluded that with a higher max charge per delay, standard BS 5228 [43] is fulfilled.

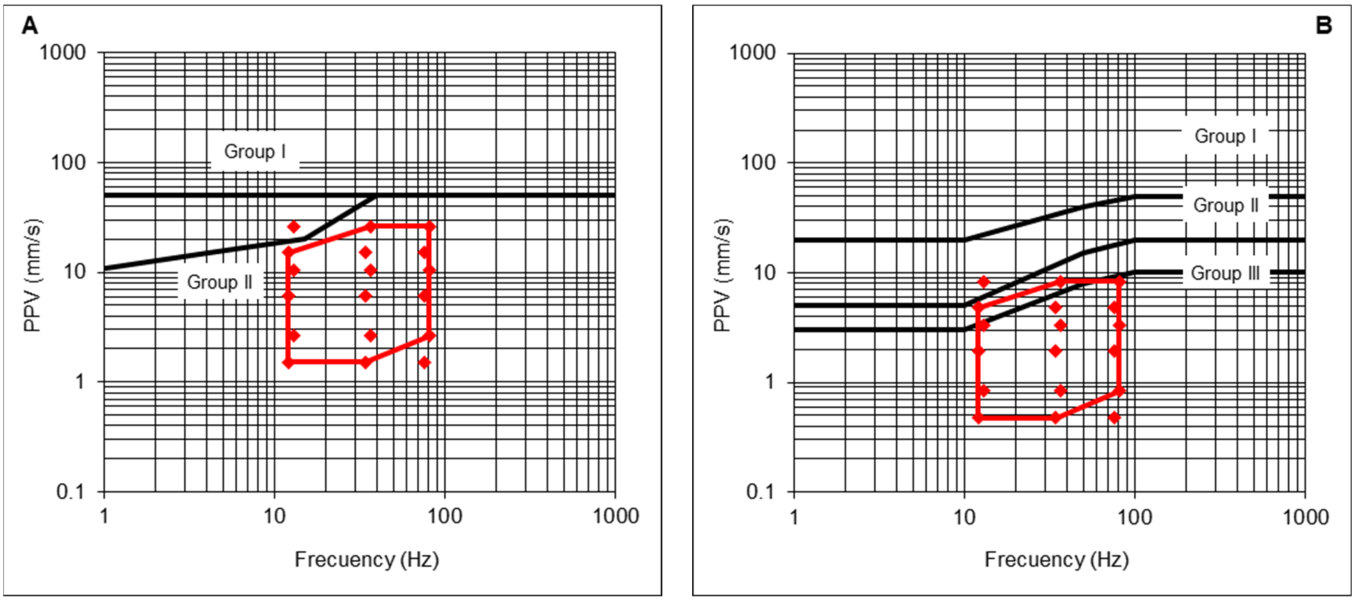

Figure 6. Representative areas of ground vibrations in the damage criteria BS 5228 [43] and DIN 4150 [45].

However, if the criterion of DIN 4158 [45] is to be applied, the allowed speed limit is v_G = 6 mm/s; then, the max charge per delay must be lower. Representing the area following the procedure with Q_{med} = 4.5 kg (Figure 6B), we can see that the load has to be reduced to meet the prevention criterion of DIN 4158 [45].

5. Calibration and Usage of the Procedure: El Perecil Quarry

The procedure detailed in the above subsections was applied to an actual case study. El Perecil quarry is located in the north of Spain (Asturias), is owned by Cementos Tudela Veguín S.A. and extracts limestone and schist, having also layers of sandstone. Limestone is exploited as the main material by blasting, while schists are obtained by 20% blasting and 80% ripping. On the other hand, a few inhabited areas around the quarry could be affected by ground vibrations.

Vibrations were monitored in 12 control points according to the area of the quarry in which the bench to be blasted was (Figure 7). The vibrations generated were recorded using Instantel-Minimate and Vibracord seismometers. Both had the characteristics required by Spanish standard UNE 22381 [44] on vibration control, specifically, three seismic channels for measuring vertical, longitudinal, and transverse velocity waves; velocity measurement with the range 0–125 mm/s (resolution 0.01 mm/s); frequency range of 2–250 Hz; an additional channel for low-frequency sound pressure measurements (air-blast wave); and a sampling period of 1 ms. Seismometers are normally calibrated once a year.

The detailed information about the case study can be found in [59]. The data of 109 blasts from this quarry were used: 48 vibration records of from point A and 61 records from point E.

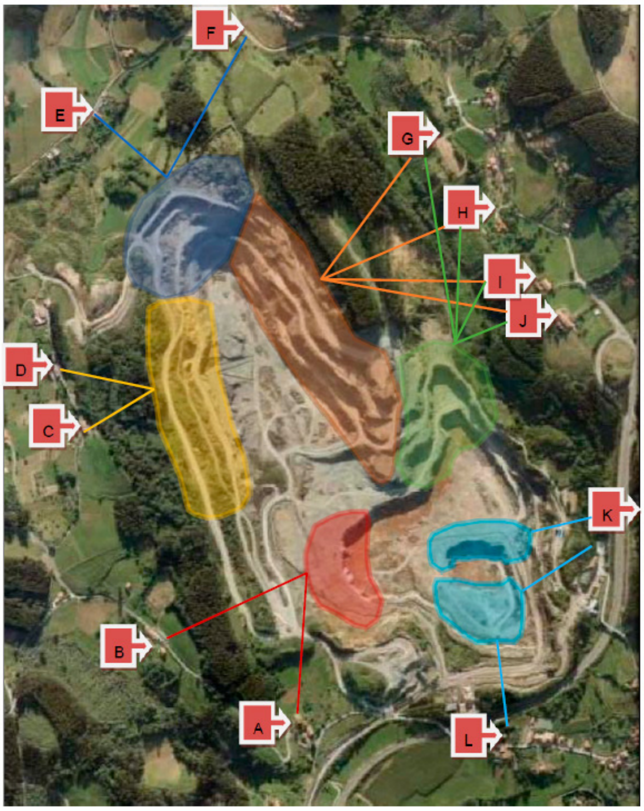

Figure 7. Control points' location around the quarry [59].

5.1. Direct Use of General PPV and Frequency Attenuation Laws

The proposed procedure is illustrated using measurements from point A (Figure 7). Data from the year 2006 were used to predict the representative area of the blast for the years 2007, 2008, 2009 and 2010, using the general attenuation laws of velocity and frequency in limestone rock mass, defined by the following parameters:

- PPV attenuation law: $K_v = 3085$; $\alpha = 0.757$; $\beta = 1.651$; $c_{vmax} = 2.5$; $c_{vmin} = 0.25$;
- Frequency attenuation law (low frequencies): $K_f = 77.4$; $c_{fmax} = 2.2$; $c_{fmin} = 0.35$.

A certain number of data was required to determine the specific rock-mass behavior of the case study (Figure 3), as well as an average value of the fundamental ground vibration frequency and the representative area for the following years, as shown below.

PPV and f_{med} values from 2006 are represented with their corresponding attenuation laws (Figure 8A,B, respectively), assuming that these general laws can be used in this case. On the other hand, it must be considered that the quality standard of the quarry analyzed requires working with 40% of the velocity, v_{GII}; then, $c_S = 0.40$.

The average frequency deduced from the experience was $f_{med} = 50$ Hz at the end of 2006, while the usage of Equations (17)–(19) gave $f_{med} = 30$ Hz. Although they are significantly different, both values, 50 and 30 Hz, lead to very similar results.

The procedure to predict the blast results during 2007 is as shown in Equations (26)–(31), where we assume that Q had not been previously calculated, and the distances are $D_{min} = 250$ m and $D_{max} = 630$ m.

$$f_{min} = 0.35 \times 50 = 17.5 \text{ Hz} \tag{26}$$

$$v_{GII} = 10.5 \text{ mm/s} \tag{27}$$

$$v_{lim} = 0.4 \times 10.5 = 4.2 \text{ mm/s} \tag{28}$$

$$Q_{max} = \left(\frac{4.2}{3085 \times 2.5 \times 630^{-1.651}} \right)^{1/0.757} = 62 \text{ kg} \tag{29}$$

$$Q_{min} = \left(\frac{4.2}{3085 \times 2.5 \times 250^{-1.651}} \right)^{1/0.757} = 8 \text{ kg} \quad (30)$$

$$Q_{med} = \frac{41 + 16}{2} = 35.2 \text{ kg} \quad (31)$$

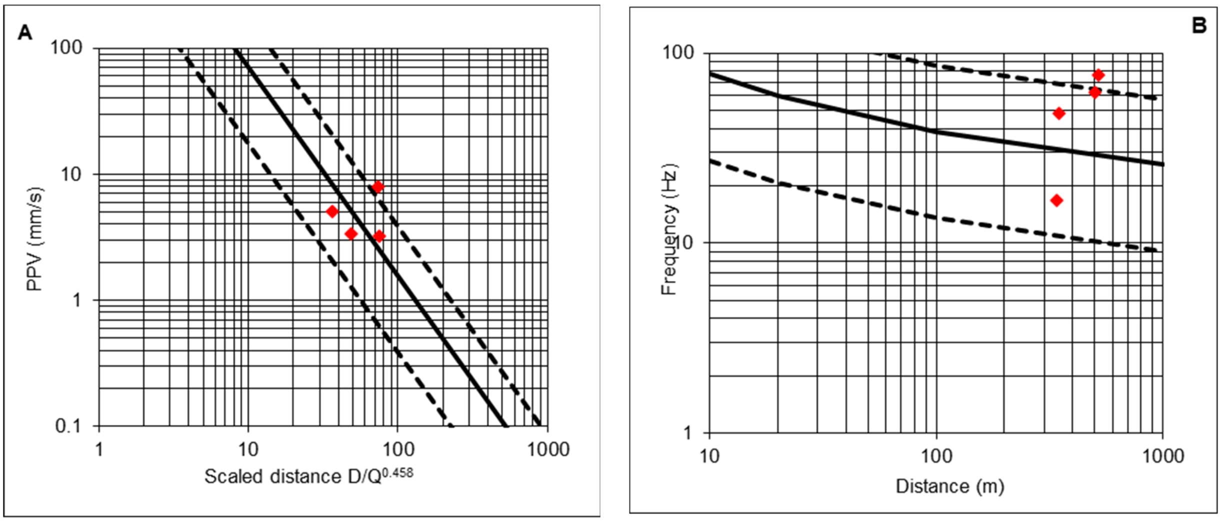

Figure 8. PPV and frequency values from blasts carried out in 2006.

The representative area obtained is shown in Figure 9A, using Q_{med} = 35.2 kg and the actual data, while Figure 9B shows the representative area defined by Q = 66.7 kg, the real average maximum charge per delay. Overall, the real charge used, Q, is bigger than Q_{med}, which was estimated under the most conservative assumptions.

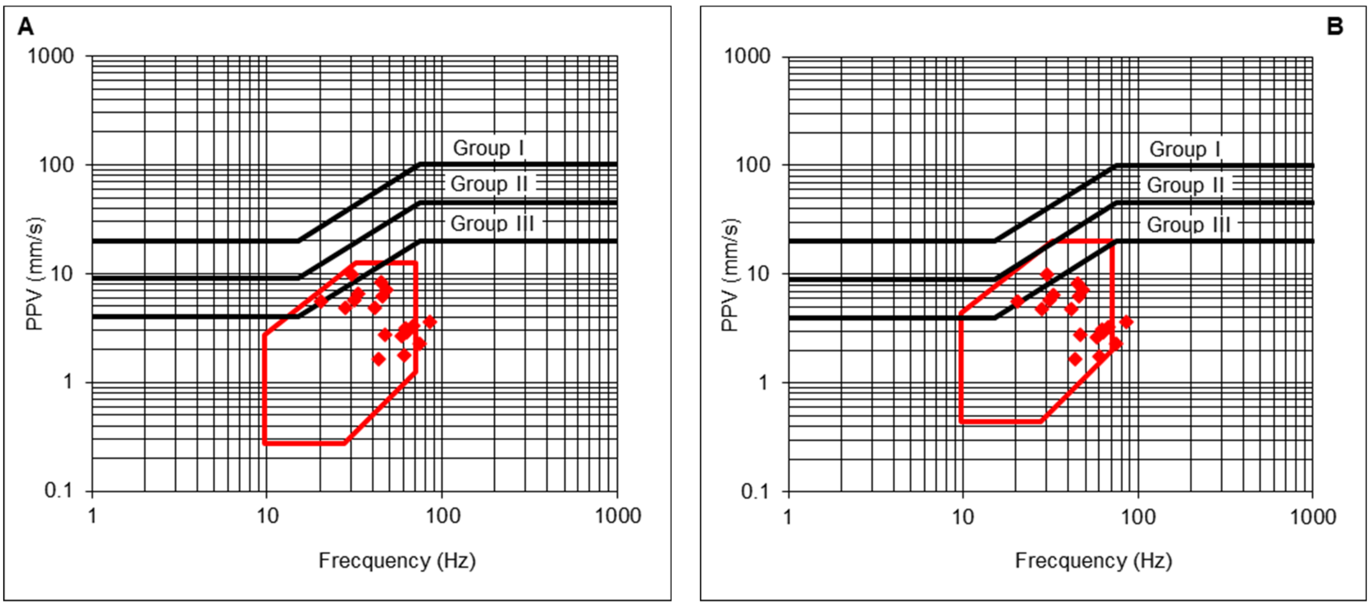

Figure 9. Actual data and representative areas predicted with Q_{med} (**A**) and Q (**B**) for 2007.

Two aspects must be analyzed in order to assess the capability of the procedure.

A high percentage of the real points must be within the estimated representative area. In this the study, the results fulfilled this condition, because 94% of the actual results (Figure 9) were within the representative areas predicted, verifying the capability of the procedure.

The upper limit of the representative area should give adequate information regarding the damage prevention criterion. Thus, the upper limit predicted what happened in both cases, since actual PPV values were lower than the limit curve for the protection of Group II structures.

The same procedure was repeated using data from 2008, 2009 and 2010. In 2008, the minimum and maximum distances were D_{min} = 250 m and D_{max} = 480 m, respectively. If the estimated charge per delay, Q_{med} = 21.3 kg, was used to define the representative area (Figure 10A), the percentage of success was 91% (10 out of 11). By using the real average charge, Q = 75.3 kg, (Figure 10B), 100% of points were within the representative area.

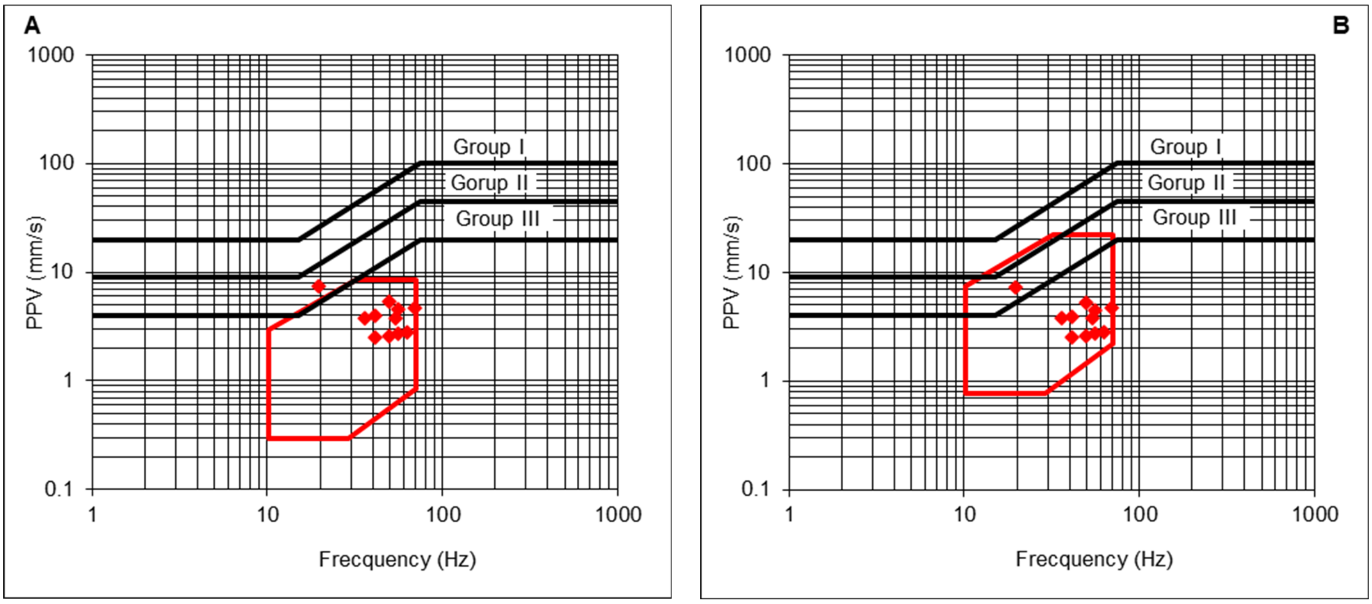

Figure 10. Actual data and representative areas predicted with Q_{med} (**A**) and Q (**B**) for 2008.

In 2009, the minimum and maximum distances were D_{min} = 280 m and D_{max} = 420 m. If the estimated charge per delay, Q_{med} = 18.1 kg, was used to define the representative area (Figure 11A), the percentage of success was 90% (8 out of 9). Using the real average charge, Q = 44.6 kg, 90% of points were also within the representative area in Figure 11B.

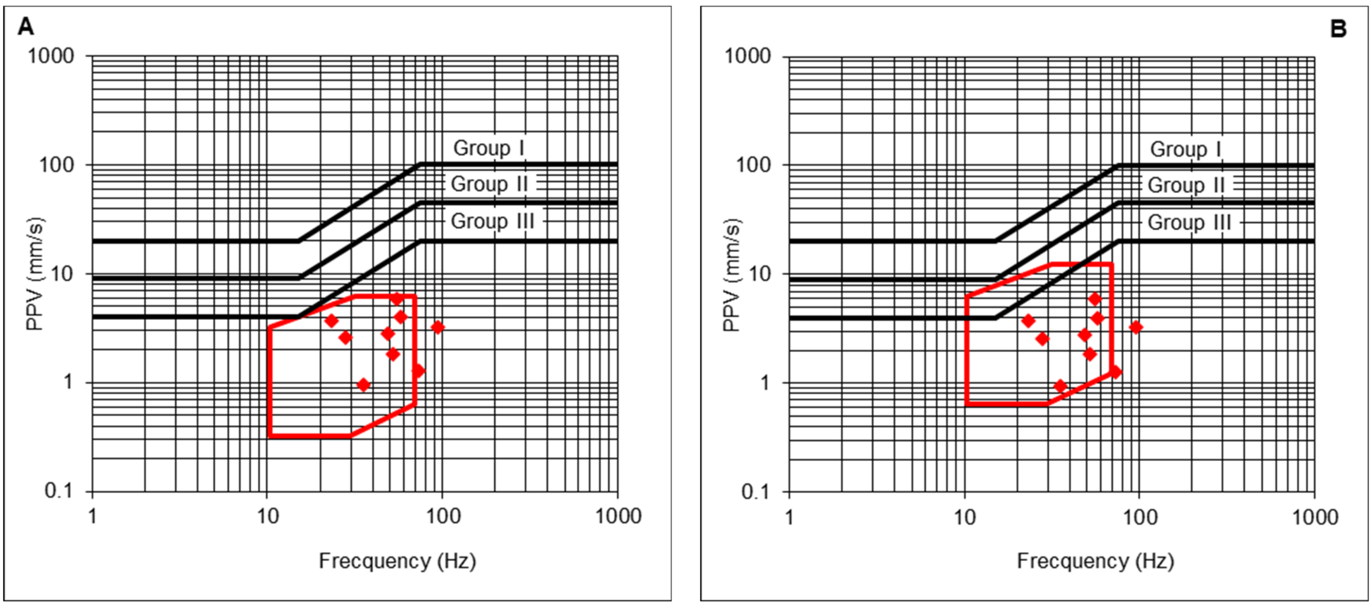

Figure 11. Actual data and representative areas predicted with Q_{med} (**A**) and Q (**B**) for 2009.

Regarding 2010, the minimum and maximum distances were D_{min} = 260 m and D_{max} = 440 m. If the estimated charge per delay, Q_{med} = 18.7 kg, was used to define the representative area (Figure 12A), the percentage of success was 83% (5 out of 6). Using the real average charge Q = 50 kg, 100% of points (6 out of 6) were within the representative area in Figure 12B.

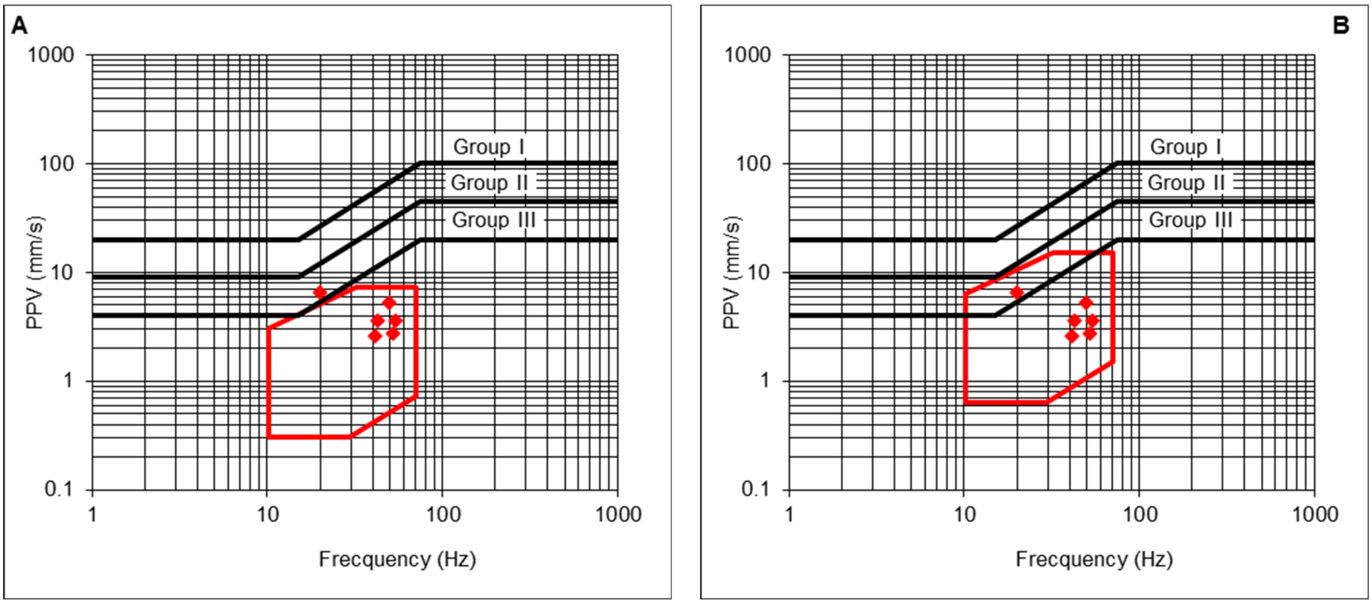

Figure 12. Actual data and representative areas predicted with Q_{med} (**A**) and Q (**B**) for 2010.

The global balance for the four years, between 2007 and 2010, is that real points were within the representative area in 91% of the cases. Therefore, the general PPV and frequency attenuation laws empirically determined for limestone rock masses could be used in this case study. It should be noted that the trigger threshold of seismographs is usually set at 1 mm/s. For that reason, there are very few representative points of blasts performed far away from structures, since the PPV does not reach the 1 mm/s threshold.

5.2. Particularization from the General PPV and Frequency Attenuation Laws

Sometimes, the general PPV and frequency attenuation laws are not accurate enough to predict the effects of blasting. However, the attenuation laws can be modified to improve the predictions as more data become available. In this regard, point E (Figure 8) was taken as an example to predict the representative points of the blasts for 2009 and 2010, based on the initial data from 2006. In this case, only calculations with Q_{med} are described.

As it can be seen in Figure 13, the PPV values measured in 2006 were smaller than the ones predicted by the general law. From the 16 measurements, the average frequency was f_{med} = 31 Hz, and the distance varied from D_{min} = 300 m to D_{max} = 850 m. Following the above-described procedure, Q_{med} = 53.7 kg was determined, followed by the representative area for the blasts carried out in 2006. The area and actual point cloud are represented in Figure 14A. Thus, the results were considered as acceptable; consequently, the procedure could be used to predict the blast-induced effects for 2009.

The representative-area definition for 2009 was performed using f_{med} = 31 Hz and distances from blasts to buildings, D_{min} = 280 m and D_{max} = 560 m. Subsequently, Q_{med} = 23.9 Kg and the predicted area were determined (Figure 14B). Nevertheless, the comparison between the predicted area and the actual data from 2009 verified that the results were not as good; about 60% of the points (9 out of 14) were within the estimated area, indicating that frequencies were higher than those measured in 2006.

The measurements recorded in 2009 allowed us to correct the frequency attenuation law by increasing c_{fmax} = 3.5. The representation of the point cloud from 2006 and 2009, together with the attenuation laws, allowed us to see that the coherence increased, and 90% of measurements were within the limit curves (Figure 15).

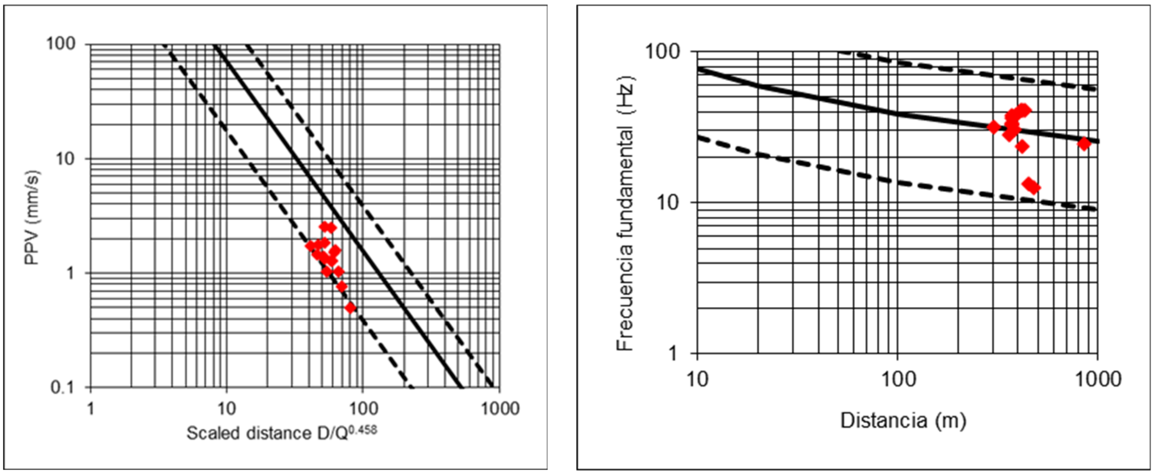

Figure 13. Values of PPV and frequency from blasts carried out in 2006 (point E).

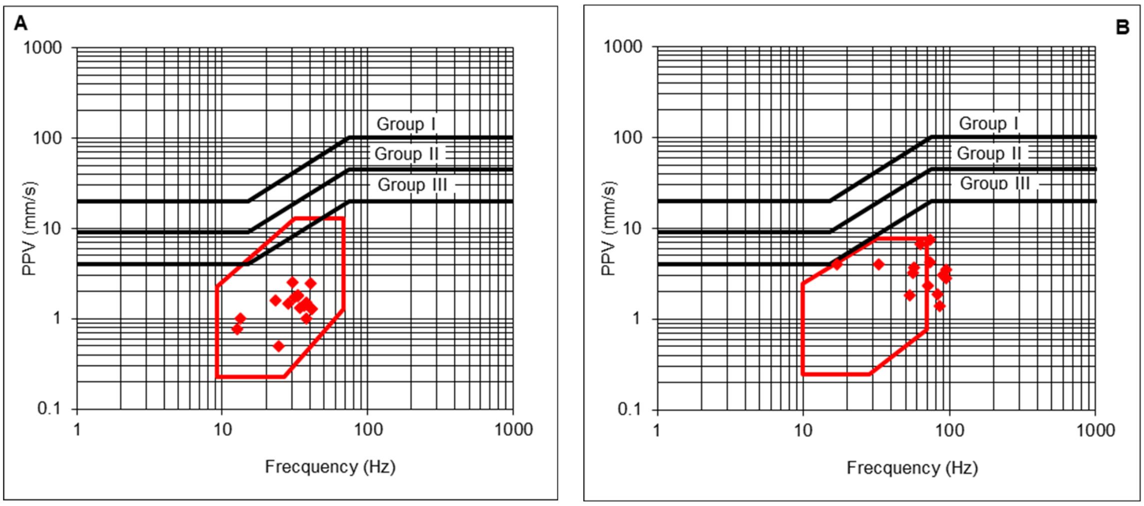

Figure 14. Representative areas predicted and actual data for years 2006 (**A**) and 2009 (**B**) (point E).

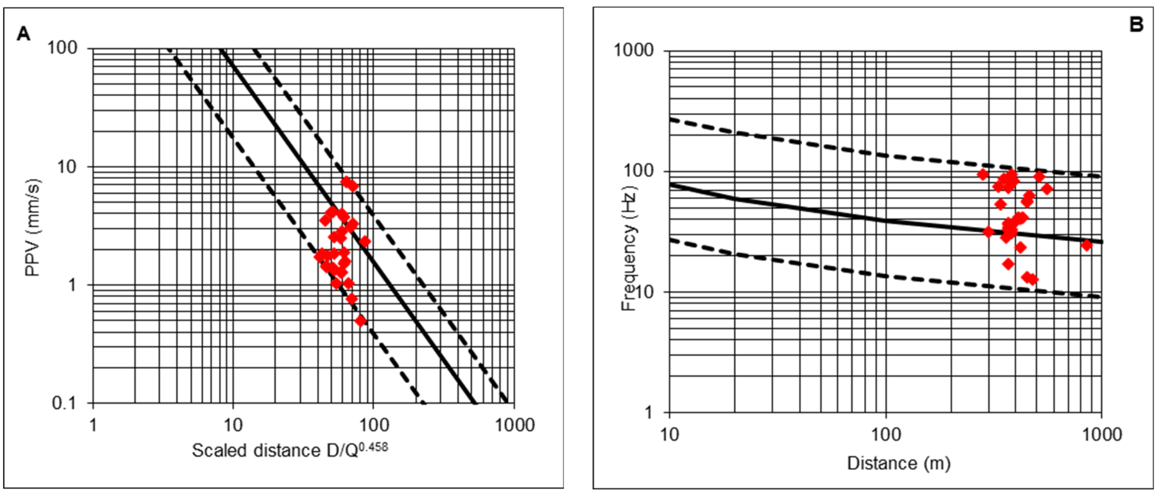

Figure 15. PPV and frequency values from blasts carried out in 2006 and 2009.

Now, we can predict the representative points of the blasts for 2010, based on the initial data from 2006 corrected with data from 2009.

The average frequency was determined using data from 2006 and 2009: f_{med} = 48 Hz. Knowing that the planned distances were D_{min} = 250 m and D_{max} = 650 m in 2010, the vibration prediction was performed using Equations (32)–(37).

$$f_{min} = 0.35 \times 48 = 16.8 \text{ Hz} \tag{32}$$

$$v_{GII} = 10.1 \text{ mm/s} \tag{33}$$

$$v_{lim} = 0.4 \times 10.1 = 4.0 \text{ mm/s} \tag{34}$$

$$Q_{max} = \left(\frac{4.0}{3085 \times 2.5 \times 650^{-1.651}}\right)^{1/0.757} = 63 \text{ kg} \tag{35}$$

$$Q_{min} = \left(\frac{4.0}{3085 \times 2.5 \times 250^{-1.651}}\right)^{1/0.757} = 8 \text{ kg} \tag{36}$$

$$Q_{med} = \frac{63 + 8}{2} = 35.5 \text{ kg} \tag{37}$$

The area was defined in the damage criterion abacus using Q_{med} = 35.5 kg, D_{min} = 250 m and D_{max} = 650 m (Figure 16A). The procedure provided a good result, as it can be verified by comparing it to the actual data, reaching 100% of the data within the estimated area. Besides, Figure 16B shows that the area predicted with the general attenuation laws, although acceptable, obtained less accurate results, i.e., 88% success.

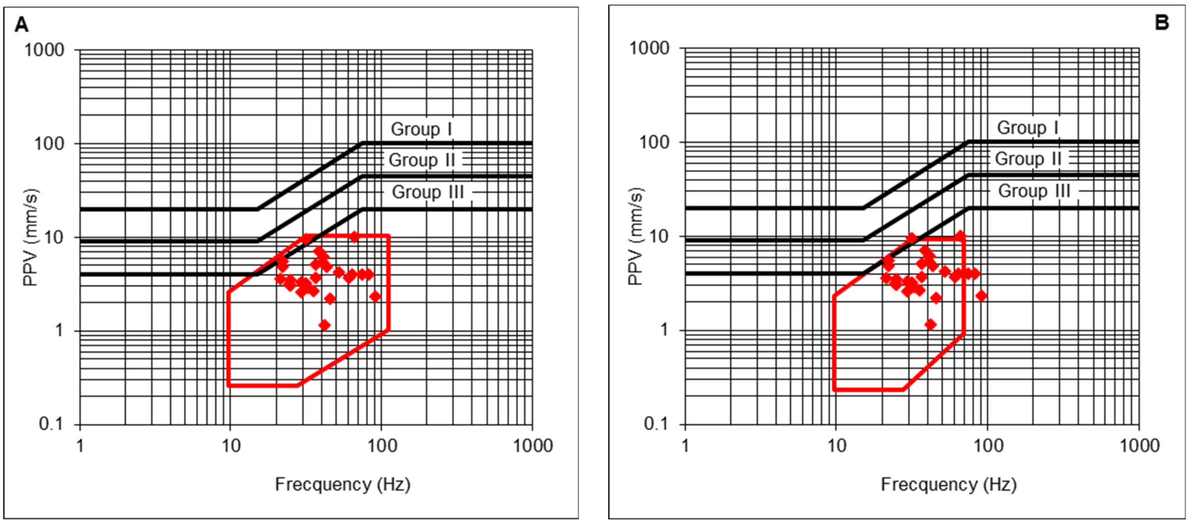

Figure 16. Representative areas predicted for 2010 using corrected (**A**) and general (**B**) attenuation laws.

6. Discussion

A procedure was developed to define a blast representative area in the abacus of damage criterion. The main advantages that we find in the method are the following:

(a) The variability of the result of a blast can be represented. The presentation of an area as an outcome helps to understand that many different vibration results can be equivalent, and all of them are valid. The difference between them stems from the variability in the blasting process, both due to natural causes (heterogeneity of the rock mass) and due to operational or blasting causes (dispersion in the pyrotechnic detonators, exact geometry of the blastholes, etc.);

(b) It is a method that integrates the use of speed and frequency together. From an exclusively scientific point of view, it is possible to study the variations in both variables independently. However, from a more operational point of view, that of the engineers who design the blasts, a vibration study must necessarily take both variables into account at the same time, because the damage prevention criteria defined in all the standards have been defined as a function of those two variables;

(c) If the method is calibrated, it can be quickly checked whether the blast result is as expected—a large part of the blast results (points) must be within the representative area. In addition, although the max charges per delay are defined based on the distances to the structures, the representative area can be estimated with the distances at which the seismographs have been placed;

(d) The proposed method was designed to be useful and easy to understand for any type of technician. It is relevant because, sometimes, the technicians of the institutions in charge of assessing the environmental impact of the project that requires authorization do not have experience in blasting and/or vibrations;

(e) The method can be used in different ways. If they are blasts where the distances to the structures to be protected are known, the max charge per delay can be chosen, and the method would help us to decide whether or not it is a good option. Likewise, a procedure is proposed to define the representative area of the blast, even if the max charge per delay is not known, since the damage criterion itself indirectly limits the load to be used;

(f) The method allows easy calibration to adapt to the specific conditions of a site;

(g) Finally, although for consistency we used the damage criterion of the UNE [44] standard, the proposed procedure can be used with any damage criterion.

On the other hand, we found certain limitations to the method:

(a) As in any empirical method, the parameters must be defined for each specific place. In principle, the proposed model can only be used in the case of limestone and only as a first approach;

(b) It was shown to be useful in blasting limestone, a rock with medium characteristics, and for this reason, we believe that it could be used in other types of rock; however, we cannot be conclusive, and it is not guaranteed that it can be extended to other types of rock;

(c) Specific PPV and frequency attenuation laws were chosen, but others could have been chosen; no studies have been performed on determining which combination of velocity laws and frequency laws is the best for each case;

(d) Since it is an empirical method that is not based on physical or mathematical laws, fundamental variables might not be taken into account, so it must be used in conditions similar to others in which it has been used successfully;

(e) As with other empirical methods, since it is easy to use, and the results are easy to interpret, it can give a false sense of knowledge about the subject; however, it is not a method that allows technicians to be dispensed with, as the analysis must always be supervised by someone with knowledge of blasting.

7. Conclusions

The proposed method improves the management of vibrations generated by blasting; it is here compared with the current approach commonly used, and it is based on Q, Dmin and Dmax to define a representative blast area in the damage prevention criterion abacus; it also provides more detailed information about the behavior of vibrations in a user-friendly system. Besides, it is based on a well-known and calibrated system.

The new approach was developed and verified using the results from 75 blasts in different limestone quarries, and it is grounded on two widely used attenuation laws, one for the PPV and another for the frequency, making the procedure useful under different conditions.

The actual representative points from 48 blasts fit perfectly within the associated area predicted by the proposed procedure. On the other hand, the system can be improved by means of some adjustments, as it is demonstrated by the analysis of the results from 57 blasts in the same quarry.

Further research should be conducted to apply the system in other conditions, such as civil works or mining other types of rock masses. Besides, the approach proposed could be adapted to any kind of damage criterion, as well as any other method that allows PPV and frequency to be estimated.

Author Contributions: Conceptualization, R.R., P.F. and M.B.; methodology, R.R., P.F. and M.B.; validation, P.R.F., M.B. and R.R.; formal analysis, R.R. and M.B.; investigation, P.F., P.R.F. and R.R.; writing (original draft preparation), R.R. and M.B.; writing (review and editing), M.B., R.R. and P.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available within the manuscript.

Acknowledgments: The authors would like to acknowledge the company Cementos Tudela Veguín, S.A., for important contributions to this research study, as well as the contribution of the company Caleras de San Cucao through several University of Oviedo-Company contracts (FUO-17-033 and FUO-18-167).

Conflicts of Interest: The authors declare no conflict of interest.

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