Quarry blast vibration monitoring methods

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Abstract

The environmental impact resulting from the propagation of blast vibrations in quarries, due to the use of explosives, is of great importance and usually the cause of the most complaints from populations living close to exploitation sites.

In the following document, a study is presented with the objective of characterizing the propagation of blast vibrations in two different quarry sites. Both located in Arrabida's Natural Park, they are Outão's quarry, where marl and limestone are exploited, and Vale do Covão's quarry, where only limestone is exploited.

Vibration monitoring field work took place from March to July of 2021 and resulted in obtaining 118 blast vibration records in Outão's quarry and 87 blast vibration records in Vale do Covão's quarry.

For the fulfillment of this study the Johnson Model was used to characterize the blast vibrations propagation in the vicinity of the blasts. For such, multiple linear regression was applied to the data sets taken from each quarry, making it possible to develop a prediction model for the vibration's amplitudes for each of the case studies.

Keywords: Surface rock blasting; Multiple linear regression; Vibration monitoring; Prediction models; Outão's quarry; Vale do Covão's quarry.

1. Introduction

The utilization of explosives in surface rock blasting has been gaining more representation due to its cost benefit relation, as it is the fastest and more economical excavation method. However, there are several associated environmental impacts, with the production of ground vibrations being what stands out the most, as it is the one that most inconveniences and causes complaints in populations, which occurs more frequently and can also cause damage to existing structures in the surroundings of explosive application sites.

Vibration consists of an oscillatory movement of a given material, which has been moved away from its equilibrium position, so it is like an elastic response of the ground to the passage of a stress wave that can have direct or indirect origin in a dynamic demand, of natural or artificial origin [1]. The main characteristics of ground vibrations are: amplitude (expressed through the physical quantities present in the wave phenomenon: displacements, velocities or accelerations), frequency and duration [2].

After detonation, volumetric and surface waves propagate in all directions, these being the waves we call vibration and that will reach nearby targets, such as people or buildings. Vibration usually tends to decrease with distance, being attenuated by various factors, however, in practice, this phenomenon is often not verified. Examples are stratified media where, if their geometry so favors it, the waves can concentrate or overlap with other reflected ones, thus causing higher vibration values to be verified at points further away from the source, the so-called phenomena of local amplification [3]. The frequency is very important in the structural damage criteria, because when the dominant frequency of the event and the natural frequency of the structure approach, these phenomena of amplification or resonance can result, consequently, in an aggravated dynamic response that may occur in a structure at a greater distance than another that doesn't vibrate.

The conventional blast pattern in surface rock blasting intends to adjust fragmentation and control the displacement of the material to be blasted, by applying an explosive charge in the drill holes [4]. This is associated with a crucial procedure in the application of explosive substances, the design, which should be dynamic throughout the exploitation. With good design, not only the blast is more likely to go as planned, as it is controlled, both in terms of production and fragmentation, and in the environmental impacts generated [5].

For the optimization of vibration amplitudes there are several procedures, some more practical and with lower costs, others using more developed technologies and consequently more expensive. In a first approach the geometry of the blast pattern and the initiation systems to be applied must be carefully designed [5]. Related to these, reducing the height of the benches may be a procedure to be taken into account, as well as the use of multiple initiation systems, reducing the explosive charge triggered by delay.

All over the world, there are standards with the objective of limiting the maximum values of vibration amplitude originating from geotechnical activities, which affect the surrounding structures, as in Portugal since 1983. With this limitation imposed, the need arose to create models that would allow to predict the vibration amplitudes, according to the explosive charge used and the distance to the receiver, so that those responsible for the blasts can adjust the blast patterns, reducing as much as possible the inconvenience caused to the population and always guaranteeing the safety of the structures. However, the limits presented in the various existing standards are always higher than those of human perception, which causes the discomfort of populations to prevail and that they often associate damage in structures, with different origins, to damage caused by vibratory phenomena.

According to what was just introduced, this study aims to propose a prediction model for vibration amplitudes for each of the quarries under study. For this, Johnson's model was used, as it was considered sufficient and effective in creating the intended models. The equation defined by Johnson in 1971, presented below, is *also recognized by several authors as the most used due to its versatility and ease of application* [5].

$$v = aQ^b D^c \tag{1}$$

Where v represents the resulting vibration speed (PVS: peak vector sum) [mm/s]; Q the maximum explosive charge per delay [kg]; D the distance between the blasting and the monitoring points [m]; a, b e c the characteristic coefficients of the location and the blasting pattern. To determine the coefficients a, b and c it is necessary to follow a methodology, with the main step being the implementation of multiple linear regression.

2. Methodology and vibration monitoring

The methodology applied in carrying out this study is divided into two parts, field work and later data processing. As for the field work, this consisted mainly of monitoring the loading of the blasts and monitoring the vibrations caused by the blasts.

The vibration monitoring took place from March 1st to July 3rd, being divided during this period between the two quarries under study. For monitoring, several engineering seismographs of the *Instantel* brand were used, properly calibrated and following the requirements presented in the Portuguese standard 2074/2015 [6]. In most trials, two seismographs were used for simultaneous monitoring in different locations.

The locations chosen for the placement of the seismographs were strategic, trying to cover all directions around each of the quarries and as many distance intervals as possible. However, there were some limitations to the location of the monitoring points, mainly due to the characteristics of the surroundings, either due to the intense existing vegetation, or the terrain not presenting conditions for the installation of the seismograph, as well as the absence of structures in some places.

To calculate the distances between the blasts and the monitoring sites, two different methods were used. For Outão, a topographical model in *AutoCad* format was used to mark each blast and to obtain the coordinates of each monitoring site, calculating the distance between places using the given coordinates. For Vale do Covão, as there is no topographic model that includes the chosen monitoring sites, *Google Maps* was used to mark each blast and respective monitoring locations, calculating the distance between them using the data provided by the application.

After the fieldwork, a database was created for each case study, these databases were analyzed, outliers were removed and multiple linear regression of the data was performed, using the *SPSS* software, with the objective of creating a vibration propagation model for each of the quarries.

3. Case studies

In this article, two case studies are addressed, both located in the Arrábida natural park, with small populations around, with strong pressure from the population to reduce the environmental impacts caused, namely the vibrations to which they are exposed. They are two very distinct quarries at various levels, one is isolated, located in Outão, next to Vale da Rasca, in Setúbal, and the other in Vale do Covão, belonging to a group of several existing quarries, next to Pedreiras, in Sesimbra. Geographically, the two quarries are shown in figure 1.

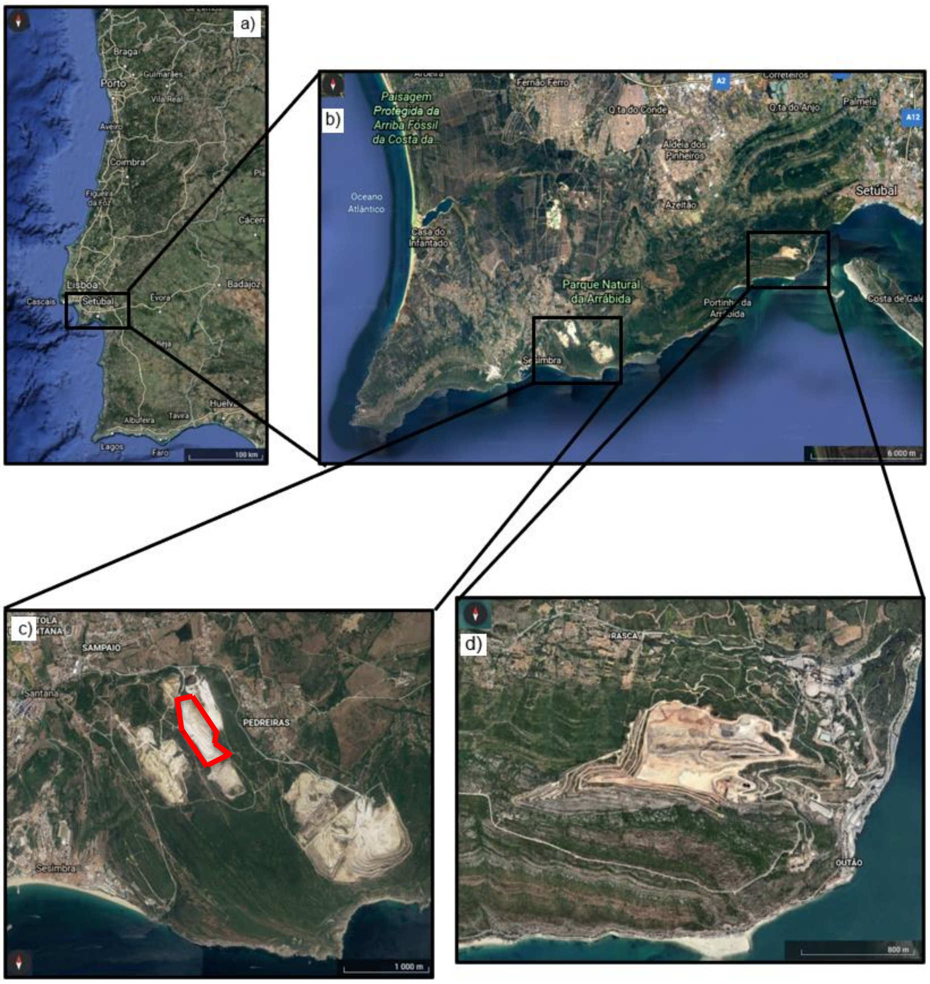

Figure 1 - Geographical location of the quarries under study: a) aerial photograph of Portugal mainland; b) aerial photograph of the Arrábida Natural Park; c) aerial photograph of the Vale do Covão's quarry (within the red polygon); d) aerial photograph of the Outão's quarry. (Google Earth)

The explosives commonly used are *Senatel Pulsar*, for the bottom charge and *Senatel Powerpac*, for the column charge, both products from *Orica Mining Services, S.A.* As for detonators, mostly non-electric detonators are used, *Exel* ^{TM} *MS*.

3.1. Outão's quarry

The Outão quarry is located next to the Secil cement factory, a few kilometers from Setúbal, southeast of the village of Vale da Rasca and northwest of Forte Velho do Outão. It has an annual production capacity of approximately 2 million tons.

To reduce environmental impacts, specifically vibration amplitudes, several minimization measures are already applied, such as: reducing bench heights, careful choice of blast pattern geometry and the use of multiple initiation. This last measure is the easiest to introduce and has been applied to increasingly lower benches (recently for benches from 12 meters high), with the aim of reducing as much as possible the inconvenience caused to the surrounding populations.

The quarry currently has a uniform layout of only one, but it is actually a set of two quarries of different materials, on the north side the existing rock is mostly marl and on the south side, limestone. The analysis carried out in this study considered the quarry as a single element, making no distinction from the geological material present. This choice was made, not only because the data when analyzed separately were not conclusive, but also because there are several types of geological materials in the area in question, with the measurement sites located in areas with a mixture of limestone, marl and other rocks, that is, the rock mass under study turned out to be the set of all these geological structures as a whole.

In figure 2, the 9 monitoring points used are presented. These were coded by letters and colors, according to the classifications of the structures, namely:

- sensitive structures, shown in red: A, B, C e H;
- current structures, shown in yellow: D, E, F e G;
- and reinforced structures, shown in green: I.

Figure 2 - Location of monitoring sites in Outão's quarry (Google Earth)

3.2. Vale do Covão's quarry

The Vale do Covão's quarry is a limestone quarry, located in Lugar do Covão, in Santana's neighborhood, in Sesimbra. It has around 700 thousand tons of annual production capacity. As in the previous quarry, care is taken to reduce environmental impacts, such as careful choice of blasting pattern geometry.

For the vibration monitoring in this quarry, eight sites were used, being presented in figure 3, as follows:

- In red are places referring to sensitive structures, none existing in this case study;
- In yellow, places referring to current structures: B, C, D, E, F, G e H;
- And in green the only reinforced structure: A.

Figure 3 - Location of monitoring sites in Vale do Covão's quarry (Google Earth)

4. Results and discussion

In Outão's quarry 118 vibration records were obtained and in Vale do Covão's quarry 87. From these records, the vibration speed and the dominant frequency of the events were gathered.

The vibration velocity values used in this study are the PVS (peak vector sum). The dominant frequency of the event was determined by analyzing the dominant frequencies of each terrain component (longitudinal, transverse and vertical), and the frequency corresponding to the wave of greater amplitude was selected, in the event of equal maximum amplitudes, the dominant frequency chosen is the lowest of the components in question.

To assess the integrity of the various linear regressions, the coefficient of determination (R^2) was used. This coefficient is a measure that assesses the ability of a model to predict or explain an outcome, and it tells how close the observed values are to the values predicted by the regression. It is important to note that this coefficient only indicates the magnitude of the association [7].

The first treatment of the data obtained was the extraction of outliers. To be able to extract these values using graphical processes, it was necessary to fix one of the data parameters, as there were variations in all, the maximum delay load (Q) was chosen for this purpose, however instead of setting a value of Q for each graphical representation, it was decided to divide the data into Q intervals, analysing the rate of change of each one so that it was as small as possible, ensuring a reasonable interval and with enough data to represent and analyse it graphically. A limit value of 10% of the data was considered, that is, it was not possible to extract more than 10% of the total data from each case study, so that this percentage was distributed across the entire sample size, the same rule was applied for each interval of Q, that is, for each graphical representation.

In Outão's quarry, 10 outliers were removed from a total of 118 records, and in Vale do Covão's quarry, 6 outliers were extracted from a total of 87 records. The number of outliers, in both cases, was less than 10% of the sample because the removal of more values did not improve the determination coefficients.

With a database free of outliers, the coefficients a, b and c referring to the Johnson model and characteristics of each case study were determined. For this process, the SPSS statistical software was used, as already mentioned, where the necessary multiple linear regressions were performed, and the respective results and quality parameters of the models were acquired.

For the application of linear regression to the vibration propagation model it was necessary to apply logarithms to all terms of the equation in question, so that the exponents became coefficients, thus, adapting equation (1), the following equation was obtained.

$$log(v) = log(a) + b\ log(Q) + c \times \log(D) \quad (2)$$

$$\equiv$$

$$y = b_0 + b_1 x_1 + b_2 x_2$$

After applying multiple linear regression, it was necessary to convert the results provided by SPSS into the original coefficients, a, b and c, for that $a = 10^{b_0}$, $b = b_1$ and $c = b_2$. It is important to note that the data would only be validated if, as expected, the coefficient b, referring to the explosive charge, was positive, as the increase in this results in the consequent increase in the verified vibration velocity, and the coefficient c, referring to the distance between the location of registration and blasting, were negative since the relationship between distance and vibration velocity is always inverse. The table below was then obtained.

Table 1 - Results for each case study

Equation	Coefficients			Coefficient of determination
Outão's quarry				
$y = b_0 + b_1x_1 + b_2x_2$	$b_0 = 1{,}978$	$b_1 = 0{,}353$	$b_2 = -0{,}969$	$R^2 \approx 55\%$
Equivalence	$a = 10^{b_0}$	$b = b_1$	$c = b_2$	
$v = aQ^bD^c$	$a = 95{,}061$	$b = 0{,}353$	$c = -0{,}969$	
$v = 95{,}061 \times Q^{0{,}353} \times D^{-0{,}969}$				
Vale do Covão's quarry				
$y = b_0 + b_1x_1 + b_2x_2$	$b_0 = 2{,}003$	$b_1 = 0{,}455$	$b_2 = -1{,}081$	$R^2 \approx 66\%$
Equivalence	$a = 10^{b_0}$	$b = b_1$	$c = b_2$	
$v = aQ^bD^c$	$a = 100{,}693$	$b = 0{,}455$	$c = -1{,}081$	
$v = 100{,}693 \times Q^{0{,}455} \times D^{-1{,}081}$				

The results were compared with the bibliography reference values for limestone, presented in table 2, through the graphic representation of isokinetic lines of the obtained equations and the theoretical one.

Table 2 - Characteristic coefficients a,b and c for limestone [8]

Rock mass	a	b	c
Limestone (type not specified)	580	0,6	-1,4

In the isokinetic lines related to the Outão quarry, it was possible to verify that these, theoretical and from the obtained equation, tend to come closer for lower charge per delay and to move away for higher charge per delay, not being totally parallel. This phenomenon was already expected because, as mentioned above, the Outão quarry does not only have limestone in its constitution, with influence from other rock masses, such as marl, noting that the theoretical values presented are for limestone only. Therefore, the isokinetics do not invalidate the results obtained, on the contrary, they validate them because both are in the same range of values and show that there is a distinctiveness in the existence of marl.

In the case of isokinetic lines referring to the Vale do Covão quarry, consisting only of limestones from the quarry, it is possible to validate the equation because, although these are not coincident, they are parallel and in the same range of values, which would be expected since the equation it is the adjustment to the real characteristics of the rock mass under study.

5. Conclusion and future works

The main objective of this dissertation was to build a prediction model of vibration amplitudes for each of the quarries under study, using multiple linear regression techniques and using Johnson's model (1971) as a basis. These models would allow to simulate situations in real time, whenever pertinent and necessary.

The case studies were two quarries belonging to the Secil group, located in the Arrábida natural park, close to small residential areas, and therefore both are the target of considerable attention in terms of environmental impacts. The monitoring campaigns in the two quarries lasted approximately 4 months and gave rise to around 205 observed events. With this monitoring, it was possible to verify that the Portuguese standard 2074 of 2015 is being complied within the two case studies, both of which aim to not exceed the most restrictive limit of this guideline, reducing as much as possible the resulting environmental impacts.

The model created for the Vale do Covão quarry has a better coefficient of determination, and it is to be expected that, as a result, the model will be more accurate than that of the Outão quarry. Although the results have been validated, the coefficients of determination were not as high as intended, however they are above 50%.

In the case of the coefficient of determination referring to the Outão equation, of only 55%, it can be explained by the fact that the analysis carried out considers the quarry as a single element, not taking into account the existing geological heterogeneity that could affect the results obtained through the physical characteristics of the terrain.

In monitoring, as already mentioned, the great difficulty felt was the impossibility of recording in some directions of the quarries due to the characteristics of the surroundings, such as dense vegetation, high slopes, very degraded roads, or the absence of structures in some places.

Despite all these difficulties, it is considered that the main objective of this study was fulfilled.

For future work, the creation of a new vibration amplitude prediction model is suggested, including the average distance from the bench, using recent 3D laser equipment, which do not totally depend on the user's acuity, together with a boretrak equipment, for evaluation of the quality and accuracy of the holes considered.

It is also suggested that a new prediction model of vibration amplitudes, including the powder factor of the explosives, be carried out. This parameter to be included will have to vary considerably over the monitoring period, otherwise it will not provide any constructive data for the model, something that is very difficult to apply in the context of normal working conditions in a quarry.

Finally, for the case study of the Outão quarry, it is suggested that a considerably larger database be carried out, applying a vibration amplitude prediction model that considers the different geologies, the locations of the receptors and the origin of the blasts, thus realizing what influence they have on the created model.

6. References

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