A New Blast Vibrations Analysis Methodology

Vinicius Gouveia de Miranda, O-Pitblast, Lda. & PhD Student - Oporto University (Portugal)
Francisco Sena Leite, O-Pitblast, Lda.
Céu Jesus, O-Pitblast, Lda.
Raquel Sobral, O-Pitblast, Lda.

Abstract

The urgent need for improvements in the control and mitigation of environmental and social conditions associated with the extraction and processing of raw materials is increasingly a demand imposed by legal entities and institutions. Therefore, this present article proposes an improvement of the estimation in the magnitude of the vibrations resulting from rock blasting methodologies in the surrounding areas, incorporating the heterogeneity caused by uncontrollable parameters, such as geological and geotechnical characteristics. This methodology combines the use of empirical vibration attenuation laws commonly known and with terrain discretization techniques using Voronoi's decomposition. For the validation assessment of this methodology, the data set collected and compiled is composed by 88 vibration measures collected in 16 sample points in one area of study of which 2/3 of the samples were used to create the model and 1/3 for the validation. Using normality tests for statistical residue analysis, it is possible to infer that this present model has null residual mean, as well as a smaller sum of residual errors. Comparing the methodology present in this paper with the procedures executed nowadays, a reduction of the errors associated with the estimation is obvious, highlighting a better characterization of the behavior of the vibrations associated with rock blasting.

Introduction

The vibration phenomena associated to rock blasting is always related with possible damages to natural or human structures. Vibrations associated to environmental impacts are frequently the genesis of conflicts between communities, so that the minimization of their effect is a challenge and a fundamental objective for the blast engineers (Oriard, 1999).

When a detonation takes place inside the borehole, the pressure increment generates almost an instantaneous dynamic tensile wave on the surrounded rock which will be propagated through the terrain, centralized on the borehole (Sanchidrián & Muñiz, 2000).

From a mechanical point of view, a vibration is an oscillatory movement of a particle around its stable position, generated by an impulse. This movement can be extremely complex due to the existence of fractures and/or joint, layers of different types of rocks and the blast of consequent boreholes delayed with a particular interval. The overlap of these tensile waves generated from different holes is one consequence of the complexity of factors that can affect the propagation of explosion-generated waves (Couceiro, 2013). These waves can be transmitted on the interior of the terrain mass - compressive (P) and shear (S) waves, and at the surface of it - surface (R) waves (Dowding, 1985).

The vibration level, resulted from a blast, is affected by several variables (controllable and non-controllable) and they can be (Jimeno *et al*., 1995):

- Maximum instantaneous charge;
- Distance to the blast;
- Powder factor;
- Explosive type;
- Delay times;
- Geometric variables such as: drill diameter, bench high, burden, spacing, sub-drill, stemming, holes inclination, decoupling ration, blast size;
- Geology and rock characteristics.

PPV (Peak Particle Velocity – maximum velocity that a particle moves while a vibration wave is passed through it) – is one of the principal parameter to evaluate vibrations, relatively to the potential damages that it might cause (Hammon *et al*., 1990). And to better understand the blast vibration phenomena and allow a clear comprehension of it, it is common to compare it to seismic phenomena (sine waves) (Siskind, 2005) as represented by Equation 1.

$$\boldsymbol{u(x,t) = u_{max} \cdot \sin\left(\frac{2\pi \cdot f}{c} \cdot x + 2\pi \cdot f \cdot t\right)} \qquad \textbf{Equation 1}$$

Where:
u = Displacement
f = Propagation frequency
c = Propagation velocity
t = Time

Due to the referred reasons, all the engineering projects that can generate ground vibration near communities or sensible structures are submitted to studies of the terrain attenuation laws and a constant control is made during all the activities of the project.

This paper presents a new methodology to improve the terrain characterization in terms of the calculation of attenuation laws.

Background

Attenuation Law

The prediction of vibration phenomena is a very powerful procedure in order to control and mitigate safety and environmental issues due to the possibility to identify potentials risk and beforehand, adjust the blast variables to minimize those risks. To better characterize the blast vibration effects in a heterogenic terrain, the best procedure is to estimate it and the best way is to use experimental (or existent) data and build a prediction model, usually called – Attenuation Law (Figure 1).

The vibration attenuation is represented by Equation 2.

$$\dot{u} = a\left(\frac{R}{W^{1/2}}\right)^{m} \qquad \textbf{Equation 2}$$

Where:

$\dot{u}$ = Particle velocity
R = Distance from blast
W = Maximum instantaneous charge
a, m = Terrain influence factors (linear coefficients)
$\frac{R}{W^{1/2}} = SD$ = Square root scaled distance

Scaled distance is a function of the distance and the charge. The application of the square root to the charge is derived from the fact that a borehole represents a cylindrical charge and its diameter is proportional to the square root of the charge (Dowding, 1985).

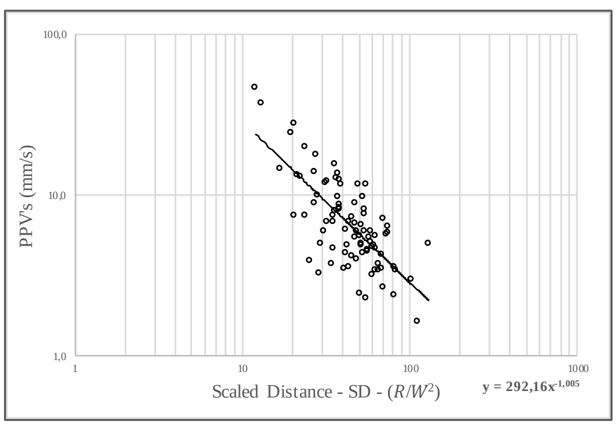

Figure 1. PPV based attenuation law

Absolute Minimum Residues Regression

In order to generate the best regression model that better represents the registered data, the least square method (LSM) is normally used with a logarithmic data. However, in this case, one single outlier has a huge negative effect on the definition of the regression line (Hamming R. W., 1973, p. 431). To bypass this issue, the present analysis used the least absolute residue method (LARM) (Miranda *et al.*, 2016) in order to generate the best fit regression line where the absolute residue is minimized[1]. The regression model is represented by the Equation 3.

$$\dot{u} = a(SD)^m + \varepsilon \qquad \textbf{Equation 3}$$

And to generate the best fit line, it is necessary to:

Minimize $\sum_{i=1}^{n} \varepsilon_i$ **Equation 4**

Subject to $\dot{u} - a(SD)^m \leq \varepsilon_i,$
$\dot{u} - a(SD)^m \geq -\varepsilon_i$

And $\varepsilon_i \geq 0, i = 1, 2, \dots n$

Where:
ε = Residue[2]

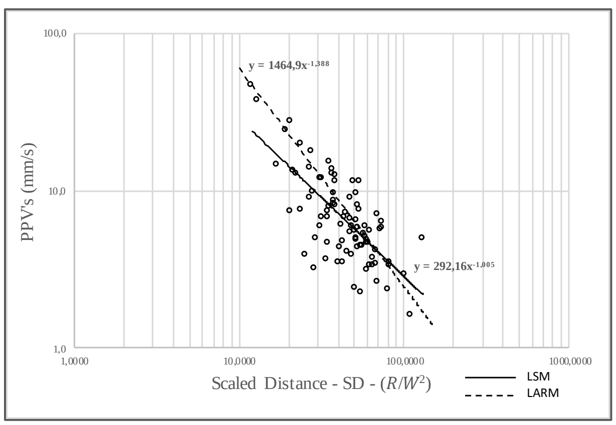

Figure 2. LSM vs. LARM approximations

Clusters

To define vibration influence areas, it is necessary to classify the seismograph positions and organize them by relatively homogeneous groups (Figure 4). This technique is defined as cluster analysis and it uses a series of statistical procedures to classify objects with certain degree of similitudes (Reis, 2001).

By definition of the methodology used in the present research (Single Linkage Analysis), giving two groups (A, B), a cluster analysis groups the elements in a way that the distance between these groups is the smallest distance between two elements from each one (Tan *et al.*, 2014).

$$D(A, B) = \min_{a \in A, b \in B} d(a, b) \qquad \textbf{Equation 5}$$

[1] The least absolute residue methodology is barely used due to its mathematical complexity (Hamming R. W., 1971, p. 249). However, the solution can be achieved by Linear Programming Technics.

[2] Stochastic perturbation or stochastic error term (Gujarati & Porter, 2010, p. 40).

Where:
$D(A, B)$ = Distance between cluster A and B
$d(a, b)$ = Distance between two points in cluster A and B

This methodology allows the generation of a dendrogram (graphic representation of the data grouping process) (see Figure 3) and since the definition of the ideal number of clusters is still a subjective method (Reis, 2001, p. 325), the researchers defined a cut value that better defines the clusters distributions.

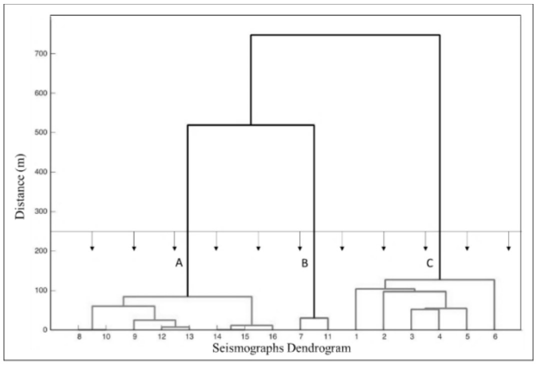

Figure 3 - Seismograph Dendrogram

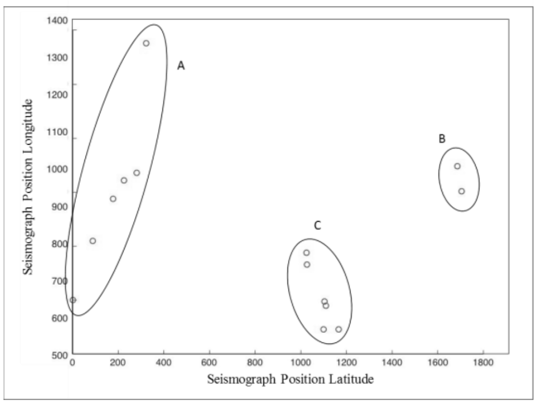

Figure 4. Seismograph positions (cluster definition)

Voronoi Diagrams

For this present study, it is intended to subdivide the terrain into regions in which each region represents a set of seismographs. Voronoi diagrams then divides the terrain into areas whereby any point inside an area is assigned closest to the reference seismograph found within that area (Figure 5). From the definition (Hjelle & Dæhlen, 2006), giving a conjunct of points $C = \{c_1, \dots, c_N\}$ and assigning a region (K) to each one, this must follow:

$$\boldsymbol{K(c_i) = \{x : d(x, c_i) < d(x, c_j), j = 1, \dots, N\}} \qquad \textbf{Equation 6}$$

Where:
$K(c_i)$ = Voronoi region of c_i
$d(x, c_i)$ = distance between a point in region $K(c_i)$

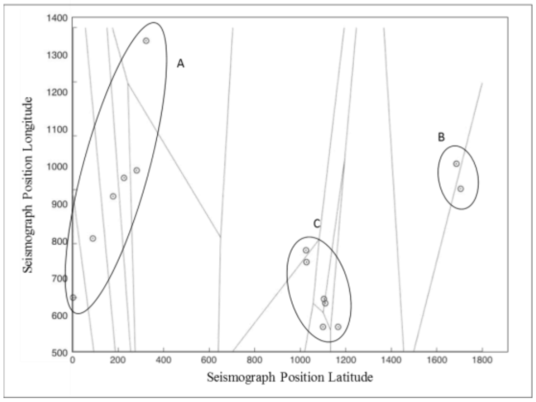

Figure 5. Voronoy diagram based on seismograph position

Methodology

Cluster Analysis and Central Point Identification

In order to organize the seismograph information, the first step was to group the seismograph positions by a cluster analysis. Knowing the seismograph groups, it was necessary to determine the central point of each cluster in order to proceed to the Voronoi discretization of the terrain (Figure 6).

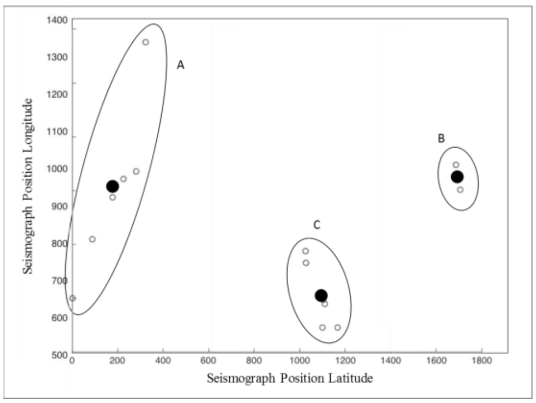

Figure 6. Cluster central point identification

Voronoi Diagram from Clusters

The cluster's central points are submitted to a Voronoi algorithm and a mesh is created (Figure 7).

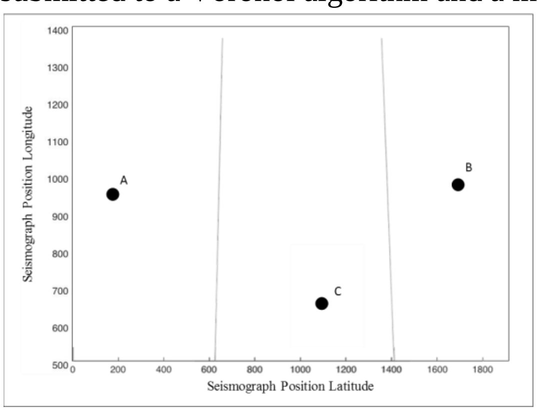

Figure 7. Voronoi diagram definition

Voronoi Cells Attenuation Law
In this phase, all the vibration values of seismographs on the same cell are used to create an attenuation law (recurring to the Absolute Minimum Residue). The algorithm detect the regions interface and when a vibration signal changes from one zone to another, the behavior of this signal follows the law present on the actual zone (Figure 8).

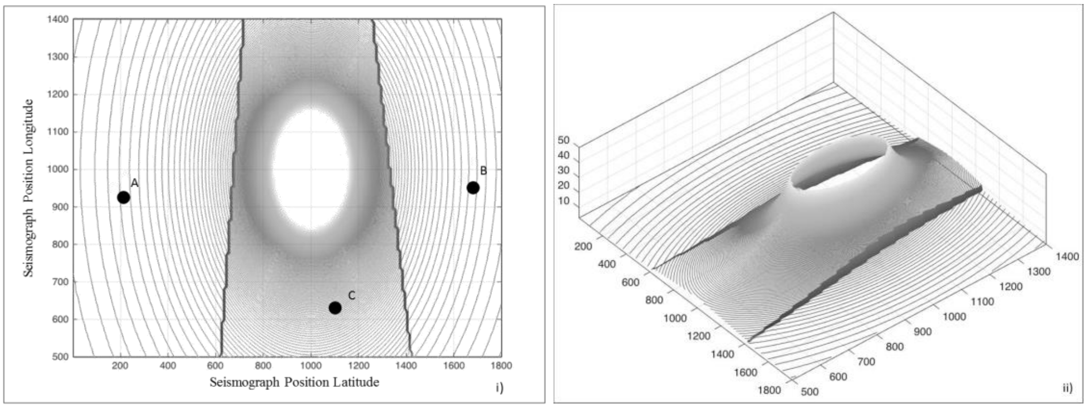

Figure 8. Attenuation law representation with Voronoi discretization. i) Plan view; ii) perspective view.

Results and Discussion

Database
The database on which the algorithm was developed and the project tested is composed of 88 vibration measurements from an engineering project located in Brazil carried out in 21 blasts. To register the data, the Instantel's Blast Vibration and Overpressure Monitor (Minimate Blaster™) was used, and the model was built in MATLAB (developed by MathWorks®) which is an interactive software for numeric calculations.

General Attenuation Law Predictions
In building a general attenuation law, without taking into consideration the geology and morphology of the ground, the vibration waves tends to travel through the terrain uniformly (Figure 9). This practice is not so accurate since it does not take in consideration the possibility of a vibration wave lose (or gain) intensity when moving through certain regions, for example, watered or fully fractured region.

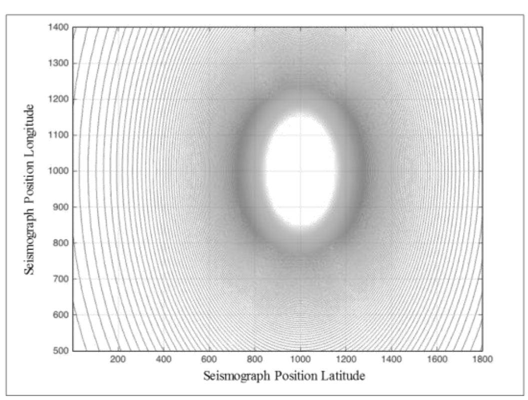

Figure 9. General attenuation law

Attenuation Law from Voronoi Discretization
In another way, for the same blast, when the terrain is subdivided into regions (in this case Voronoi diagrams based on central points of each cluster), the vibration limits can be determined more accurately. In Figure 10 it is clear the difference between this two cases since, in ii), the regions are delimitated by a different behavior of vibration levels.

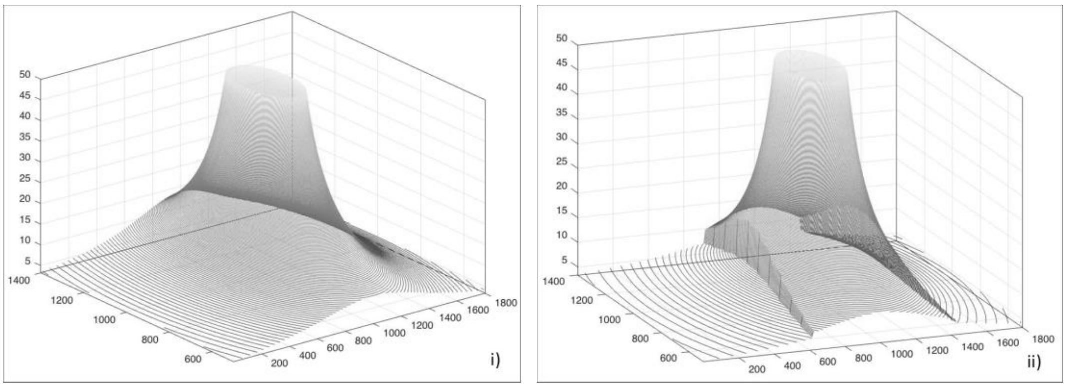

Figure 10. i) General Attenuation law approach; ii) Terrain discretization attenuation law approach

Model Validation
For the validation of this methodology, 1/3 of the data (30 measurements) were used to prove that the prediction analysis has great approximations when compared to the real data collected on the field.

Table 1. Real data comparison

Real Vibration	No terrain discretization	Terrain discretization
7,33 mm/s	9,56 mm/s	7,55 mm/s
13,72 mm/s	15,42 mm/s	12,96 mm/s
21,84 mm/s	20,38 mm/s	21,24 mm/s

Conclusion
The identification of potential risk that a blast might cause is a very powerful and useful tool. The possibility to plan and adjust the blast parameters in order to reduce and minimize the undesired secondary effects has a great importance for the blast engineer and the surrounding communities.

This new methodology shows a better prediction as compared to the actual procedures, since the predicted values were more precise when compared to the real acquired data.

Using a discretization of the terrain (using Voronoi diagrams based on the cluster analysis of seismograph position) and defining the attenuation law to each region instead of a general law to the entire terrain, gives a much better characterization of the site in terms of vibration attenuation.

The integration of this algorithm in blast design software is a possibility to improve the blast plan procedure in order to detect beforehand, the potential vibrations risk in a particular zone and apply changes to reduce this situation.

Acknowledgements

We would like to gratefully thank EXPLOG CEO Ismael Prado for the provided data and the opportunity given us to carry out this research project. We would like to thank the University of Porto - Engineering Faculty (Mining Department - FEUP) for the support and help in the development of the research, especially Engineer Alexandre Leite and Engineer José Soeiro de Carvalho. UFPE (Pernambuco Federal University) mining engineering professors, especially Carlos Magno is acknowledged for the essential support. Also to Darlington Mensah (Mining and Geological Engineer), for the essential support during the algorithm test phase and Susana Almeida (Mining Engineer) and António Rodrigues (Mining Engineer student) for the support in the project test phase.

References

Aurenhammer, F., Klein, R., & Lee, D.-T. (2013). *Voronoi Diagrams and Delaunay Triangulations.* Singapore: World Scientific Publishing Co. Pte. Ltd.

Bernardo, P., & Gama, C. D. (2006). Suggestions to Improve Portuguese Standard for Vibration Control in Constructions. Lisboa: Instituto Superior Técnico.

Couceiro, P. J. (2013). *Análisis Espectral de Los Fenómenos Sísmicos Asociados a Las Voladuras Subacuáticas.* Madrid: Escuela Técnica Superior de Ingenieros Industriales.

Dowding, C. H. (1985). *Blast Vibration Monitoring and Control.* Englewood Clifs: Prentice-Hall, Inc.

Gomes, J. P. (2016). *Metodologia para Análise de Vibrações Provocadas por Desmontes com Recurso a Explosivos.* Porto: Faculdade de Engenharia da Universidade do Porto.

Gujarati, D. N., & Porter, D. C. (2010). *Econometría.* México: McGraw-Hill.

Hamming, R. W. (1971). *Introduction to Applied Numerical Analysis.* United States of America: Hemisphere Publishing Corporation.

Hamming, R. W. (1973). *Numerical Methods for Scientists and Engineers.* United States: Courier Corporation.

Hammon, S. O., Leet, D., Parish, C. W., & Janney, W. (1990). *Blasting Damage and Other Structural Cracking.* New York: American Insurance Associations.

Hjelle, Ø., & Dæhlen, M. (2006). *Triangulations and Applications.* Heidelberg: Springer.

Jimeno, C. L., Jimeno, E. L., & Carcedo, F. J. (1995). *Drilling and Blasting of Rock.* Rotterdam: A. A. Balkema.

Miranda, V. G., Leite, F. S., Jesus, C., & Sobral, R. (2016). *A new Approach to 3D Modeling of Blast Free Faces.* Florida: ISEE.

Oriard, L. L. (1999). *The Effects of Vibration and Environmental Forces.* Ohio: International Society of Explosives Engineers.

Reis, E. (2001). *Estatística Multivariada Aplicada.* Lisboa: Edições Sílabo, Lda.

Sanchidrián, J. A., & Muñiz, E. (2000). *Curso de Tecnología de Explosivos.* Madrid: Fundación Gomes Pardo.

Siskind, D. E. (2005). *Vibration From Blasting.* Cleveland: Internation Society of Explosives Engineers.

Tan, P.-N., Steinbach, M., & Kumar, V. (2014). *Introduction to Data Mining.* Pearson Education, Limited.