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Multidirectional Modelling of Blast-Induced Ground Vibrations

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***Abstract*— In complex blasting projects, the challenge of keeping blast-induced ground vibrations under control requires the use of better peak particle velocity predictors. In some cases, traditional prediction methods, such as some classes of scaled distance approaches, are not able to easily incorporate anisotropic behaviors of the terrain. Since the propagation paths are usually formed by heterogenic materials, omnidirectional attenuation techniques may not be sufficient to proper describe the vibration's problem. Facing this challenge, a simple multidirectional blast-induced ground vibration model is developed in order to take into account possible azimuthal attenuation rates. In this paper, comparisons between the traditional scaled distance model and the proposed multidirectional approach are examined. Finally, a case study is presented in order to study the azimuthal attenuation rate of blast-induced ground vibrations in the Panama Canal Expansion Program.**

Index Terms **— Vibrations, anisotropy, multidirectional, blasting.**

I. Introduction

Blast-induced ground vibrations remain ranked as one of the most critical side-effects in mining, quarrying and civil works activities. Since blasting techniques are extensively used in these operations, the fully understanding of blast-related events, such as ground vibrations, are desirable. In the last decades, several researches have contributed to the current knowledge of this field, developing techniques to model and predict the expected ground motion from a given blast configuration [1, 2, 3, 4, 5, 6].

In certain circumstances, ground vibrations can cause damage to structures [7, 8, 9], a part of being a constant social concern when nearby communities exist around of the project [10, 11]. Thus, it is inconceivable to perform major engineering projects, where sensitive structures or urbanized areas are present, without carrying out works to characterize the attenuation of ground vibration velocities [12] and their control.

The prediction of ground vibration phenomena, based on the fundamental's physics of the seismic waves, is extremely difficult because the rock masses are not constituted by a perfect isotropic medium [13]. However, through specific vibration studies, it is possible to determine, in statistical terms, the laws that govern the attenuation of seismic waves at different confidence levels. Among several available techniques, such as signature hole analysis or numerical simulations, the use of scaled distances is often used to study the attenuation law in a given region of the space.

Traditional scaled distance approach is commonly used to correlate properties of the problem, such as distance and charge, with the expected vibration peaks. Over the past years, many researchers have published vibration prediction formulas and experimental results [14, 7, 15, 16], which the resulting methodologies are still used today. Nevertheless, these formulas are normally incapable to capture anisotropies, unless several models are built for different regions of the space [17]. Under these sensibilities, a better knowledge over the anisotropic effects is required to proper control blast-induced vibration amplitudes. Since both geological and geotechnical characteristics of the propagation medium, including its topography, influence the attenuation mechanisms of seismic waves amplitudes, specific studies along of different propagation paths are normally required.

Thus, this paper aims to expand the traditional scaled distance approach into a multidirectional parametric space in order to better predict the expected ground vibration at different directions. It incorporates the anisotropic behavior of the propagation medium by considering the direction of monitoring points in the parametric space. This multi-directionality assessment allows us to obtain the azimuth attenuation parameters that describes the vibration problem in the examined space. Finally, the proposed model is compared with the traditional scaled distance approach in an important blasting project carried out during the expansion program of the Panama Canal.

II. Model Development

The most common and widely used blast-induced ground vibration predictor has the following form

$$PPV = K\left(\frac{R}{\sqrt{W}}\right)^{\beta} \quad (1)$$

where PPV is the peak particle velocity (mm/s); R is the distance from the blasting to the observed point (m); W is the maximum instantaneous charge (kg); K and β are adjustable site-specific parameters.

The values of K and β depends of several features of the problem such as the propagation medium, anisotropic effects, blasting geometries, timing, initiation sequence, orientation, confinement, type of explosive and range of the data under analysis [18]. Typically, K correlates with the intensity of the vibration and is influenced by geology, confinement, explosive-rock coupling, rock strength and others. In contrast, the attenuation factor β expresses how fast the ground medium absorbs the seismic energy along of the propagation path.

The relationship between distance and charge, $R/\sqrt{W}$, is known as scaled distance, sd. A priori, it does not take into account the direction of the propagation wave in the analysis of blast-induced ground vibrations. However, the concept of scaled distance can be extended to a parametric space by decomposing it into parametric or scaled coordinates. Taking

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the scaled distance equation

$$sd = \frac{R}{\sqrt{W}} = \sqrt{\left(\frac{x_b - x_m}{\sqrt{W}}\right)^2 + \left(\frac{y_b - y_m}{\sqrt{W}}\right)^2} \qquad (2)$$

where sd is the scaled distance; x_b, y_b and x_m, y_m are the blast and monitoring coordinates in the cartesian space, the parametric coordinates can be defined as

$$x_n = \frac{x_b - x_m}{\sqrt{W}} \qquad y_n = \frac{y_b - y_m}{\sqrt{W}} \qquad (3)$$

where x_n and y_n are the parametric or scaled coordinates of the monitoring point in the parametric space, having in its origin the blast coordinates.

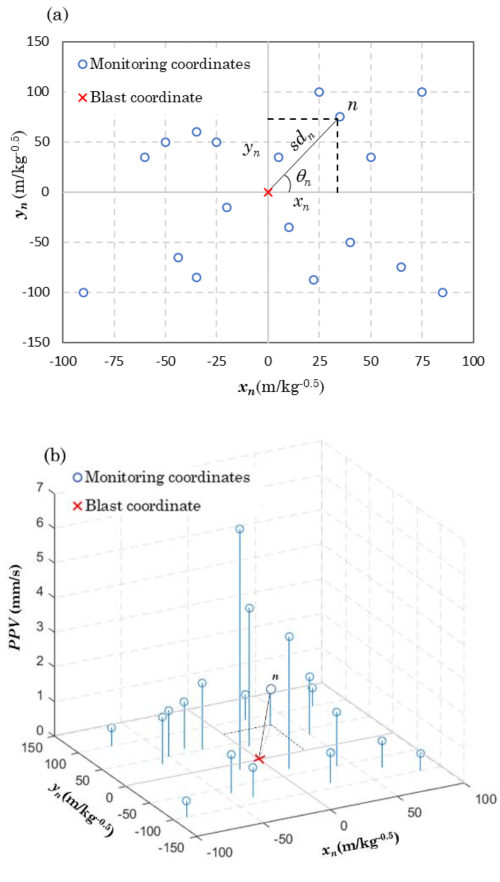


Fig 1: Schematic monitoring and blasting locations at (a) the parametric plane space and (b) with vibration intensities

If experimental peak particle velocities are plotted in terms of scaled coordinates, instead of scaled distances, the relative orientation of monitoring points, regarding to the blast location, can be easily assessed. The Fig 1(a) shows a schematically representation of the parametric plane space, where the relative orientation of the monitoring point n, together with its scaled distance sd_n, are identified. Thus, based on this concept, the relative orientation angle θ_n can be obtained by

$$\theta_n = \operatorname{atan}\left(\frac{y_n}{x_n}\right) \qquad (4)$$

where the blast coordinate is located at the origin.

Additionally, allowing the z-axis to represent the vibration intensity, the experimental PPV distribution is visualized, as exemplified in Fig 1(b). The advantage of studying the vibration problem in the parametric space is the possibility to take into account the potential anisotropic behavior of the propagation path.

In order to assess the expected peak particle velocity in a given point n of the parametric space, it is assumed that each one of the four major directions are dominated by a specific ground attenuation structure, where a trigonometric linear combination between two adjacent directions, which encompass the monitoring point, is possible. Thus, the multidirectional model can be written as

$$PPV_n = \sum_{i=1}^{2} K_i (sd_n)^{\beta_i} (\cos\theta_n)^2 \delta(x_n \mu_i) + \sum_{j=1}^{2} K_j (sd_n)^{\beta_j} (\sin\theta_n)^2 \delta(y_n \mu_j) \qquad (5)$$

where sd_n and θ_n are the scaled distance and the relative orientation angle that the monitoring point $n(x_n, y_n)$ makes with the horizontal, respectively; δ is the Heaviside step function, where $\mu_i = 1 - 2(i-1)$ and $\mu_j = 1 - 2(j-1)$; K_i, K_j and β_i, β_j are site-specific parameters associated with scaled directions x_n and y_n, respectively.

Finally, a non-linear minimization strategy is required in order to fit the equation (5) to the experimental data. In this paper, the summation of all residues formed by the absolute difference between the experimental and modeled peak particle velocities is minimized under the constrains that $\beta \leq 0$ and $K \geq 0$. These constrains would ensure the physical meaning of the model.

III. Results and Discussions

The applicability of the proposed multidirectional model is illustrated for the case of the Panama Canal Expansion Program. This immense project has created a new lane of traffic along of the existing Panama Canal through the construction of a new set of locks. The design and construction of the third set of locks was the major project of the entire expansion program. In the Pacific sector, the excavation works required around 2000 blasts along of 7 years of activities, demanding a strong commitment regarding to the control of undesired blast side-effects, such as ground vibrations.

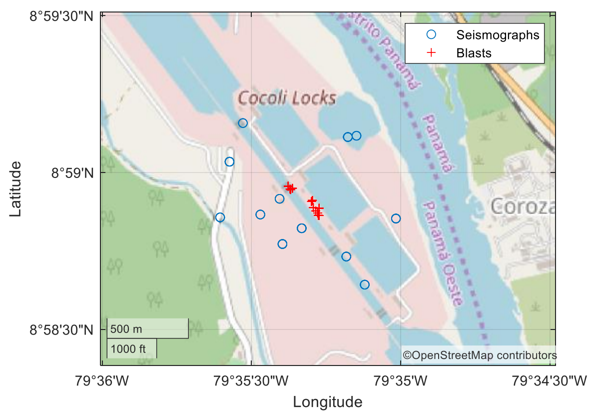


Fig 2: Seismographs and blasts locations for the first 20 blasts in the Panama Canal Expansion Program.

A total of six tri-axial seismographs were installed around of the blasting areas in other to monitor vibration levels at each one of the shots. Some of the seismograph's locations were moved to other positions in order to attend the closest sensitive structure to the blast. Seismographs and blast positions can be observed in Fig 2. Considering the heterogeneity behavior of the terrain, it is expected to find specific attenuation laws for different directions along of the studied domain. Thus, the first 20 blasts were analyzed in order to study the anisotropic behavior of the terrain and, consequently, to understand the azimuthal attenuation of ground vibrations around of the blast.

A. Geology

The pacific sector of the Panama Canal expansion program was situated in a complex set of geological domains [19]. It was dominated by Basalt, Pedro Miguel Agglomerates and La Boca Formation. The basalt domain was constituted by massive and columnar basalt, both medium hard to very hard, dense and tough. Pedro Miguel Agglomerates was a pyroclastic formation, generally of coarse texture, medium-hard to hard, dense, dark gray, massive to moderately fractured. In contrast, La Boca was a sedimentary formation of volcanic origin, with hardness varying from very soft to medium-hard, composed mainly of sandstones, siltstones, limestones and agglomerates.

B. Vibration analysis

Experimental data from 20 blasts were analyzed using both traditional and proposed multidirectional approaches in order to observe the potential differences between models and attenuation rates along of the terrain.

Fig. 3 shows the best-fit attenuation curve from the tradition scaled distance approach. Considerable scatter is observed in the data due to different propagation paths, blast orientations, topographies, geologies, and others. Then, the best-fit attenuation law is given by

$$PPV = 239.64\left(\frac{R}{\sqrt{W}}\right)^{-1.197} \tag{6}$$

where the R^2 is 0.55.

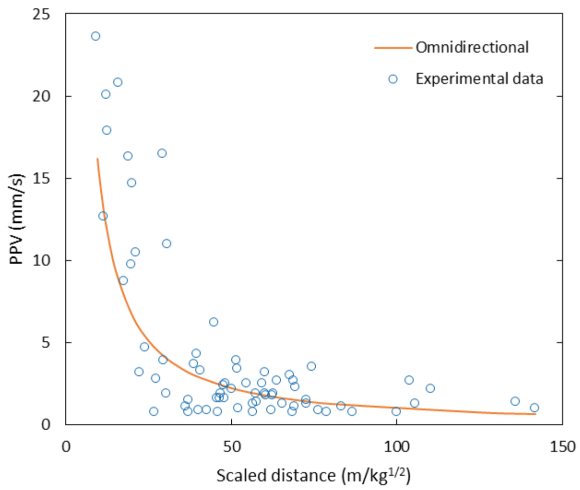


Fig 3: Traditional omnidirectional ground vibration analysis.

Since the equation (6) does not take into account possible heterogeneities of the terrain, the use of this attenuation law assumes an omnidirectional attenuation. As a result, the peak particle velocities would have the same attenuation rate at all directions, which is hardly found in real cases.

Based on the same set of experimental data, the proposed multidirectional model, through equations (3)-(5), were fitted via minimization of the total residue, using a non-linear minimization method. The particularization of equation (5) at the main four cardinal directions is presented in equations (7)-(10). These attenuation curves are shown in Fig 4, together with the omnidirectional model and experimental data. It is obvious from Fig 4 that different attenuation rates are necessary to proper describe the heterogenic effects of the propagation medium.

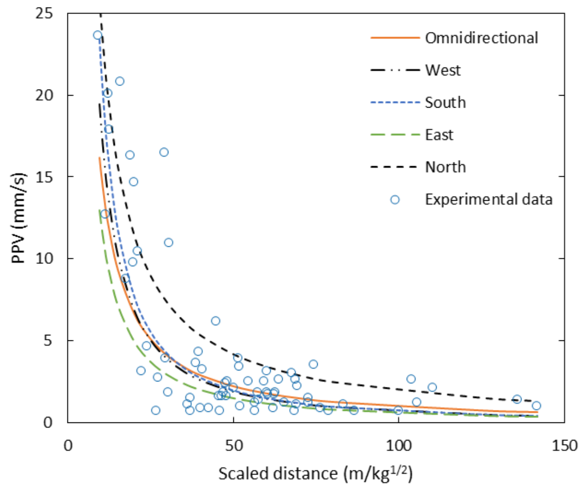


Fig 4: Multidirectional analysis at cardinal directions together with the omnidirectional model and experimental data.

$$PPV_{West} = 449.76\left(\frac{R}{\sqrt{W}}\right)^{-1.395} \tag{7}$$

$$PPV_{North} = 306.75\left(\frac{R}{\sqrt{W}}\right)^{-1.098} \tag{8}$$

$$PPV_{East} = 236.07\left(\frac{R}{\sqrt{W}}\right)^{-1.289} \tag{9}$$

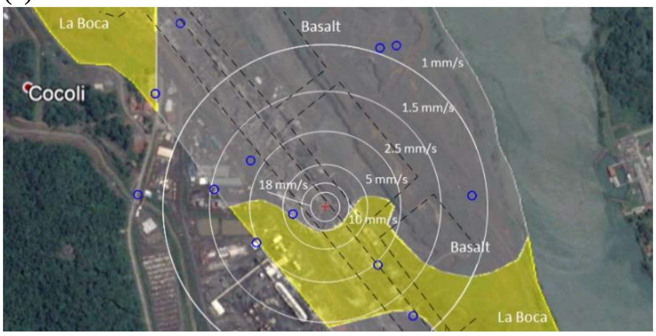
$$PPV_{South} = 674.12\left(\frac{R}{\sqrt{W}}\right)^{-1.493} \tag{10}$$

C. Iso-velocity map

The construction of iso-velocity maps is an important strategy in order to understand the terrain's anisotropy [20]. Thus, in order to illustrate the anisotropic behavior in the Panama Canal project, iso-velocities maps were generated for both the traditional omnidirectional approach and the proposed multidirectional model. For this purpose, the Blast #14 was selected. Boreholes were drilled in 89mm and loaded with 76mm watergel cartridges. The powder factor was 0.41 kg/m^3 and the maximum instantaneous charge was 29kg. Pyrotechnic detonators of 25ms and 67ms as inter-hole and inter-row delay were used, respectively.

Fig 5 (a) shows the iso-velocity map produced by the traditional omnidirectional approach. As expected, there is a symmetric attenuation rate of ground vibrations everywhere. This type of analysis averages the anisotropic properties of the terrain, representing it as a homogeneous body. This type of results is usually unrealistic and leads to poor PPV predictions. On the other hand, Fig 5 (b) shows different attenuation trends, depending of the seismic propagation direction, resulting from the application of the proposed multidirectional model. The anisotropic iso-velocity map shows an interesting find when superposed with geological domains, since different geologies are present in the studied area [19]. In this case, La Boca formation is found on the south region of the blast, which quickly absorbs the seismic energy, while on the north, where the Basalt is predominant, it is transmitted for longer distances. Thus, this comparative assessment evidences the importance of multidirectional analysis when studying blast-induced ground vibrations.

(a)



(b)

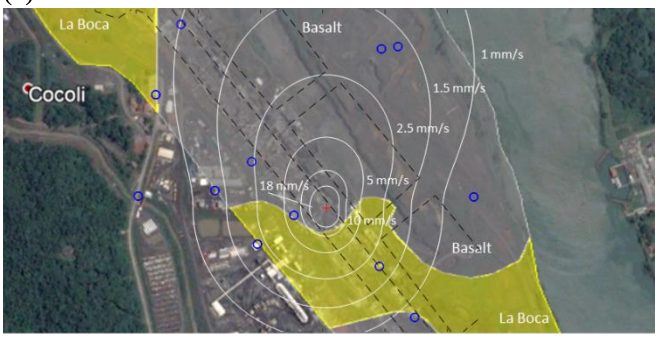


Fig 5: Iso-velocity map from blast#14 with geological domains superposed for (a) traditional analysis and (b) multidirectional analysis.

IV. Conclusion

A simple multidirectional blast-induced ground vibration model has been developed. It is based on the traditional scaled distance concept, which is extended to a parametric space by decomposing it into parametric x_n - and y_n-coordinates. In this parametric domain, the relative orientation of monitoring points, regarding to the blast location, establishes the basis for the azimuthal analysis of the attenuation rates at different directions. Thus, the formulation of the problem is found to be the trigonometric linear combination of two of the four cardinal attenuation laws. Finally, the proposed multidirectional model was used to study the anisotropic behavior of blast-induced ground vibrations at the Panama Canal Expansion Program, reinforcing the importance of using better ground vibration predictors when compared with the traditional scaled distance practices.

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