Simulation of vibration generated by underwater blasting using statistical analysis and numerical modelling

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ABSTRACT: Rock blasting in urban settings is always extremely demanding in what regards the control of ground vibrations and other environmental impacts. Extensive underwater blasting was performed in the Leixões Harbour, an important harbour surrounded by a dense urban mesh. Macro-seismometers were installed in the perimeter and recorded more than one thousand blasts. After completion of the works classical curve fitting statistical analysis of peak particle velocity (PPV) as a function of charge and distance to the blast was performed. PPV spatial distributions were determined for the duration of the construction and maps of ground peak vibration velocity drawn. The results showed that the accuracy of the attenuation law is within the usual range for this kind of phenomenon. However, factors like terrain morphology or geology variations cannot easily be included in a regression law but can be treated in a simple numerical model. A dynamic finite-difference model was developed and the influence of these features was studied thus increasing the understanding of the problem and providing valuable insights into some aspects of the usually large dispersion in the PPV.

1 INTRODUCTION

Rock blasting in an urban setting always implies negative impacts on the environment which must be carefully handled.

Vibrations propagate through the ground and may damage buildings, population and sensitive equipment. Vibration nuisance level depends mainly on vibration intensity and frequency content and these depend mainly on the charge in each blast time delay, distance from the blast location and geology of the ground crossed by the waves. Other less relevant factors are the type of rock where the blast occurs and the geometric configuration of the blast (existence of free surfaces, depth of boreholes, etc.).

In most practical situations it is not possible to monitor all structures that may be hit by vibrations. Spots where vibration is measured must be picked carefully having in mind two goals: the immediate protection of existing structures and future analysis that extrapolates the results to places where measurements could not be made. Unfortunately, it is sometimes difficult to find places that satisfy both requirements and where it is possible to safely install the seismometers.

The works for increasing the depth of the Leixões Harbour in a densely populated urban area involved blasting a large volume of submerged rock. The monitoring of vibrations was achieved through the use of several seismometers positioned according to a continuously updated instrumentation plan.

Upon completion of the blasting it was necessary to provide the Harbour Administration with elements to assess which complaints from the population (mainly related to cosmetic cracking inside buildings) were fair. Vibrations measured at the monitoring points were extrapolated and peak velocity values in non-monitored buildings were estimated and compared with the limits of the Portuguese vibration code (IPQ, 1983). Two different estimation methods were used. The first consisted on the classical approach of adjusting an attenuation equation with the general formula $PPV=f(W,R)$, where PPV stands for Peak Particle Velocity and represents the maximum of the norm of the velocity of vibration on the three directions, W the maximum explosive mass blasted in each instant and R the distance to the blast. The second method made the use of Multilayer Perceptron Neural Networks and was presented in other paper (Resende *et al*, 2008). Attenuation laws obtained by both methods were applied to the blast charges and locations and velocity distributions were estimated for the region around the harbour, allowing the drawing of iso-velocity maps. These were compared with measurements made by the blaster in several buildings and a good match was attained.

Finally, numerical modelling was employed to study if these tools are adequate to study alternative scenarios.

2 VIBRATION CONTROLL OF THE LEIXÕES HARBOUR DEEPENING WORKS

The Leixões Harbour is located in the metropolitan area of Oporto, the second Portuguese city. Set on the mouth of river Leça, the harbour is crossed on the Eastside by a 6-lane motorway (Fig. 1).

Figure 1. Leixões harbour aerial view (from www.apdl.pt).

The geotechnical characteristics of the ground are not thoroughly known by the authors. The underlying rock mass consists of fractured alkaline granite, with a medium to coarse grain size. Nevertheless, outcropping schist formations are visible at the transition from land to sea. The soil overlying the rock substratum inside the harbour area was deposited there during construction. The terrain is almost completely built. From contacts with the population it was learned that a significant number of older buildings have shallow foundations on sand.

2.1 *Blasting works and measurement of vibrations*

Blasting took place during 2006. Three different companies operating three platforms were involved. The *modus operandi* except for a few minor differences, was similar. Each blast consisted of successive detonations in boreholes arranged in a regular mesh with 2.0 to 2.5 m spacing. Electronic delay caps were used to reduce the instantaneous charge but in the occasions where the number of boreholes was higher than the number of available caps two or more columns were detonated simultaneously.

The blasting area was extensive and included the whole harbour and the turning basin; therefore the monitoring points were chosen between the blasts and the built areas, and also in some of the most representative structural typologies. Three 16 bit Geosig macro-seismometers model GSR-16 were used. Seismometers location had to be changed frequently to follow the location of the blasts, to address complaints from the population and to adapt to the records in each location. Monitoring spots are shoen in Figure 5. The devices were set to keep only records of which the acceleration values exceed a previously defined limit value for each of the three directions. Those values were defined at each site. Therefore, when establishing new observation points, shoot levels were adjusted slightly above local noise levels.

Each recorded event lasted five seconds of which one second corresponds to vibration arriving before the triggering peak. The effective duration of each waveform varied with the measurement point, the blast charge and the sequence of shots, having normally been of several tenths of second, but lasting, in some cases, almost 2 seconds. The acquisition rate was 250 Hz. With this acquisition rate it is theoretically possible to identify frequencies up to 125 Hz. Given the distances between blasts and measurement points and type of ground, it is above the maximum expected frequencies.

2.2 *Measured data*

997 blasts were performed, resulting in 2006 records (on average, each blast was recorded in two different positions). Figure 2 shows a typical blast record.

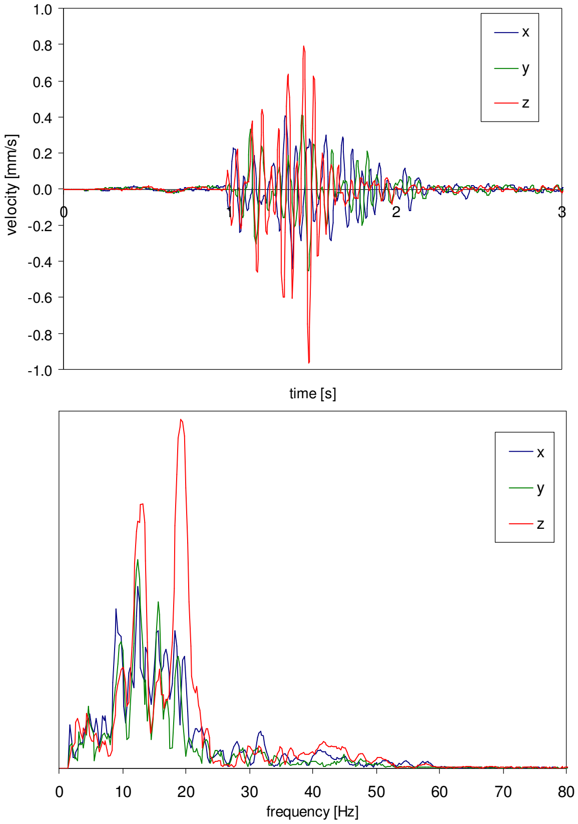

Figure 2. Vibration record: velocity (top) and frequency (bottom).

Figure 3 characterizes both distance between monitoring spots and blasts, explosive mass and the scattering of *PPV* as a function of the distance scaled with the cube root of the explosive mass. Instantaneous charges ranged from 5 to 95 kg and distances from about 95 to 1200 m. Maximum *PPV* was in the order of 30 mm/s but the majority of peak velocities were less than 10 mm/s.

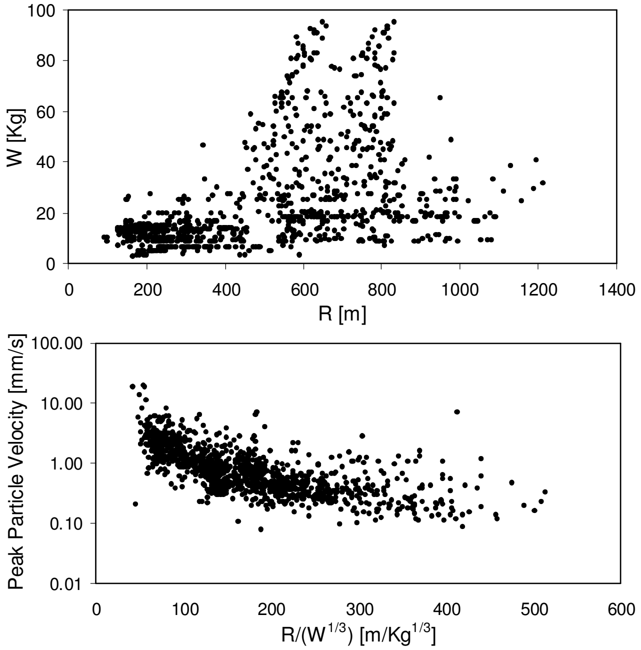

Figure 3. Scatter of the explosive mass and monitoring distance (top) and of the peak particle velocities (bottom).

3 ATTENUATION LAW

It is possible (Dowding, 1996) to establish a law that characterizes the attenuation of the norm of the Peak Particle Velocity:

$$PPV(W,R) = k \cdot R^m \cdot W^n \tag{1}$$

where *k*, *m* and *n* are parameters that depend on the characteristics of the blast and of the propagation path, and are determined by curve fitting.

By defining a new variable, quotient of the distance and the cubic or square root of the blasting mass it is possible to obtain a simplified form of the previous expression which is widely used. This results in a less effective adjustment to the data because of the loss of one degree of freedom, so the complete law with three parameters was used.

The three parameters were determined through Newton-Raphson minimization of the squares of the deviations of the logarithms of *PPV* using the complete set of 2006 records. The values of the law parameters were 1904, -1.46 and 0.31 for *k*, *m* and *n* respectively. The resulting law and observed points are represented in Figure 4 on a log-log plot.

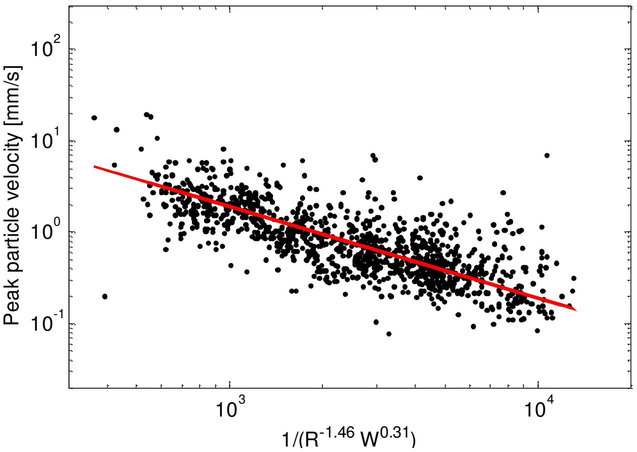

Figure 4. Attenuation law obtained by non-linear regression.

The linear correlation coefficient is 0.63 and is within the order of the values usually found in this kind of analysis.

Figure 5 shows the distribution of peak velocities in the surrounding area of the harbour obtained by the attenuation law and also the neural network model. Both methods provided similar results and overall matched peak particle velocity values. There were, however, some blasts that yielded *PPV* much higher than the average. The interest in finding out what happens then lead to the development of a simple dynamic numerical model that may explore the mechanisms that lead to singular results.

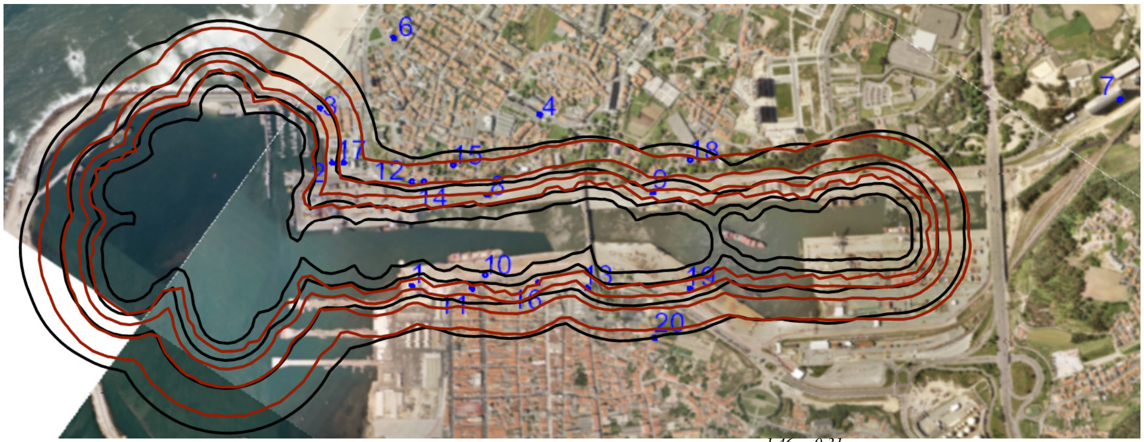

Figure 5. Iso-velocity lines calculated using the regression equation $PPV = 1904\ R^{-1.46} W^{0.31}$ (black) and neural network (red). Velocities increase from the inside to the outside. Numbers in blue indicate monitoring points.

4 FINITE-DIFFERENCE NUMERICAL MODEL

An elastic finite-difference model that represents a cross-section normal to the channel is represented in Figure 6. The model was developed in FLAC3D and has a total length of 1250 m and a depth of 150 m bellow the bottom of the channel, which has a width of 105 m and a depth of approximately 16 m. The model is just one element thick but since absorbing boundaries are installed at the base and sides, 3D spherical wave dispersion is approximately simulated. Compressive and shear wave propagation speed in the model is 3000 and 1500 m/s respectively. Finite-difference zones sides are regular and 3 m long, meaning that frequencies up to 125 Hz are correctly transmitted (Itasca, 2008).

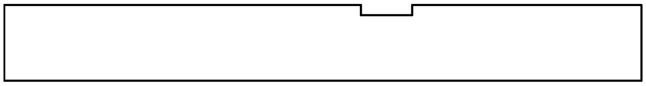

Figure 6. Contour of finite difference model.

The loading is simulated by a single-pulse negative exponential wave applied at the face of one element in the centre of the channel. Real loadings consisted on multiple non-simultaneous blasts but it is considered that time-delays between boreholes are sufficient to prevent wave cooperation. The veracity of this hypothesis will be investigated in the continuation of this study.

In this first step of the study, two scenarios were simulated. In the first, the model is homogenous, while in the second a 100 m wide intercalation of soft material (compressive and shear wave velocities are 700 and 350 m) that goes from the surface to the bottom of the model is inserted 300 m away from the harbour channel. Figure 7 shows the peak velocity amplitude obtained through the attenuation law, spherical geometric attenuation (the inverse of distance to the blast) and the two modelling scenarios.

It can be observed that the geometric attenuation itself is not sufficient to explain the decrease in vibration amplitude. The reference model matches the attenuation law up to 250 m away from the blast and then starts diverging. It should be noted that most records used to calibrate the attenuation law were measured at distances up to 600 m. Finally the intercalation causes the PPV to go up in the soft material and then decrease. The slope of the attenuation graph after the intercalation is similar to the reference model. This response is caused by the transition of the waves (both surface and bulk) between mediums with different impedances. As there must be stress continuity, transition from hard to soft material increases the strain and particle velocity, and the opposite occurs when passing back to hard material.

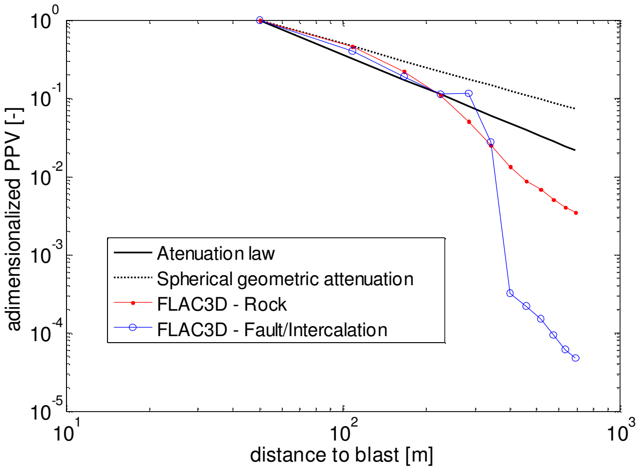

Figure 7. Contour of finite difference model.

5 CONCLUSIONS

Founded on detailed analysis of vibration data collected in various monitoring points in the area surrounding extensive underwater blasting works, an attenuation model was defined. The dispersion in peak velocity values in relation to the average is significant, as expectable in conditions such as those that occurred in this case. Nevertheless, the attenuation law presents reasonable results and was essential for the Harbour Administration management of complains.

Through a simple numerical model it was possible to understand how one singularity on the ground can lead to considerable variations on the vibration amplitude. More scenarios related not only to the ground properties but also to the topography and blast conditions are being studied and will be presented in future works.

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