Simulation of the vibrations produced during the rock excavation by different methods

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Abstract

The ground vibrations generated during rock excavation are always undesirable because of the damage that can be caused to building structures. This paper describes a numerical model that allows the simulation of ground vibrations due to blasting (mining), which can be transmitted over a great distance, and ground vibrations due to the use of hydraulic boom breakers (civil works) that are only important near the origin. Software for nonlinear dynamic analysis based on Finite Element Method is used. In the model the ground and the effect of a blasting (a very high instantaneous pressure) or a pick action (periodic load) are simulated. The calculated results are compared with real data proving that the model can reproduce the real phenomenon.

1 Introduction

Some times, in mining or civil works, it is necessary to excavate very strong rocks. In these cases the blasting of a great amount of explosives in zones near residential areas is frequent. On the other hand, the hydraulic breakers are very useful tools for excavating or breaking up strong rock without blasting (Figure 1). These actions generate vibrations through the ground that can damage structures or buildings that are near (case of the hydraulic hammers) or even far away (case of the blasting), phenomenon that started to be studied from 60's [1] and [2].

Nowadays, the correct blasting design or the proper use of a hydraulic breaker related to the ground vibrations are based on empirical data: vibrations transmisivity laws and damage criteria.
The vibration transmissivity laws, obtained from a number of field measurements [3] and [4], allow to determine the dominant frequency of the vibration and the peak velocity of a particle in the ground surface. In Figure 2 the laws corresponding to granite rock are shown. This velocity is estimated from the scaled distance $D/Q^{0.5}$ or $100D/I^{0.5}$, where $Q$ is the maximum charge per delay in kg, $I$ is the impact energy of the hammer in J, and $D$ is the distance from the vibration origin to the analyzed point in m.

On the other hand, the damage criteria is defined, for each kind of structure, as a limit in the peak vibration velocity at the analized point. In Figure 3 the criterium corresponding to the UNE 22381:1993 standard [5] is shown.

Assuming for example a blasting in granite with a charge per delay $Q=250$ kg, it could be estimated that the vibrations at a distance of 650 m would be defined by a peak velocity of 12 mm/s and a dominant frequency of 40 Hz. Entering with this values in the graphic of the damage criterium it can be seen that the blasting could cause damage in structures of Group III (archeologic, historic or special architectonic structures very sensitive to vibrations).
In the same manner, a hydraulic hammer of 2150 J energy impact acting against granite would generate at a distance of 3 m vibrations with a peak velocity of 20 mm/s and frequency of 92 Hz, that also can damage any structure Group III.

Figure 3: Damage criterion of UNE 22381:1993 Standard

These empirical methods give a minimum information (although, using safety coefficients, it is enough for almost all the projects) and then it is interesting to use other calculation tools, [6] and [7], that allow to achieve a most complete information, as the one achieved during the vibration control works (frequencies spectrum, duration of the vibration...etc.) which is the aim of this paper.

2 Development of FEM models for estimating vibrations

Models have been developed using commercial software [8] based on Finite Element Method (FEM) that allows a non linear dynamic analysis. The non complexity was an objective in its elaboration, the analysis was done in 2-D and under plain strain hypothesis.

The used software allow to analyze mechanical events involving large deformations, non linear material properties, kinematic motion and forces caused by that motion. Event simulation considers vibration, impact and motion of the part or connected parts of the model. Loading resulting from changes in motion are computed and applied internally. In the analysis, non linear material behaviour and non linear deformation can be included. The basic equation of event simulation is:

\[ [M]\{a\}+[C]\{v\}+[K]\{d\}=0 \quad (1) \]

in which \([M]\) is the mass matrix, \(\{a\}\) is the acceleration vector, \([C]\) is the damping matrix, \(\{v\}\) is the velocity vector, \([K]\) is the stiffness matrix and \(\{d\}\) is the displacement vector.
2.1 Vibrations caused by blasting

The geometric model (Figure 4) is a block of ground 2000 m length and 500 m height, with a bank of 20 m in its upper zone in which the blasting is simulated. The model has 10754 elements and 10767 nodes. The boundary conditions are: horizontal displacements to be null at lateral boundaries and vertical displacements to be null at the bottom of the model.

![Geometric model for vibration analysis (blasting)](image)

Figure 4: Geometric model for vibration analysis (blasting)

The ground consist of granite rock mass with an average mechanical properties obtained from experience: density $\rho = 2650 \text{ kg/m}^3$, elastic module $E = 60000 \text{ MPa}$ and Poisson coefficient $\nu = 0.22$. Due to only near the drillings in which the explosive is introduced the rock yield, an elastic behaviour of the rock mass is assumed. The pressure generated by the blasting is simulated as a perpendicular to bank pressure $P$ acting instantaneously (time minor than 10 ms). That pressure causes the model to vibrate.

Varying the pressure $P$ (equivalent to the explosive charge) and relating the maximum vibration velocity with scaled distance ($D/P^{0.5}$), a curve similar to the empirical ground vibrations transmisivity law can be obtained (Figure 5).

The dominant frequency of the vibration at a distance of 100 m, about 40 Hz, is very near the frequency measured in the field works. It is interesting to remark that from the simulation, other frequencies (between 10 and 50 Hz) are estimated, which would be taken into account in the blasting design.

![Transmisivity law and frequencies spectrum (blasting model)](image)

Figure 5: Transmisivity law and frequencies spectrum (blasting model)
The way of using the model is as follows: taking a maximum charge per delay $Q$, the ground response is determinated introducing in the model the pressure $P$ that the blasting generates in the rock mass far away from the yielding rock zone around the drilling. The experimental relationship between $P$ and $Q$ for using the model is approximately:

$$P = 0.65 \times Q^{0.90}$$  \hspace{1cm} (2)

2.2 Vibrations caused by hydraulic breaker hammers

In this case, the main hypothesis are the same as in the other one: 2-D plain strain state and non lineal dynamic analysis FEM model. The model symmetry allows to analyze only half of it, establishing in the symmetry axis a null displacement in the direction perpendicular to it. Figure 6 represents the meshed model used in the simulation.

The total model dimensions are 1000 m $\times$ 1000 m, and the element size in it grows in the direction of the boundaries.

Figure 6: Geometric model for vibration analysis (hydraulic breaker hammer)

The material properties are: density $\rho = 2650$ kg/m$^3$, elastic module $E = 85000$ MPa and Poisson coefficient $\nu = 0.22$. It is necessary to use a greater elastic module than in the other case, 40% superior, in order to fit the frequencies given by the model to those measured in the field.

This is coherent with the scale in which the work is done. The material has an elastic module equal to intact rock one rather than rock mass module, due to the discontinuities in the granite in these dimensions, are not relevant.

The action of the breaker hammer on the ground has been modeled like a nodal force applied to the superior left corner of the mesh. This force is time dependent and is defined by a curve consistent in several cycles of loading and unloading repeated at a hammer pick frequency. Taking in consideration the
Characteristics of the hydraulic breakers employed in fragmentation of strong rocks, the impact frequency of 7.2 Hz (435 impacts per minute) has been taken.

One of the most important data influencing the results of the model is the form of the wave of loading-unloading cycles. The best fitting with the experimental results has been achieved assuming these cycles as a sum of an exponential curves with different duration for loading and unloading phases.

Relating the peak vibration velocity with the scaled distance \( D/F^{0.5} \) a curve similar to the ground transmissivity law is obtained (Figure 7).

As it can be seen in the frequency spectrum at a distance of 5 m, the dominant peak frequency is 93 Hz, near to the measured one, but other components (between 50 and 100 Hz) should be taken into account in the case of using the breaker hammer near to buildings.

![Graphs showing transmissivity law and frequency spectrum](attachment:image.png)

Figure 7: Transmissivity law and frequencies spectrum (breaker model)

The way of using the model is as follows: taking an impact energy \( I \), the ground response is determined introducing in the model the periodic force \( F \), with a frequency of 7.2 Hz, that the impact pick generates in the rock. The experimental relationship between \( F \) and \( I \) for using the model is approximately:

\[
F = 3.0 \times I^{0.40}
\]

3 Conclusions

In this paper, it is shown that it is possible to study the vibrations generated in the rock mass during its excavation with blasting or with hydraulic hammers using non complex FEM models.

The achieved results are important due to it allow to analyze ground vibrations by means of powerful calculation software with clear advantages (determination of the frequency spectrum, possibility to do 3-D analysis, simulation of the structures supported on the rock mass...etc).

Obviously, more elaborated models allow more accurate results and this is the reason why the researching continues.
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5 References


