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Technical Note

A methodology based on geomechanical and geophysical techniques to avoid ornamental stone damage caused by blast-induced ground vibrations

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1. Introduction

Blasting is necessary for many operations in underground and open pit mines. Explosives are employed not only in mining operations, but also in civil construction works. Blasting is applied where mechanical means such as bulldozers or hydraulic excavators are unable to break up and excavate the rock mass.

When a charge of explosive is detonated at certain depth inside of a drill hole, gases at very high pressure and temperature are formed. Although blasting is considered one of the cheapest and fastest ways to break rocks, only a small proportion of the energy released by the explosives, approximately 15–30%,[1,2] is used to fragment the rock mass. The remaining energy, which is below the elastic limit of the rocks, is dissipated and is responsible for unavoidable and undesirable effects such as ground vibrations, air blasts, fly rocks, noises and back breaks.

Among all the negative effects caused by blasting, ground vibrations can be the most dangerous since they can damage structures of nearby buildings. In addition, if the frequency of ground vibrations is within the natural frequency range of the structure, it may lead to more damage due to the phenomenon of resonance.3 The magnitude of ground vibrations depends on blasting parameters (amount of explosive per delay, number of blast events, powder factor of explosive, diameter and depth hole, burden, spacing), geological and geomechanical parameters and distance between blast and monitoring point.

Prediction of ground vibrations is very important in order to reduce possible damage from blasting. The most commonly used descriptor of ground vibration is peak particle velocity (PPV). Dauetas et al.[4] and Athanasopoulous and Pelekis[5] report theoretically that the strain induced in the ground during vibration is directly proportional to particle velocity. Due to anisotropic rock mass parameters, complexity of local geology and blasting parameters, prediction of PPV is a difficult task. However, in recent decades many researchers have proposed different models providing suitable predictors of PPV values. Most of these models are based on two parameters: (i) maximum charge of explosive per delay and (ii) distance from the blast to the measuring point. Many empirical predictors have been developed based on data obtained from different mines providing different attenuation equations.[6–15] Recently, a number of works have focused on applying artificial intelligence techniques such as artificial neural networks (ANNs).[16–23]

In ornamental stone quarries, blasting is carried out in order to eliminate fractured zones and other zones where the rock mass is not of high enough quality to be of ornamental value. These blasts are carried out using small amounts of explosive. When the rock mass is very large, as in the case analyzed in this paper, it is necessary to determine the maximum charges that can be applied while ensuring that the surrounding ornamental stone will not be damaged. Currently, the technique used to avoid damaging the surrounding rock is mechanical precutting through chain saw or diamond wire (to a lesser extent, precut blasting is also used). The objective is to isolate the rock mass to be blasted. Using mechanical precutting involves some disadvantages, such as high economic cost, reduction of production rate and limitation of the total charge of explosive.

In the present work, a methodology to obtain the attenuation equation for the rock mass surrounding the blasting site is proposed.

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Besides vibration monitoring, rock mechanical tests and seismic refraction method were applied in order to obtain rock characteristics and seismic wave propagation velocity. The tests were conducted at “Alpi” marble quarry located in the town of Pinoso in the southeast of Spain.

2. Mathematical modeling of vibrations and seismic waves

Vibrations can be easily modeled using the general law of the blasting vibration attenuation equation. This law, as shown in Eq. (1), is the mathematical relationship among the peak particle velocity of ground vibration PPV (mm/s), the maximum explosive charge weight per delay (kg) and the distance between the vibration source and the observed point (m).

$$PPV = \frac{K}{D^{\beta}} Q^{\alpha} \tag{1}$$

in which K, α and β represent the influence of (i) the blast design, (ii) the physical properties of the transmitting medium, i.e., the local geology, and (iii) the site topography. They can be determined by multiple regression analysis of the measured field data, transforming Eq. (1) into a logarithmic equation:

$$\log PPV = \log K - \beta \log\left(\frac{D}{Q^{\alpha/\beta}}\right) \tag{2}$$

Eq. (2) can be simplified by definition of the scaled distance, $SD = D/Q^{\alpha/\beta}$, in which case it is reduced to

$$\log PPV = \log K - \beta \log SD \tag{3}$$

Besides the general law, several empirical equations are used in blasting monitoring to estimate the peak particle velocity. Some of the existing equations, adapted to the general law, were provided by the USBM,[24]

$$PPV = \frac{K}{D^{\beta}} Q^{\beta/2} \tag{4}$$

Langefors and Kihlström,[25]

$$PPV = \frac{K}{D^{\beta}} Q^{2\beta/3} \tag{5}$$

and the Central Mining Research Institute[26]:

$$PPV = n + \frac{K}{D} Q^{1/2} \tag{6}$$

It is important to highlight the difference between the particle vibration velocity and the propagation velocity of the seismic waves. Among the many types of seismic waves, two general categories can be identified: body waves, which travel below the surface, and surface waves, which travel across the surface. Body waves are divided into longitudinal or primary waves (P-waves) and transverse or secondary waves (S-waves). For this type of study, only body waves are taken into account. If seismic waves are considered as elastic waves, the propagation velocity of P and S waves is related to rock mass density ρ (kg/m^3), Young´s modulus E (kg/m s^2) and Poisson´s ratio ν (dimensionless) according the following formulation[27]:

$$V_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \quad V_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{7}$$

The ratio V_P/V_S is generally around 1.70. Therefore, P-waves travel faster than S-waves through the rock mass to reach seismographs first.

3. Description of study area

The Alpi quarry is located in Monte Coto, one of the most important marble mining areas of Europe. The area is within the municipality of Pinoso and belongs to the province of Alicante in the southeast of Spain. The extracted ornamental stone is a cream color stone, fine-grained, compact, with a uniform background that may show small, irregularly scattered veins slightly darker than the surrounding rock, and is known as “Crema Marfil Coto Marble”. From a geological perspective, the rock is a nummulite limestone from the Eocene and belongs to the Prebaetic System. The rock mass is massive and quite homogeneous (GSI values around 70). The mining area stretches for several kilometers and is operated by different mining companies.

Fig. 1. General view of the mine face.

The marble mass is being worked using an open cast mining method through descending benching. The mean height of the benches is 7 m. Marble blocks are extracted using diamond wire, chain saws and hydraulic and pneumatic drillers. Explosives are used only to break up zones without ornamental value. The quarry produces approximately 45.000 t/year of marble (Fig. 1).

4. Experimental procedure

This research project aims to estimate the damage criteria and site-specific law of attenuation of the rock surrounding blasting zones. Ground vibrations induced by explosives were measured by seismographs in three directions for a sufficient number of shots. Laboratory test were also conducted in order to obtain rock mechanical properties, and seismic refraction technique was applied to determine propagation velocity values of the seismic waves. The final result will be the “charge-distance law”, the relationship that determinates the maximum allowable amount of explosive at a certain distance that ensures no damage to the rock mass with ornamental value.

4.1. Ground vibration data

Ground vibrations were recorded for thirty-five blast events, considered as rights, at different distances from the blasting points. The maximum amount of explosive charge per delay and the distance between blast holes and monitoring stations were measured carefully. The three ground vibration components, transverse, vertical and longitudinal, were registered by means of three seismographs with triaxial geophones (Instantel Minimate Pro 6). Peak particle velocities, among many other data, were provided directly by the analysis software implemented in the seismograph.

For the present study, vertical blast holes were drilled with a 90 mm diameter, in 5 m high benches. Each blast-hole was charged with 1.25 kg of gelatin dynamite, ANFO to complete the charge and sand as stemming. Non-electric connectors were used to initiate the blasting. Table 1 shows the explosive charge per delay, distance to the seismograph and peak particle velocity values for some blast events.