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NUMERICAL MODELLING OF BLAST-INDUCED GROUND VIBRATIONS

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In recent years, the mining industry has dealt with a significant amount of criticism regarding the side effects of production blasting. In practice, explosive material is placed into a series of boreholes in a rock mass, and then detonated to fragment the rock so that it can be disposed or transported for further processing. The detonation of an explosive charge is a rapid and high-energy reaction which imparts shock waves into the surrounding rock mass; however, not all energy is consumed in the fragmentation process. One of the most significant side effects of explosive blasting is the generated ground vibrations, which can travel a great distance from the site. With mining sites being located closer to urban areas due to urban growth, these generated ground vibrations can easily pose a problem for residents in the form of discomfort or structural damage. The focus of this paper is on the initial development of a numerical model to characterise the propagation of vibrations in these areas with two distinct aspects. The first part is focused on modelling the vibratory source. Since detonation and rock fragmentation are highly complex phenomena, the equivalent cavity theory is applied in order to maintain a single elastic ground model. The second part deals with the development of a ground model to simulate wave propagation and estimate the level of vibrations produced. The goal of this research is to develop numerical models which can be used by mining operators to predict the ground vibrations generated depending on factors such as the blast design, site configuration and geological parameters.

Keywords: blasting, ground vibration, numerical modelling, equivalent cavity

1. Introduction

Explosive blasting has been increasingly employed in industry, for the collection of raw material or for the excavation of underground spaces. While increasing the efficiency of this process is beneficial for the site operators, the energy released during detonation is never totally consumed and inevitably leads to undesirable side effects, such as air blasts, fly rock and ground vibrations [1].

Ground vibrations are the most concerning environmental side effect of blasting due to their long propagation distances (several hundreds to thousands of meters) and the difficulty in controlling them [2]. Due to the rapid expansion of urban areas in recent years, blasting sites are often located close to such zones and the blast-induced vibrations can lead to discomfort to residents or structural damage [3].

In order to accurately characterize these vibrations, it is essential to understand and characterize the blasting source. The present work employs the equivalent cavity theory which has proven to be useful in the past [4]. This source is then coupled to a numerical ground model for the simulation of wave propagation in the ground in order to estimate the level of vibration in the surroundings of a blasting site.

As part of the initial research stages, this paper focuses on the comparison of several representations of the source as a time-dependent pressure applied on a blasthole wall, using the equivalent cavity theory.

2. The blasting process

Explosive blasting is the controlled detonation of explosives in order to fragment a certain quantity of rock. To undertake this process, several boreholes are drilled into the rock mass and then explosive material is placed in each hole. These explosives are then wired to a detonator and triggered from a safe distance. After the blast, the fragmented rock is retrieved and disposed or transported to be used for further processing. The blasting phenomenon has many variables, such as the explosive type and amount, the blast sequence, the geology of the site, etc..

During a blast, the ground can be characterized into different zones [5] whose radii depend on the blast design and the site geology and geometry. The blast zone is the location where the detonation takes place. The detonation produces a rapid and stable chemical reaction which propagates through the cavity at the Velocity of Detonation (in the region of thousands of meters per second) and produces high temperature and pressure gas [6]. This detonation generates a shock wave which propagates into the surrounding rock mass.

Directly surrounding the blast is the near-field area; in this region, the rock experiences heavy damage through shearing as well as gas expansion through new and existing cracks, which leads to fragmentation and plastic deformation [7] which are the useful effects of blasting. From a vibration point of view, this zone is characterized by a rapid non-linear attenuation of the magnitude of the ground waves.

Once the waves have been attenuated to the point where they only cause elastic deformation, the second region begins, known as the far-field area. In this zone, the ground vibrations behave as elastic waves and no not induce any damage [8]. This zone is the most critical regarding undesirable ground vibrations since they can travel several hundreds of meters and cause discomfort or damage in the surrounding urban areas.

3. Ground vibrations

Like other human activities such as railway [9, 10] or road traffic [11, 12], explosive blasting generates several types of ground waves. Rayleigh waves (R-waves) propagate along the surface of the ground and carry the most significant part of the released energy ($\sim$67$\%$) [13]. Body waves propagate outwards in all directions from the source and can be categorized between longitudinal pressure waves (P-waves) and shear waves (S-waves), carrying respectively about 8$\%$ and 25$\%$ of the energy, and whose velocities (C_P and C_S, respectively) in an elastic medium depend on the material properties as given in Eq. (1) [14]:

$$C_P = \sqrt{\frac{2G(1-\nu)}{\rho(1-2\nu)}} \qquad\qquad C_S = \sqrt{\frac{G}{\rho}} \tag{1}$$

where ρ is the density of the material, G is the shear modulus and ν is Poisson's ratio.

The body waves in the ground can reach velocities up to 6000 m/s. The complexity of the propagation in the far-field can vary significantly depending on the geological factors such as material or discontinuities as illustrated in Fig. 1.

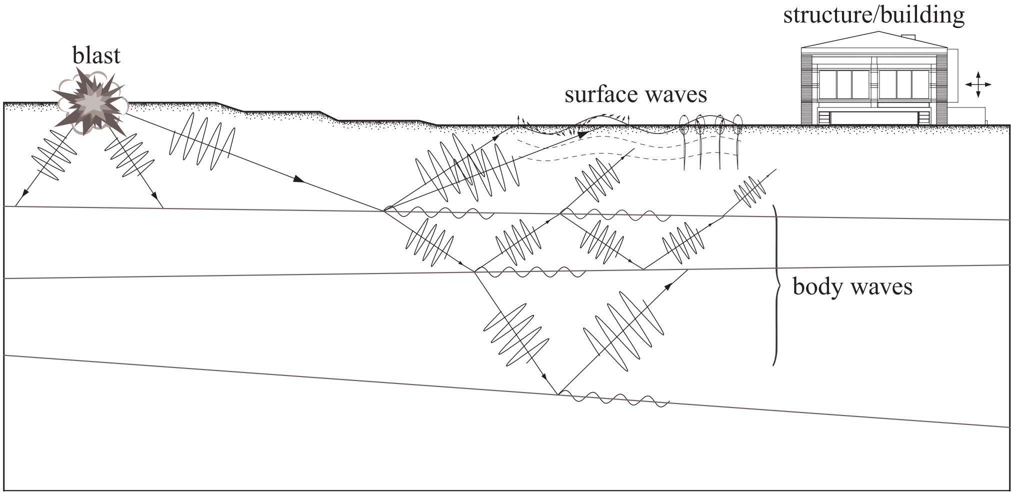

Figure 1: Illustration of the complexity of body wave propagation, from [16].

Several approaches exist to predict the magnitude of blast-induced ground vibrations and the most widely used approach is the charge weight scaling technique given in Eq. (2):

$$\mathrm{PPV} = K\left(\frac{d}{Q^n}\right)^{-B} \tag{2}$$

which gives the Peak Particle Velocity (PPV) of the resulting ground vibrations at a distance d from the source, Q is the charge weight, and the constants K and B are related to the site configuration and blast design, respectively [15].

This technique has the advantage of being inexpensive compared to other approaches. However, only the PPV is obtained, with no information about the frequency content of the vibrations [16]. The approach also does not take into account the geological configuration of the far-field which can have a significant influence on the wave propagation.

In order to obtain the complete picture of ground wave propagation, a numerical model should be developed.

4. Equivalent cavity theory

Blasting and rock fragmentation are highly complex phenomena and the development of a numerical model detailing these processes is a difficult and expensive alternative. To avoid these complexities, the equivalent cavity approach is used, which consists of replacing the actual blasthole(s) and near-field area by an "equivalent" blasthole characterized by its own radius and wall pressure [4]. The region in which the waves do not behave linearly is contained inside the equivalent cavity and allows for only an elastic ground model corresponding to the far-field region.

It is possible to employ either a spherical or a cylindrical cavity. However, a spherical cavity will tend to neglect the contribution of shear waves and thus, a cylindrical cavity is chosen for this model. The radius of the elastic zone (where there are no residual deformations in the ground) is given in Eq. (3) [17]:

$$r_{eq} = \frac{\sqrt{C_P}}{10}\sqrt[3]{Q} \tag{3}$$

Existing models from previous studies use an equivalent cavity radius equal to nine times the radius of the actual blasthole [18, 19].

The pressure of the equivalent cavity can be calculated from Eq. (4) [20]:

$$P_{eq,max} = kP_{B,max}\left(\frac{r_c}{r_{fr}}\right)^{\frac{2+G}{1-G}}\left(\frac{r_{fr}}{r_{nf}}\right)^{\frac{2-G}{1-G}} \tag{4}$$

where r_{fr} is the radius of the fragmented zone, r_{nf} is the radius of the permanently deformed zone, G is the shear modulus, k is a factor depending on the number of blasts (k = 1 in the case of a single blasthole) and $P_{B,max}$ is the actual peak blasthole pressure which can be obtained from Eq. (5) [21]:

$$P_{B,max} = \frac{\rho_0(\mathrm{VoD})^2}{2(\gamma_{CJ}+1)}c^{2\gamma_{CJ}} \tag{5}$$

where ρ_0 is the density of the explosive, VoD is the velocity of detonation, γ_{CJ} is the coefficient of adiabatic expansion and c is the coupling factor (ratio between the radius of the charge and radius of the blasthole). In the case of a fully-coupled blast, $\gamma \simeq 3$ and c = 1 and the blasthole pressure is obtained from Eq. (6) [21]:

$$P_{B,max} = \frac{\rho_0(\mathrm{VoD})^2}{8} \tag{6}$$

5. Ground Modelling

For this study, the finite element method is used to simulate ground wave propagation. This approach has proven to be effective in the field of ground vibration prediction in previous studies, due to its versatility and ability to represent any kind of geometry [22].

As mentioned previously, the velocity of the ground waves can amount to several thousands of meters per second. Also, since blasting is a rapid process (~10 μs), the time step used for simulations must be chosen accordingly. The Courant-Friedrichs-Lewy criterion gives the maximum element size depending on the maximum wave velocity and the time step in order to obtain accurate results (Eq. (7)) [23].

$$L_{FE} = v_{max}\Delta t \tag{7}$$

For this study, the size of the finite elements is around 1 cm. It is apparent that using a three-dimensional model with dimensions over several hundreds of meters would be computationally expensive, and as an alternative, an axisymmetrical model is used, which has the advantage of being able to represent shear waves which have a significant importance in blasting. An elastic homogeneous isotropic material (limestone) with viscous damping is used. The model has a length of 300 m, a height of 20 m, and the cylindrical equivalent cavity has a radius of 1 m and a depth of 5 m. A schematic representation of the model is presented in Fig. 2 and the material properties are shown in Table 1.

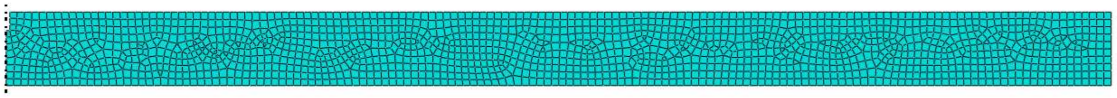

Figure 2: The axisymmetric finite element model developed (the mesh size is increased for visibility).

Table 1: Material properties used for the ground model (limestone).

Density [kg/m^3]	Young Modulus [MPa]	Poisson's Ratio [-]	Viscous Damping [s]
2600	77	0.25	4×10^{-4}

6. Source function comparison

This section is dedicated to the investigation of the influence of source function shapes on the magnitude of the predicted ground vibrations.

The source function of the numerical model is represented as a uniform time-dependent pressure applied to the equivalent cavity surface. Equation (8) illustrates that the blasthole pressure is expressed as the product of the peak pressure value and and amplitude shape function.

$$P(t) = P_{max} \times A(t) \tag{8}$$

Equation (9) gives a realistic formula for the amplitude function [24]:

$$A(t) = exp\left(1 - \frac{t}{t_0}\right)\frac{t}{t_0} \tag{9}$$

where t_0 is the rise time.

The drawback of using such a profile is the large number of points required to accurately replicate the function. Alternatively, selecting a simplistic shape function allows for the use of a larger time step, resulting in increased computational efficiency.

To investigate this possibility, the results obtained with a realistic source amplitude function were compared with simpler profiles. The first alternative is a triangular function with similar rise and decay times as the realistic profile and the second was a square function with a time window equal to twice the rise time of the realistic function. The three source profiles used are presented in Fig. 3.

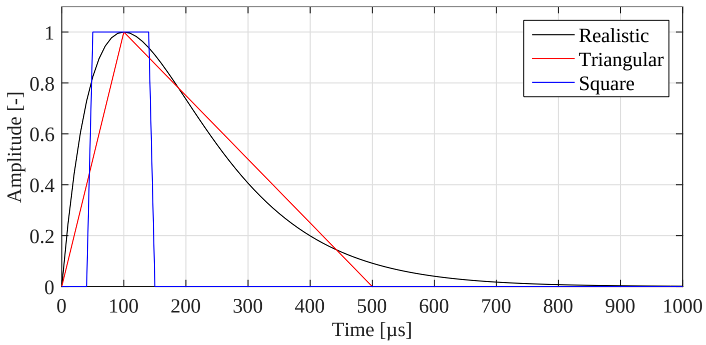

Figure 3: Illustration of the pressure function shapes used.

The comparison was made based on the Peak Particle Velocity (PPV), which is the maximum absolute value of a signal and is the recommended indicator for the analysis and comparison of the effects of ground vibrations on people and structures [25].

Figure 4 presents the predicted PPV of the vibrations every 25 m from 50 - 275 m from the source, in the radial and vertical directions. The triangular source function appears to yield satisfying results compared to the realistic profile, which is no surprise given their similar shapes. The square function, however, gives poor results compared to the other two amplitude profiles.

These discrepancies are explained by the fact that the surface area under each curve on Fig. 3 is directly proportional to the total energy of the source. Therefore, it is apparent that the square profile used presents much less energy than the other two functions.

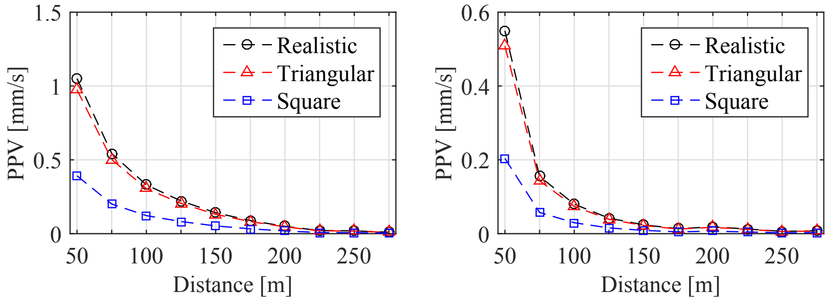

Figure 4: Radial (left) and Vertical (right) PPV obtained with the realistic, triangular and square source profiles.

Another comparison was made using a square profile which has the same surface area as the realistic function from Eq. (9). Figure 5 shows both the realistic and the new square amplitude profiles.

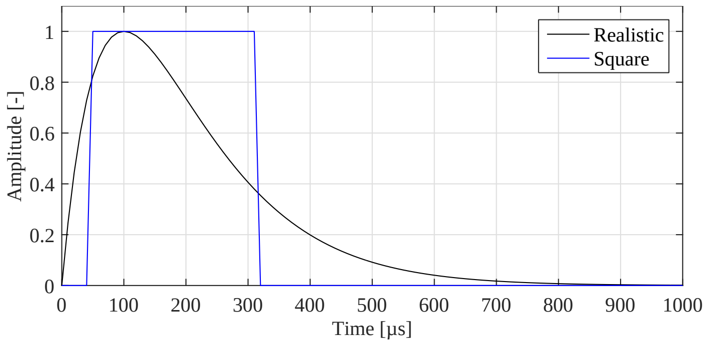

Figure 5: Illustration of the realistic and new square profiles. Both profiles present the same surface area.

As shown in Fig. 6, the results obtained from the realistic and adjusted square functions are remarkably close. The variation between the two sets or results both for the radial and vertical PPV do not exceed 5%. This confirms that the realistic amplitude function can reasonably be substituted for a simpler profile while keeping an acceptable accuracy as long as the peak amplitude and the total energy are equal.

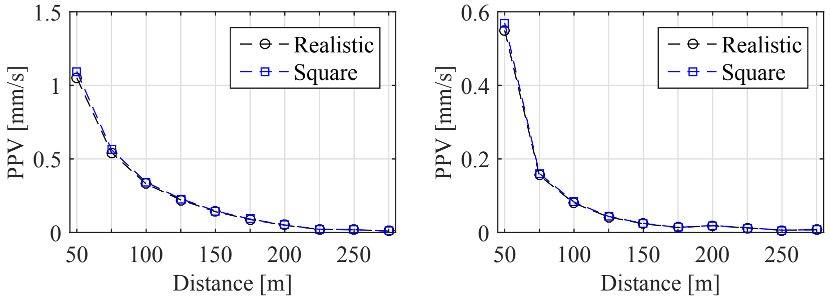

Figure 6: Radial (left) and Vertical (right) PPV obtained with the realistic and adjusted square source profiles.

7. Conclusions

This paper outlines the initial stages of a research project aimed at the numerical prediction of blast-induced ground vibrations. Blast-induced wave propagation is a complex and rapid phenomenon which can travel long distances, resulting in numerical models with high computational times. Therefore, the first steps were focused on the investigation of approaches to reduce the computational complexity of such models. This was performed by developing an axisymmetrical homogeneous elastic ground model using the equivalent cavity theory and lowering the time step requirements by using simpler source amplitude function profiles.

The results presented in this paper show that simpler source function shapes can reasonably be employed to increase the time step and thus reduce computational times, as long as the substitute profile has the same peak value and energy as the original function.

Further steps include an investigation regarding the mesh size, especially in the proximity of the blasting source, followed by a more accurate representation of the ground in order to take into account the geological configuration (e.g., layers, cracks). The later objectives include the addition of a possibility to simulate several blasts in a sequence, which is mostly how blasts are performed in mining. This will lead to a versatile numerical model which can be used to predict the level of ground vibrations in the neighbourhood of a blasting site.

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