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Coupling of two methods, waveform superposition and numerical, to model blast vibration effect on slope stability in jointed rock masses

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ABSTRACT

Drilling and blasting is a major technology in mining since it is necessary for the initial breakage of rock masses in mining. Only a fraction of the explosive energy is efficiently consumed in the actual breakage and displacement of the rock mass, and the rest of the energy is spent in undesirable effects, such as ground vibrations. The prediction of induced ground vibrations across a fractured rock mass is of great concern to rock engineers in assessing the stability of rock slopes in open pit mines. The waveform superposition method was used in the Gol-E-Gohar iron mine to simulate the production blast seismograms based upon the single-hole shot vibration measurements carried out at a distance of 39 m from the blast. The simulated production blast seismograms were then used as input to predict particle velocity time histories of blast vibrations in the mine wall using the universal distinct element code (UDEC). Simulated time histories of particle velocity showed a good agreement with the measured production blast time histories. Displacements and peak particle velocities were determined at various points of the engineered slope. The maximum displacement at the crest of the nearest bench in the X and Y directions was 26 mm, which is acceptable in regard to open pit slope stability.

1. Introduction

Explosives are a worthy and indispensable source of energy required for fragmentation, excavation and displacement of a rock mass. During rock blasting, an enormous amount of energy in terms of pressure (up to 50 GPa) and temperature (up to 5000 K) is released [1,2]. Despite significant developments in explosive technology, the explosive energy efficiency has not made any substantial progress. Only a small fraction of the energy (less than 30%) is used for the breakage and displacement of the rock mass, while the remainder of the energy is wasted in undesirable effects such as ground vibrations, fly rock, air blast, lights, and back breaks [3].

In large open pit mines where annual production exceeds tens of millions of tons of ore, a large quantity of explosive is consumed in each blast round in order to fracture and displace the rock mass. The blast vibrations from these mines may be detrimental to the environment when there is dense population in the vicinity [4,5]. Furthermore, excess ground displacement may damage the free rock face and generate back break, which reduces stability of mine walls, creates problems while drilling the next round of blasts, and generates over size boulders. This adversely affects the mine economics and the socio-economic development of the surrounding area [6].

A blast-induced shock wave is simultaneously attenuated by material damping and geometrical spreading when it propagates through an intact medium. However, when a shock wave propagates through a jointed rock, its attenuation is also affected by the joint surface characteristics, the rock wave impedance of both walls of each discontinuity, the angles between the discontinuities, and the direction of propagation.

Several methods allow for the prediction of ground vibrations caused by mine blasting operations. These methods can be described as empirical, artificial intelligence, waveform superposition, and numerical.

Perhaps the most widely used method is the so-called "scaled-distance" method, based on the empirical principle that states: "peak particle velocity (PPV) at a point is inversely proportional to the distance from the blast and shows a square root dependence on charge weight" [7]. Many different relations have been proposed for the prediction of peak particle velocity (PPV) [8–19]. All of these relations were determined using regression methods

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on measured PPV data and scaled distance. These predictors were then employed to estimate the PPV at any point. These estimates were mainly based on two parameters: maximum charge per delay and distance from the blast to the measuring point. Geological type, geotechnical type, explosive type, and blast geometry have not yet been incorporated into this type of relation. Because the number of influencing parameters is high, artificial neural networks (ANN) and several artificial intelligent methods (AIM) were developed to predict rock blasting vibrations. Many researchers used ANN and support vector machines to estimate the PPV and air blast [20–27]. Empirical methods and AIM only provide an estimation of the maximum amplitude of particle velocity and give no information about the complete seismic waveform.

Waveform superposition modeling that includes all parameters, i.e. modeling of the complete seismic waveform produced by a blast, would overcome the weaknesses of empirical and AIM methods. Waveform superposition modeling, a combination of field measurements of an elementary signal and simulations by signal summation, was originally reported by Anderson et al. (1985) and Hinzen (1988) [28,29]. Blast vibrations are simulated at a location of interest around a single-hole shot, based upon the real blast vibrations measured at that location. Therefore, changing the location, i.e. the distance and direction from the hole, results in a new measurement and simulation. Over the past years, many developments in wave superposition were carried out. Blair (1999) studied the influence of some variables such as scatter of delay time, weight of explosive per delay, transmitting medium and random fluctuations on vibration signatures on vibration using a Monte Carlo model [30]. Also, Blair (2011) reviewed all of these developments [31]. The waveform superposition method was used to control the blasts carried out in the Val d'Azergues cement factory in France, and was also validated to simulate blasting vibrations in Sar Cheshmeh copper mine in Iran [32,4].

Numerical methods can calculate blast-induced seismic waveforms at any distance and direction from the blast by employing the mechanical properties of the medium. Such methods use measured velocity time history of the blast as input and simulate the propagation of blast waves within a rock mass. In the regions near the blast in large surface mines where vibration intensity is too high, it is not possible to measure total blast vibrations by conventional instruments. Therefore, modeling of production blast vibrations with numerical methods is difficult at points in the vicinity of the blast.

The coupling of two methods, waveform superposition and numerical, is a logical approach to overcome this problem. Firstly, production blast vibrations are modeled based upon measurements of a single-hole shot vibration at a location near the blast. Modeled time history of the blast is then used as a boundary condition in order to numerically simulate the vibration at any given point within the rock mass. In this paper, UDEC is used to simulate blast vibration throughout the rock mass at Gol-e-Gohar iron mine, based upon production blast vibrations measured at a point near the blast. It should be noted that waveform superposition model used in this study is in its initial form and does not take into account the influence of scatter of delay time, random fluctuations on blasthole signatures, and etc, on vibration. In fact, the similitude on blasthole signatures is a basic assumption of linear superposition method, if the blasthole signatures are significantly different, we cannot use linear superposition method.

1.1. The waveform superposition method

The waveform superposition method is based on the principle that the measured time history at a given point is the result of linear superposition in the time domain of the time histories emitted by each of the single-hole charges. Due to the linearity of the problem and the superposition principle in which any distributed source can be described as the sum of multiple point sources, there is no additional difficulty in modeling a very complicated source. In addition to spectral amplitudes, all phase effects from the superposition are included in the synthetic seismogram.

The procedure begins by drilling a single hole and loading it by a charge similar to the holes of the actual blast pattern. The displacement or velocity time history is then measured at locations where the ground vibrations are to be predicated or reduced. The next step is to simulate the complete blast seismogram at specific locations by superposition method. The single assumption for the medium, is that the paths of waves for the single-hole shot and the production blast are the same.

1.2. The numerical method with UDEC

Rock mass fractures consist of surfaces of various sizes ranging from microcracks to faults. These structures or discontinuities make rock masses discontinuous, inhomogeneous, and anisotropic. Discontinuities can control the mechanical and hydraulic behavior of a rock mass and dominate its dynamic and static response. The representation of existing structures within a rock mass for numerical modeling purposes is very difficult. Major fractures such as faults can be treated as single elements in a numerical model as they are few in number. However, minor fractures such as joints are often ignored because of their large quantity. Thus, the rock mass is treated as a continuous medium with equivalent properties. Various methods such as the finite element method (FEM), the boundary element method (BEM), and the finite difference method (FDM) were used when the number of joints and displacements was small [33–38]. Alternatively, the distinct element method (DEM) was specifically designed to solve computations within discontinuous media [39]. In this method, a rock mass is represented as an assemblage of discrete blocks and joints are represented as interfaces between blocks. Blocks can be moved, rotated, or deformed individually. The interfaces may also be compressed, opened, or slipped. Therefore, DEM can handle non-linearity problems that may arise from a large displacement, rotation, slip, or separation of the medium. A large number of joints can be considered without difficulty in modeling and computation.

The discontinuities of a rock mass have a great effect on its response under a dynamic load such as rock blasting. While the effects of single joints on wave transmission were investigated by different authors, very few studies on the wave propagation through jointed rock masses were performed [40–50]. Concerning the effects of multiple fractures on wave propagation, a simplified approach was adopted that deals with multiple reflections by assuming a short wavelength approximation [51–53]. The universal distinct element code (UDEC) was used to model wave propagation across fractured rock masses and their response to dynamic loads [54–60]. In comparison with theoretical and experimental methods, numerical modeling has proven to provide an economic approach with acceptable accuracy to study dynamic problems of rock masses.

2. Case study

2.1. The Gol-E-Gohar iron ore mine

The Gol-E-Gohar iron ore area is located 55 km southwest of Sirjan and 325 km northeast of Shiraz, between 55°15′40″E and 55°22′33″E longitudes and 29°03′10″N and 29°07′04″N latitudes, at an altitude of 1740 m above sea level (Fig. 1). This area contains approximately 1135 million tons of geological iron ore distributed