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Simulation of bench blasting considering fragmentation size distribution

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ABSTRACT

Reasonable simulation of the bench blasting has great significance on designing of rock blasting, and the proper consideration of blasting fragmentation size has strong influence on the simulation accuracy. This paper presents a new approach based on the three dimension Distinct Element Code (3DEC) method (Itasca Consulting Group, Inc. 2003) to model the dynamic cracking and casting process of bench blasting with reasonable consideration of blasting fragmentation size. Firstly, an equivalent blasting load consisting of the stress wave pressure and the detonation gas pressure was introduced into the 3DEC model, and it was applied on the outer boundary of blast-induced crushed zone to guarantee the simulation efficiency. Then, the whole numerical model was divided into discrete blocks by several sets of artificial joints to enable the rock to crack, fragment and cast, and at last form a muck-pile, and the artificial joints were assigned with the same mechanical parameters to rock mass itself to avoid the impact of them on stress wave propagation. Different from general discrete schemes which discretize the model with uniform blocks or random balls, the discrete size adopted in this paper gradually increases with distance from the blast source according to the Harries' model (Harries, 1973). At last, the proposed method was examined and verified by simulation of a blasting crater comparing to the field experiment, and then applied to explore the casting process of bench blasting. The simulated muck-pile profile agrees well with the result predicted by the traditional ballistics theory. The simulation also indicates that the casting distance of bench blasting increases with the bench height (*H*), but decreases with the burden distance (*W*), while the height of muck-pile increases with both the *W* and *H*. So the muck-pile profile of bench blasting is more sensitive to the *W* than *H* after consideration of rock fragmentation size, and the optimization of blasting designs can be significantly enhanced by utilizing the full capabilities of this approach.

1. Introduction

The bench blasting has been widely used in the mining, construction of the hydropower engineering and traffic engineering all over the world [1], and the fragmentation size distribution is an important parameter for prediction of the profile of bench blasting muck-pile, which not only reflects the rationality of blasting design, but also influences the transportation efficiency of rocks and mining/excavation economic benefit directly [2].

Based on the statistics of the field tests carried out by researchers from different countries in the past 50 years, several empirical or semi-empirical formulae have been established for bench blasting design and the prediction of rock fragmentation size distribution [1–4]. But the application of these methods was limited for the variation of the engineering geology conditions and blasting configurations. Because the field bench blasting tests are very expensive and time consuming, the numerical simulation method has become a powerful means for researching of the muck-pile profiles of bench blasting and their influencing factors, especially the Discrete Element Method (DEM) [5,6]. Compared with commonly used continuous numerical method (such as the finite element method (FEM) including the LS-DYNA [7], ANSYS (a FEM software developed by the ANSYS Inc), ABAQUS [8] and so on), the DEM is more suitable for simulation of cracking and casting process for its capability of modeling the large deformation, failures, motion and rotating or dispersing of elements during blasting [5,6,9,10].

The main branches of the DEM family include the discontinuous deformation analysis (DDA) developed by Shi in 1988 [11], the particle flow code (PFC) proposed by Cundall and Strack in 1999 [12] and several kinds of the finite-discrete element method [9].

Based on the DDA code, Mortazavi and Katsananis [13] introduced a dynamic blast-hole expansion model to consider the effects of the physical properties of the intact rock, blast geometry and

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existing discontinuities, and the distribution and orientation of pre-existing discontinuities. Ning et al. [14] further extended the DDA code in the simulation of blast-induced rock mass failure by tracking the blast chamber volume dynamically, and an instant explosion gas pressure was derived from the chamber volume using a simple polytrophic gas pressure equation.

For the PFC method, the explosion was modeled as a time-varying pressure applied at the edge of a cylindrical region 3 times the diameter of the original borehole to account for the region of crushed rock which would develop near the center of the detonation [15,16].

Minchinton and Lynch [17] used the combined finite-discrete element program MBM2D to simulate dynamic stress field development, and crack penetration as well as the motion and stacking of the rock fragments. The Distinct Motion Code (DMC) has also been developed for modeling gas flow and rock motion during blasting [18].

Although DDA and PFC and other discrete or finite-discrete methods have achieved great success in blasting simulation, there are also some limitations. For example, the treatment of natural joints in DDA need to be further improved because the joints in DDA are rigid [9]. The methods of determining the rock mechanics parameters in PFC and MBM2D and DMC are very complex, and it is difficult to control the joints attitude [19]. But the discreteness of the numerical model is an important part in discontinuous numerical methods, which probably affects the simulation result [20]. The rock mass was usually dispersed into uniform blocks in common blasting simulation models, as there are no appropriate methods for determining the distribution of joints [5,6,9,10].

In addition, except for FEM and DEM, all kinds of extended FEMs and mesh-free methods have also been developed for civil engineering applications [21–23]. In these methods, the numerical model is discretized by scattered set of points, which can allow interpolation of field variables to be accomplished at a global level without meshes [24]. These methods are ideal for simulation of fracture problems and large deformation problems, but much higher CPU time than the FEMs should be consumed [22–26].

The 3DEC is also a numerical program based on the DEM [9,27]. Compared with the DDA, PFC and mesh-free methods, the 3DEC is more flexible in numerical model discreteness and has a strong advantage to simulate deformation and failure of jointed rock mass [19]. The 3DEC has been widely used to study blast wave propagation in jointed rock masses [28,29], but it has not been fully explored for simulation of formation of blasting muck-pile and its profile.

In this paper, an equivalent blasting load considering the stress wave pressure as well as the quasi-static load of detonation gas was introduced into the 3DEC model, and it was applied on the outer boundary of blast-induced crushed zone to improve the simulation efficiency. The numerical model is divided into discrete blocks by several sets of artificial joints with the same mechanical parameters to the rock mass itself, and the discrete size gradually increases from the blast source to faraway according to the theory of Harries on the distribution of blasting fragmentation sizes [30]. The proposed discrete method was verified by simulating the rock cracking and casting process of a blasting carter, and the results are in good agreement with the field test. Then the method was adopted to simulate the bench blasting, and the mimetic muck-pile and the characteristic parameters of the profiles are investigated in this paper.

2. Blasting simulation with the 3DEC

2.1. Strategy of blasting simulation with the 3DEC

The rock mass is modeled as an assemblage of 3D deformable blocks in 3DEC, and the boundaries of these blocks are regarded as the discontinuities, which can be either natural joints or artificial joints that do not exist in the real geometry. Under the action of blasting load, the rock mass will be fragmented into individual block along their boundaries to form a muck-pile at last. So, there are two main strategies need to be adopted for blasting simulation with the 3DEC code:

(1) The equivalent blasting load should be introduced into the model to guarantee and increase the simulation accuracy. It was applied on the inner boundary of the blasting-induced fracturing zone (or outer boundary of the blasting crushed zone) to ignore the complicated process of explosive detonation and rock crushing to save computing resources and to improve calculation efficiency further. This simplification method has been proved to be feasible to model the dynamic response of the rock mass subjected to blasting load by indoor experiments and field monitoring [31], and the specific process of calculating the equivalent blasting load will be described in the Section 2.2 subsequently.

(2) In order to give full play to the advantages of the 3DEC method, the numerical model should be divided into discrete blocks by several sets of artificial joints to enable the large deformation, fracturing, rotation, and casting of rock blocks during blasting simulation. The rock blasting fragmentation size also can be considered by adopting a special fragmentation size distribution model. Then, the muck-pile accumulation of blocks can be reasonably reproduced numerically. The mechanical parameters of the artificial joints are assigned to be the same with the rock mass itself, and its influence on wave propagation will be discussed in Section 2.3.

Obviously, the most important input parameters for bench blasting simulation, the equivalent blasting load and its time history, and the existence of artificial joints all have strong influence on the simulation results. The research of Vu-Bac et al. [32,33] indicated that the influence of the several critical parameters on the whole performance of simulated material should be carefully examined and assessed. So, a numerical experiment and a field test have been conducted to investigate the influence and to verify the input parameters.

2.2. The equivalent blasting load

2.2.1. Detonation process

In order to simulate the casting process of bench blasting with the 3DEC, the equivalent blasting load should be introduced into the model for no explosive material can be specified in this software. So, the explosive detonation process should be briefly reviewed first.

During rock blasting, after the detonation of explosive, both the exploding-induced shock wave and sustaining pressure of detonation gases are exerted immediately on the wall of blast hole. The pressure is much higher than the rock mass strength, thus a thin crushed zone (as shown in Fig. 1) is developed around the blast hole, in which the rock mass has been extensively broken and behaves like a fluid [34]. When the shock wave passes through the crushed zone, most energy is consumed on rock fragmentation, and then it converts to the less destructive stress wave. As the stress wave and the permeation of gases at high pressure encourage the initiation and propagation of radial cracks, a fractured zone is formed outside the crushed zone [35]. With further attenuation, the stress wave converts to the seismic wave. The seismic wave could not cause rock failure, but only lead to elastic vibration of the rock until the energy is absorbed completely [36].

Because the main purpose of the simulation carried out in this paper focuses on the blast-induced casting of rock fragmentation and formation of muck-pile, the blast-induced crushing process can