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Journal of University of Science and Technology Beijing
Volume 15, Number 3, June 2008, Page 209

Mineral

Numerical simulation of parallel hole cut blasting with uncharged holes

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(Received 2007-05-30)

Abstract: The cavity formation and propagation process of stress wave from parallel hole cut blasting was simulated with ANSYS/LS-DYNA 3D nonlinear dynamic finite element software. The distribution of element plastic strain, node velocity, node time-acceleration history and the blasting cartridge volume ratio during the process were analyzed. It was found that the detonation of charged holes would cause the interaction of stress wave with the wall of uncharged holes. Initial rock cracking and displacement to neighboring uncharged holes become the main mechanism of cavity formation in early stage.

Key words: parallel hole; cut blasting; cavity formation; numerical simulation

1. Introduction

Cut with parallel holes is widely used in tunneling and shaft sinking operations in different types of rock masses because of the simplicity in drilling and planning and the possibility of obtaining high efficiency of blast holes. However, experiences show that the fragmentation and efficiency of any tunneling practice are dominated by the performance of those cut holes to a certain extent because these holes are supposed to produce new free surfaces and space for detonation of blast holes initiated thereafter [1].

Tunneling with parallel cut holes means that the rock between uncharged holes and charged cut holes is to be fragmented by stress wave and expansion of the gaseous products from detonation of charged cut holes and to be put forward to the uncharged holes and the original surface, before the cut is pulled out as a result. This cut will perform as free faces and space to which the helpers will blast. This shows that the rock fragmentation from the helpers will be controlled by the performance of cut holes, and affects the pulling of contour holes consequently.

In an effort to improve blast design and control fragmentation of tunneling operations, many researches on tunneling with parallel cut holes have been conducted in recent years. The fragmentation mechanism, parameter selection, and fragmentation simulation of parallel hole cut blasting were studied and discussed by different researchers [2-7]. Through mechanical model study and numerical analyses, Zhang *et al.* found that area of empty holes needed to be determined with the depth of charged holes in parallel hole cut blasting [4].

Because of the high temperature and high pressure of the instant process of explosive detonation, difficulties still exist for technical experimental methods to assure blast results with effectiveness and reliability. Therefore, an effort to estimate the reasonability of a cut blast design and to optimize the selection of blasting parameters, such as drill pattern and charge quantity, was made. To achieve the above, computer simulation with ANSYS/LS-DYNA 3D nonlinear dynamic finite element software [8] and the process of parallel hole cut blasting with uncharged holes, based on blasting dynamics, were carried out. The results of the research may serve as a reference for stress analyses and parameter selection of parallel hole cut blasting with uncharged holes.

2. Constitutive model and state equation of cut blasting

The media involved in cut blasting include rock, explosives, gaseous products from explosive's detonation, stemming material, the air in uncharged holes,

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and the air outside of the face. Thus, constitutive models for each of the media need be set up and the model matching method of the multiphase system needs be selected.

ANSYS/LS-DYNA, a finite element software, can be used to analyze nonlinear dynamic problems. Two methods, *i.e.* the Lagrange method and arbitrary Lagrangian Eulerian (ALE) method are available for liquid-solid matching analyses with ANSYS/LS-DYNA. Element mutation can hardly be avoided as it is applied in numerical calculations of large deformation problems, especially, when elements are unevenly distributed. Therefore, the ALE method is selected, which can fairly deal with possible element mutation during the process of cut blasting of the multiphase media system, and multiphase media matching problems can be solved more effectively.

2.1. The HOLMQUIST-JOHNSON-COOK constitutive model of rock

The use of the HOLMQUIST-JOHNSON-COOK constitutive model makes it possible to simulate high stress and large strain and simulate the pressure produced from gas expansion of a dynamic impact process in concrete and rock. Volumetric strain, stress state of fractured area, and damage within the media can all be described with the pressure equation of the model [9].

Because damage in ordinary dynamic circumstances, such as the cut blasting, is caused generally by effective plastic strain, the HOLMQUIST-JOHNSON-COOK constitutive model is applied and its state equation can be written as follows:

(1) State equation for loading and unloading in linear elastic stage.

$$p = \mu K_e \tag{1}$$

where μ is the standard volumetric strain as $\mu=\rho/\rho_0-1$, ρ and ρ_0 are the density and original density, respectively; $K_e = p_c/\mu_c$, p_c and μ_c are the uni-axial compressive strength and volumetric strain at crushing, respectively.

(2) State equation for loading in plastic transferring stage.

$$p = p_c + \frac{(p_1 - p_c)(\mu - \mu_c)}{\mu_{p_1} - \mu_c} \tag{2}$$

where p_1 is the stress at solidification under impact, μ_c is the volume strain at solidification as $\mu_c = \rho_g/\rho_0 - 1$, where ρ_g is the grain density as there are no fissures in the media, and μ_{p_1} is the volume strain at final crushing as $p=p_1$.

(3) State equation for unloading in plastic stage.

$$p - p_{max} = \left[(1-F)K_e + FK_1\right](\mu - \mu_{max}) \tag{3}$$

where F is the factor of interpolation as $F = (\mu_{max} - \mu_c)/(\mu_{p_1} - \mu_c)$, K_1 is the volumetric plastic modulus, μ_{max} and p_{max} are the maximum volumetric strain and the maximum pressure before unloading, respectively, and μ_{p_1} is the volumetric strain as $p=p_1$.

(4) State equation for loading in ideal solid stage.

$$p = L_1\bar{\mu} + K_2\bar{\mu}^2 + K_3\bar{\mu}^3 \tag{4}$$

where $\bar{\mu}$ is the revised volumetric strain as $\bar{\mu} = (\mu - \mu_1)/(1+\mu_1)$; K_1, K_2, and K_3 are constants and equal to 127, −216, and 257 GPa, respectively, where μ_1 is the volumetric strain at solidification.

(5) State equation for unloading in ideal solid stage.

$$p - p_{max} = K_1(\bar{\mu} - \bar{\mu}_{max}) \tag{5}$$

where $\bar{\mu}_{max} = (\mu_{max} - \mu_1)/(1+\mu_1)$.

Mechanical properties of the rock and parameters of the state equations are listed in Tables 1 and 2, respectively.

Table 1. Mechanical properties of the rock

Density / (g·cm^{-3})	Elastic modulus of shearing / GPa	Elastic modulus / GPa	Poison's ratio	Internal energy ratio / (kJ·g^{-1})
3.217	18.6	46	0.15	1.267

Table 2. Parameters of the state equations

μ_{pc}	P_c / GPa	P_i / GPa	μ_{pi}	T / GPa	K_e / GPa
0.006	0.217	0.65	0.2	0.032	12

In Table 2, p_c is the compressive stress in rock, p_i is the initial ground stress, μ_{pc} is the volumetric strain corresponding to p_c, μ_{pi} is the volumetric strain corresponding to p_i, and T is the maximum of statically indeterminate tensile stress.

2.2. Model of explosive's detonation

The model *MAT_HIGH_EXPLOSIVE_BURN and the state equation Jones-Wilkins-Lee (JWL) for explosives are used to describe the performance and characteristics of explosive's detonation [8]. The state equation JWL can give an accurate description of the characteristics of the explosion products in terms of pressure, volume, and energy. The state equation is applied together with the model, thus the pressure of the explosion products is defined as a function of relative volume and internal energy:

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_0}{V} \tag{6}$$