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Analysis of damage mechanisms and optimization of cut blasting design under high in-situ stresses

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ABSTRACT

During excavation using the cut blasting method in deep rock masses, there are difficulties resulting from the in-situ stress influences. This study uses numerical simulation methods to assess the causes of the difficulties encountered in cut blasting. In order to overcome this difficulty, the Riedel–Hiermaier–Thoma (RHT) model in the LS-DYNA software was employed. In the simulation, the parameter determination for the RHT model was first carried out based on existing experimental data. Additionally, the existing blasting experiment was used to verify the determined parameters of RHT model. Second, the RHT model was adopted to investigate the damage mechanisms of cut blasting under different hydrostatic pressures and different lateral pressure coefficients. The simulation results indicate that the main causes of the complications arising in deep rock mass excavation are resistance to in-situ stresses and anisotropy in the damage propagation direction. Third, in order to overcome such difficulties, a cut blasting design optimization was conducted for a 2525 m depth of rock mass. According to the numerical simulation of this optimization, a modified cut blasting design method applicable to deep rock mass was proposed. This study can provide solutions to the cut blasting difficulties that are encountered during the excavation of deep rock masses.

1. Introduction

Currently, there is an increasing demand for mineral resources, hydropower resource exploitation, and the development of science and technology. As a result, the excavation of rock masses has gradually extended to greater depths. At present, the deepest underground cavern is the China Jinping Underground Laboratory, where the average depth is generally greater than 2000 m, and the maximum depth is approximately 2525 m. According to the back-calculated in-situ stresses, the major principal stress is approximately 70 MPa. The other two principal stresses are approximately 30 MPa in magnitude (Gong et al., 2012). When the drill and blast (D & B) method is adopted in rock excavation at great depths, cut blasting becomes difficult because of high in-situ stress influences (Xie et al., 2016). Cut blasting is important in developing a free surface for subsequent blasting, and influences the overall blasting procedure (Zhao et al., 2011). Therefore, it is important to investigate the damage evolution mechanisms of cut blasting.

Many researchers have investigated the damage evolution mechanisms of rock under blasting loads (Deng et al., 2014; Li et al., 2013, 2014; Mitelman and Elmo, 2016; Zhu et al., 2010). However, little work has been done on such mechanisms for deep rock masses under the cut blasting method (Bäckblom and Martin, 1999; Chen et al., 2007; Cunningham and Goetzsche, 1990; Ramulu et al., 2009; Bruland and Zare, 2006). Ma and An (2008) investigated the influence of free face in-situ stress and pre-existing joint planes on damage to rock masses under blasting. Wang et al. (2007) studied tension and compression damage distributions under different charge structures using the TCK model. Using a modified principal stress failure criterion, Zhu et al. (2008) applied the AUTODYN software to investigate the effects of boundary conditions, coupling mediums, borehole diameters, decouplings, and joints on dynamic rock fractures. Considering the influence of in-situ stress on rock mass damage mechanisms, Yilmaz and Unlu (2013) investigated the effects of high anisotropic in-situ stresses on blasting performance and blast-induced damage zones. Yang et al. (2015) researched the scope of damage to surrounding rock under different blasting sequences. They accomplished this by applying equivalent loads to an excavation surface. Zhao et al. (2011) used discontinuous deformation analysis (DDA) software to investigate dynamic rock response and rock fragmentation processes; however, they did not consider in-situ stress. When a deep rock mass is excavated

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Nomenclature

List of symbols

A, n	failure surface parameters of RHT model
A_1,A_2,A_3	EOS constants of rock-like materials
A_s	side width of rectangular opening
A_{JWL},B_{JWL},R_1,R_2	JWL EOS constants
B_b,B_1,B_2	cut hole burden, cut hole burden in the first quadrangle, and auxiliary blasthole burden in the second quadrangle
B,Q_0	lode angle dependence factors
$B_{\Gamma 0}$,B_{Γ}	Gruneisen parameter coefficients
c	intact rock constant
d	charge diameter
e_0,e,e_H	initial internal energy per unit mass, internal energy per unit mass, and internal energy per unit mass under Hugoniot conditions
E_0,E	initial specific internal energy of detonation products and specific internal energy of detonation products
f_c	compressive strength
F	blasthole deviation
$F_r^c(\dot{\varepsilon}_p)$,$F_r^t(\dot{\varepsilon}_p)$	compressive and tensile strain rate strength factor
H	blasthole advance
l	linear charge density
l_c,l_c	correction factor of compressive and tensile strength
N	porosity index
P_R,μ	pressure of EOS in RHT model and volumetric strain
P	pressure of detonation products
Q_{v0},Q_v	released energy of 1 kg LFB-dynamite and released energy of 1 kg LFB-dynamite explosives
S_L	slope of linear relationship
S_{ANFO}	explosive weight strength relative to ANFO
S	weight strength relative to LFB-dynamite
v_0,v	initial specific volume of detonation products and specific volume of detonation products
STP	standard atmospheric pressure and temperature
V_0,V	gas volume released by LFB-dynamite and explosives at STP
VoD	detonation velocity

Greek symbols

α_0,α	initial porosity and porosity of porous materials
α_1,α_2	angular deviation and collar deviation
$\dot{\varepsilon}_p$,$\dot{\varepsilon}_p^c$,$\dot{\varepsilon}_p^t$	strain rate, reference tensile strain rate, and compressive strain rate
ϕ	diameter of the central hole
ρ_0,ρ,ρ_e	initial density of rock, rock density, and explosive density
σ_1,σ_3	maximum and minimum principal stresses
σ_n,τ	normal effective stresses and shear stress
$\Gamma(v)$	Gruneisen parameter
σ_f,σ_{f-C},σ_f^*	stress, corrected stress, and normalized stress on failure surface
ω	JWL EOS constant

using a cut blasting method, in-situ stress causes difficulties.

To overcome these difficulties, blasting design must be optimized based on damage evolution mechanisms. At present, the successful excavation of rock masses requires appropriate blasting design of the drilling pattern, quantity and type of explosives, and initiation sequence (Zhao et al., 2011). It is important to determine the burden of cut holes, which is key in the overall blasting procedure. The basic principles behind calculating patterns and charges for a four-section cut (known as the Swedish method) were first developed by Langefors and Kihlström (1978). The method was later updated by Holmberg and then simplified by Olofsson (1990). These modified methods are applied to the calculation of cut blasting design for shallow rock masses. However, an optimized method has not been reported for determining the cut hole burden in a deep rock mass.

In LS-DYNA, three main damage models are used to simulate the damage evolution of rock mass under blasting load: the Holomquist–Johnson–Cook (HJC) model (Holomquist et al., 1993), the JH series model (Johnson and Holmquist, 1992, 1994), and the Riedel–Hiermaier–Thoma (RHT) model (Riedel et al., 1999). In contrast to the HJC and JH series models, the RHT model considers strength characteristics in the three-dimension stress space, along with deformation and failure under high confining pressure. It can better reflect rock mechanical performance under different confining pressures and high strain rates. When the D & B method is applied, the excavated deep rock masses are under dynamic-static coupling loading. At such a moment, strain rate, confining pressure, strain hardening, and damage softening have a significant influence on the mechanical performance of the rock masses. These factors are comprehensively considered in the RHT model (Borrvall and Riedel, 2011). To investigate the optimized method and determine the burden of cut holes applicable to deep rock masses, the RHT model in LS-DYNA is chosen. At present, the RHT model has been widely used to simulate the damage evolution of concrete. However, because of a lack of rock mechanical parameters, few investigations have used LS-DYNA to study the damage evolution of rock.

To apply the RHT model to the evolution of rock damage evolution under blast loading, the rock mechanical parameters are first determined based on existing experimental results (Banadaki and Mohanty, 2012). The model parameters and model rationality are verified by comparing the model results to existing blasting test and simulation results (Banadaki and Mohanty, 2012). To overcome the difficulties encountered during cut blasting in deep rock masses, the determined RHT model parameters are applied to a simulation of the damage distribution around a blasthole under hydrostatic pressure and various lateral pressure coefficients. Through the simulation, the causes of difficulties encountered during cut blasting are analyzed, and the cut blasting design is optimized to overcome these difficulties. This study provides both a method for determining RHT model parameters in LS-DYNA and a theoretical basis and reference for addressing excavation difficulties related to cut blasting in deep rock masses.

2. Verification of the RHT model

The RHT model is a tensile-compressive damage model proposed by Riedel et al. based on a modified HJC model. In contrast to existing damage models, it considers the effects of confining pressure, strain rate, strain hardening, and damage softening on the failure strength of a rock material under blasting and dynamic load. To describe pore compaction hardening effects, the pressure is governed by the Mie–Gruneisen equation of state (EOS) together with a p-α model (Borrvall and Riedel, 2011). As a complement to the model in LS-DYNA, the RHT model in AUTODYN is modified and embedded into LS-DYNA.

Based on the above-mentioned analysis, the RHT model is suitable for describing the dynamic mechanical response of deep rock mass to blast loading. Although, this AUTODYN model has been widely applied to simulate damage evolution processes in concrete, it is seldom used in rock-like material modelling. Additionally, the RHT model has not been widely applied in LS-DYNA. To apply the RHT model in LS-DYNA to simulate the rock damage evolution process, mechanical parameters must be determined based on existing rock mechanical tests. The model parameters and model applicability are verified by comparison with the blasting test results.