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2D numerical analysis of rock damage induced by dynamic in-situ stress redistribution and blast loading in underground blasting excavation

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ABSTRACT

When underground cavities are created in initially stressed rock masses by the drill and blast method, an unwanted excavation damage zone (EDZ) is induced around the cavities due to the combined effects of in-situ stress redistribution and blast loading. During rock fragmentation by blasting, the in-situ stress on blast-created excavation boundaries is suddenly released. The in-situ stress redistribution is a dynamic process that starts from the transient release of stress and reaches a final static stress state after excavation. For a circular tunnel that is excavated underground by full-face millisecond delay blasting, 2D finite element simulation is performed to investigate the rock damage induced by the dynamic in-situ stress redistribution and blast loading. The critical peak particle velocity (PPV) for the initiation of blast damage in pre-stressed rock masses is also numerically studied. The results show that the transient stress release generates additional stress waves, resulting in a larger damage zone compared with that following quasi-static stress redistribution. The effect that the additional stress waves have on rock damage becomes more obvious as the in-situ stress levels and excavation dimensions increase and as the stress release duration decreases. Blast-induced tensile stress in the circumferential direction of a tunnel is neutralized by compressive in-situ stress. In deep-buried or high-stressed tunnel excavation, dynamic stress redistribution is responsible for the formation of EDZ; the critical PPV for the initiation of blast damage first increases and then decreases with an increase in the in-situ stress. Therefore, in underground blasting excavation, the factors that affect the level of in-situ stress such as tunnel depths should be considered with respect to the blasting vibration standards and damage criteria.

1. Introduction

In underground mining and civil construction operations involving rock excavation, an undesirable excavation damage zone (EDZ) is created in rock masses surrounding the openings. Excavation-induced rock damage, which can include microcracks, spalling and even v-shaped notches in more severe cases, potentially undermines the tunnel stability and increases the excavation and support costs and delays. Investigating the characteristics and behavior of EDZ is essential for underground openings that require long-term stability. Extensive studies have been conducted to understand and predict the EDZ, and significant advances have been made in determining its formation mechanism and mechanical properties (Martin, 1997; Kaiser et al., 2004; Read, 2004; Martino and Chandler, 2004; Li et al., 2012; Siren et al., 2015; Hao et al., 2016; Lisjak et al., 2016).

The use of explosives is the most cost-effective and widely used rock excavation method. It is generally accepted that when the drill and blast method is used in underground excavation, a combination of the effects of in-situ stress redistribution and blast loading is responsible for the formation of EDZ (Martino and Chandler, 2004). Stress redistribution due to excavation causes local stress concentrations, which may exceed the rock strength, and can damage the rock masses surrounding the excavation. Blast-induced rock damage results from explosion stress waves and subsequent explosion gas expansion.

There are two problems that should be noted in understanding the interaction of in-situ stress redistribution and blast loading. Accompanying rock fragmentation by blasting, the in-situ stress that was initially exerted on the blast-created excavation boundaries is suddenly released. Theoretical and numerical studies have shown that the transient stress release produces stress waves passing through the medium, which cause a transient stress greater than the final static stress (Cook et al., 1966; Carter and Booker, 1990; Li et al., 2014; Zhu et al., 2014). However, many researchers still tend to treat the stress redistribution associated with blasting excavation as a quasi-static process. This approximation is generally acceptable if the in-situ stress level is low. However, at a moderate-to-high stress level, such as

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Nomenclature

a	excavation radius
c_f	average crack propagation velocity
c_p	P-wave velocity
D	damage variable
d_b	blasthole diameter
d_c	charge diameter
D_{cr}	damage threshold
E	Young's modulus
F	variable of random distribution
F_0	scale parameter of Weibull distribution
G	shear modulus
$\overline{G}$	degraded shear modulus
K	bulk modulus
$\overline{K}$	degraded bulk modulus
L	charge length
m	shape parameter of Weibull distribution
N	original number of elements
N_f	number of ruptured elements
p_0	in situ stress
P_b	blasting pressure peak on excavation boundaries
$P_b(t)$	blasting pressure-time history on excavation boundaries
P_w	borehole wall pressure
$P_w(t)$	borehole wall pressure-time history
r	distance
R	tunnel radius
S	blasthole spacing
t	time
t_b	initial time of stress release
t_d	stress release duration
t_r	rising time of borehole pressure
V_{cr}	critical peak particle velocity
V_d	velocity of detonation
β	damping factor
γ	specific heat ratio
Δe_{ij}	deviatoric strain increment
δ_{ij}	Kronecker delta
$\Delta\varepsilon_{kk}$	volumetric strain increment
$\Delta\sigma_{ij}$	stress increment
$\acute{\varepsilon}$	strain rate
ε_v	volumetric strain
κ	lateral pressure coefficient
λ	adiabatic expansion constant
ν	Poisson's ratio
ρ	rock density
ρ_e	explosive density
σ_1	maximum principal stress
σ_3	minimum principal stress
σ_c	uniaxial compressive strength
σ_{dc}	dynamic compressive strength
σ_{dt}	dynamic tensile strength
σ_{sc}	static compressive strength
σ_{st}	static tensile strength
σ_t	uniaxial tensile strength
φ	internal frictional angle

20–50 MPa, the strain rate induced by the transient stress release can reach a magnitude of 10^{-1}–10^{1} s^{-1} for most of the short-hole blasts that are used in underground opening excavation (Lu et al., 2012). It is generally acknowledged that when the strain rate exceeds 10^{-1} s^{-1}, the mechanical behavior of rock is a dynamic process and that the inertial effects should not be ignored (Zhang and Zhao, 2014). Therefore, during blasting excavation in highly stressed rock masses, the in-situ stress redistribution around the excavation is a dynamic process that starts from the transient stress release and reaches a final static stress state after excavation. Cai (2008) noted that in addition to blast-induced stress waves and gas pressure, the dynamic unloading or dynamic stress redistribution is another mechanism that may contribute to the formation of EDZ. According to numerical and experimental results, He et al. (2010), Zhu et al. (2014), Yan et al. (2015) and Yang et al. (2015) found that dynamic stress disturbances due to the transient stress release have a considerable influence both on the evolution and extent of EDZ around deep tunnels. Other studies show that the effects of dynamic stress redistribution are closely related to rock properties, in-situ stress levels, stress release rates and paths (Li et al., 2014; Cao et al., 2016; Yang et al., 2016a).

In-situ stress, including its magnitude and orientation, has a significant impact on the distribution and extent of blast-related rock damage zones. Many experimental and numerical studies have shown that when a blasthole is detonated in an initially stressed rock mass, blast-induced cracks are initiated and propagated preferentially along the maximum stress orientation perpendicular to the blasthole axis. The greater the compressive stress is, the more obvious this phenomenon is, and the smaller the cracked zone is (Ma and An, 2008; Omer, 2013; Yilmaz and Unlu, 2013). The pre-loading compressive stress suppresses the blast-induced cracks. High compressive stress may cause fractures around the blasthole, and these fractures may be extended or suppressed by blast-induced stress waves in different patterns (Ma and An, 2008). In addition, the presence of in-situ stress may disturb the propagation of blast-induced stress waves. In this respect, Fan et al. (2009) carried out experimental studies under laboratory conditions. Their results clearly show that the velocity of stress waves increases rapidly with an increase in the in-situ stress at lower levels, but that the velocity tends to be constant under higher stress levels.

Because of these complexities, most studies associated with EDZ tend to investigate individual damage mechanisms separately, such as stress redistribution-induced damage under quasi-static conditions or blast-induced damage for a single blasthole rather than real blasting schemes. It is still unclear how and to what degree the drilling and blasting method affects the formation of EDZ in underground excavation. There are no blasting safety criteria and standards that consider the effects of static in-situ stress and dynamic unloading. Therefore, to fully understand the formation of EDZ in underground blasting excavation, it is significant to numerically study the rock damage induced by the combination of dynamic in-situ stress redistribution and blast loading, with special emphases placed on real blasting schemes and the transient stress release.

In this study, a simplified 2D numerical model is first developed for a circular tunnel excavation using the full-face millisecond delay blasting method. Subsequently, a continuum-based damage model is programmed into the FEM software LS-DYNA to investigate the rock damage evolution induced by dynamic in-situ stress redistribution, blast loading and their combined effects. In addition, the effects of the in-situ stress on the PPV threshold for initiation of blast damage are discussed. These numerical results provide a reference for the blasting safety criteria and standards of underground blasting excavation.

2. Two-dimensional numerical model for blasting excavation of a circular tunnel

Because of the dimensional effect, the behavior of rock damage by a single-hole blast in a stressed rock mass cannot completely represent the picture of rock damage for blasting excavation in underground tunnels. Therefore, to get closer to reality, a model for a circular tunnel excavation is first developed.