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2D numerical simulation on excavation damaged zone induced by dynamic stress redistribution

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ABSTRACT

The formation of an excavation damaged zone (EDZ) around an opening in a deep rock mass is associated with the dynamic stress redistribution that starts from transient release of high in situ stress to the final quasi-static stress state after the excavation. This study applies a theoretical analysis of stress redistribution due to transient unloading in surrounding rock under hydrostatic stress field, and develops a numerical elastodynamics model for finite element analysis. Coupling the theoretical and the numerical solutions, a general damage model for heterogeneous rock mass is proposed by taking the dynamic stress redistribution due to excavation into account. Finally, the dynamic stress redistribution, as well as the induced damage zone around the excavation under different lateral pressure coefficients is numerically simulated. The numerical result indicates that, the stress wave induced by the transient unloading will initially cause the damage only in the 1/3 radius vicinity of excavation perimeter. The damage zone may then develop further under the constant quasi-static far-field stress. Therefore, the EDZ development during deep excavation is closely dependent on in situ stress, rock strength and excavation method.

1. Introduction

The formation of an excavation damaged zone (EDZ) is expected around excavated openings at depth in civil (e.g., tunnels and caverns), mining (e.g., shafts, tunnels, drifts and stopes), and petroleum engineering (e.g., borehole) (Zhu and Bruhns, 2008). Extensive studies have been performed to understand and predict the extent of EDZ, and in recent years advances have been made in the understanding of the formation mechanism of EDZ (Falls and Young, 1998; Backblom and Martin, 1999; Cai et al., 2001; Diederichs et al., 2004; Read, 2004; Martino and Chandler, 2004). It is generally accepted that in high in situ stress conditions the excavation induced stress redistribution is the main cause for the formation of EDZ, which plays a more important role on the extent of EDZ than that of the excavation method (Falls and Young, 1998). Many researchers deem that the stress redistribution during the formation and development of EDZ is a quasi-static process. This approximation is generally acceptable if the level of the in situ stress is low. In fact, excavations trigger sudden release of in situ stress which leads to a strong transient disturbance to the surrounding rock mass. Under high in situ stress condition, the released stress is rather significant in a relatively short duration. It is unclear whether the quasi-static assumption is acceptable (Lu et al., 2012). Some studies have revealed the necessity of studying the transient process of stress redistribution and related dynamic response.

As early as 1966, Cook et al. (1966) indicated that impulsive release of the applied load could lead to over-relaxation of the displacing rock, generating tensile stresses in the medium. Abuov and Aitaliev (1988) pointed out that with the formation of a new open surface in the rock mass, load-relief waves are formed, which leads to the transfer of potential energy of bulk compression into kinetic energy. During this process, particles of the rock move toward the surface of rock exposure, and a rockburst may occur when the potential energy of compression reaches a specific level. Carter and Booker (1990), as well as Wang and Huang (1998) deemed that the dynamic disturbance due to transient release rate of high in situ stress has great influence on the extent of EDZ and resultant rockburst occurrence. Cai (2008) thought that, in addition to dynamic stress wave and blasting-induced gas pressure, there is another mechanism that is dynamic unloading that may contribute to the blasting-induced rock damage. For blasting induced damage in excavation walls, the loss of confinement (excavation) and dynamic loading from wave propagation cause both intended and unintended damage. Zhou and Qian (2007) and Li et al. (2009) took the stress redistribution as a dynamic process to

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interpret the tension–compression alternation and zonal disintegration phenomena around a deep tunnel. Sun et al. (2011) and Lu et al. (2012) considered that the dynamic unloading wave induced by transient release of in situ stress plays an important role in vibration of surrounding rock. Chen et al. (2011) suggested a method to determine the radius of the broken and plastic softening zone when considering the dynamic response of surrounding rock. Yin et al. (2012) found the fractal dimension of sandstone gradually increases with the unloading rate increasing. Wei et al. (2014) explained the failure mechanism of transient unloading in surrounding rock. In conclusion, the dynamic stress redistribution induced damage zone results from two factors, i.e., a dynamic unloading stress induced by transient release of in situ stress and a quasi-static secondary stress due to the in situ stress. Therefore, the stress redistribution under high in situ stress condition is a dynamic process and rock dynamics approach could be applied (Zhao et al., 1999, 2011).

The main mechanism in the development of EDZ is the initiation and growth of cracks and fractures, owing to stress redistribution. Because of the anisotropy and heterogeneity of rock, which may be also altered with damage evolution, it is difficult to theoretically characterize the EDZ. The field instrumentation records contain unique deformation signatures that provide insight into the mechanical response of rock mass to stress redistribution and the formation of an EDZ. However, due to the limit of in situ data obtained, it is usually difficult to clarify the associated mechanism that is responsible for the formation of EDZ. Moreover, attempts to generate fractures by impulsive unloading in laboratory tests have been unsuccessful (Brady and Brown, 2004). Many researchers (Lajtai, 1998; Hajiabdolmajida et al., 2002; Suknev, 2008; Feng et al., 2012) tend to believe that the rock failure is dominated by tensile fracture at the beginning, especially under unloading condition, but arguments still exist. Therefore, it is significant to develop effective numerical models that can capture the damage evolution during the stress redistribution caused by both dynamic unloading and quasi-static in situ stresses, in order to fully characterize the spatial and temporal development of EDZ in rock mass.

To this end, it is the dynamic and quasi-static response induced by excavation of rock mass that defines the objective of this work. In this respect, an elastodynamic analysis on the dynamic unloading response of surrounding rock under hydrostatic stress field is firstly given. Then, when the stress redistribution resulted from transient release of in situ stress and quasi-static far-field stress is taken into account, a general damage model for simulating EDZ in heterogeneous rock is proposed and programmed into COMSOL Multiphysics, a partial differential equation (PDE)-based multiphysics modeling environment (COMSOL, 2008). In addition, the numerical model is validated by simulating the elastodynamic response during the excavation in homogeneous rock under hydrostatic stress field. Finally, the 2D numerical simulations on the dynamic stress redistribution and resultant damage zone under different lateral pressure coefficients (i.e., κ = 0.2, 1.0, 2.0, it is a ratio of horizontal far-field stress to vertical far-field stress) are comprehensively conducted. Although this 2D analyses is somewhat different from the real tunneling practices, for example, blasting in the mining face and the existed fractures are not properly addressed, it is really important for clarifying the associated mechanism responsible for the EDZ development due to the dynamic stress redistribution.

2. Damage mechanics – based model

Initially the porous medium is assumed elastic, with constitutive relationship defined by a generalized Hooke's law. In this regard, a modified Navier's equation, in terms of displacement under a change of applied stresses (positive for tension) is expressed as (Timoshenko and Goodier, 1951)

$$Gu_{i,jj} + \frac{G}{1-2v}u_{j,ji} + F_i = \rho\frac{\partial^2 u_i}{\partial t^2}, \quad (1)$$

where u_i ($i = x, y, z$) is displacement (m), t is time (s), ρ is rock density (kg/m^3), G is shear modulus (Pa), v is the Poisson's ratio, and F_i is the components of the net body force in the i-direction (N/m^3). This equation expresses the mechanical equilibrium in rock subjected to dynamic loading. It could be used for quasi-static analysis when the acceleration term in right-hand term is set to zero. This is general 3D equation, as for numerical simulation in Section 4, it is simplified for 2D plain strain problem.

As illustrated in Fig. 1, the damage in tension or shear mode of rock is initiated when its state of stress satisfies the maximum tensile stress criterion or the Mohr–Coulomb criterion, respectively, as expressed by:

$$F_1 \equiv \sigma_1 - f_{t0} = 0 \text{ or } F_2 = -\sigma_3 + \sigma_1[(1+\sin\phi)/(1-\sin\phi)] - f_{c0} = 0 \quad (2)$$

where f_{t0} and f_{c0} are uniaxial tensile and compressive strength (Pa), respectively, ϕ is internal frictional angle, and F_1 and F_2 are two damage threshold functions used to link the tensile and shear damage, respectively.

According to the principle of elastic damage, the elastic modulus of an element degrades monotonically as damage evolves, and the elastic modulus of damaged material is expressed as:

$$E = (1-D)E_0 \quad (3)$$

where D represents the damage variable, which lies between 0 and 1, and E and E_0 are the elastic moduli of the damaged and the undamaged material (Pa), respectively. In this kind of numerical simulation, the element as well as its damage is assumed isotropic, so the E, E_0 and D are all scalar. According to Fig. 1, the damage variable can be calculated as:

$$D = \begin{cases} 0 & F_1 < 0 \text{ and } F_2 < 0 \\ 1 - \left|\frac{\varepsilon_{t0}}{\varepsilon_1}\right|^n & F_1 = 0 \text{ and } dF_1 > 0 \\ 1 - \left|\frac{\varepsilon_{c0}}{\varepsilon_3}\right|^n & F_2 = 0 \text{ and } dF_2 > 0 \end{cases} \quad (4)$$

where ε_{t0} and ε_{c0} are maximum principal strain in tension and maximum principal strain in compression when damage occurs, respectively, and n is a constitutive coefficient and it is 2.0. In this respect, the damage variable calculated with Eq. (4) is always from 0 to 1.0 regardless of what kind of damage it may suffer. However in the damage zone figure, in order to distinctly display the two kinds of damage modes (i.e. tensile damage and shear damage), the tensile

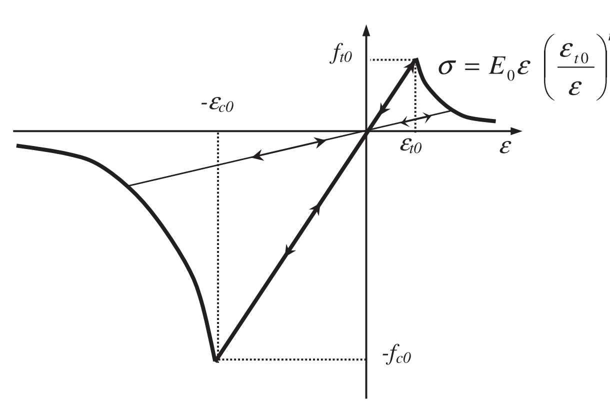

Fig. 1. The elastic damage-based constitutive law under uniaxial stress condition.