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Effect of heterogeneity on occurrence of zonal disintegration around deep underground openings

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ABSTRACT

By utilizing the two numerical codes RFPA3D and FLAC3D, the effect of heterogeneity on failure mode and failure mechanism of rock around deep underground excavations under tri-axial stress is analyzed. It is found that zonal disintegration is a large scale shear-slip failure developed in deep surrounding rock mass under tri-axial stress, which is accompanied by a large amount of tensile failure. The distance between fractures and the number of fractures have a close correlation with the rock mass heterogeneity. With an increase of the homogeneity index of the rock mass, the distances between fractures decrease and the number of fractures increases. For an intact hard rock mass with relative high homogeneity, only failure mode characterized as v-shaped notches can be formed due to the intersection of intensively developed shear bands. None of the zonal disintegration can be formed due to the fact that with increasing homogeneity, the failure mechanism of rock mass is gradually dominated by shear failure rather than tensile failure.

1. Introduction

With the rapid development of our economy, the need for power and resources is so urgent that underground excavations are developing into deeper areas. Typical failure modes of the rock mass around deep underground excavations, such as v-shaped notches and zonal disintegration (shown in Fig. 1) are constantly observed during deep underground excavation. Precursor's studies on failure modes of deep underground excavations under high tri-axial stress were earlier conducted in the so-called mine-by tunnel since 1982 at the Underground Research Laboratory (URL) of the Atomic Energy of Canada Limited. This excavation was in hard granite at a depth of 420 m, where the tri-axial stress is: $\sigma_1 > \sigma_2 > \sigma_3$, ($\sigma_2$ is in the direction of tunnel axis) [1]. It was found that the typical failure mode is the v-shaped notch which occurred at locations perpendicular to the direction of the maximum principal stress. Almost at the same time, zonal disintegration was found in deep gold mines in South Africa by using geophysical measurements, which was characterized by the existence of alternating fracture zones and relatively intact zones around the tunnel and in front of the tunnel face [2]. Nowadays, zonal disintegration has been observed in many deep mines in South Africa, Russia and in China either by using geophysical methods or borehole cameras [2–4]. Although much work has been carried out theoretically, experimentally and numerically, the mechanisms of zonal disintegration are still under debate [5–21]. The common point of view is that zonal disintegration is caused by a specific stress condition, where the horizontal stress along the tunnel axis is the maximum principal stress [12,21]. Based on this recognition, Jia studied the effect of tri-axial stress and its combinations on the failure mode of the deep surrounding rock mass, the results of which show that the tri-axial stress ratio has an important effect on the failure mode of the deep surrounding rock mass [11]. It is worth noting that a non-zonal disintegration phenomenon had been monitored in the mine-by tunnel of URL (Under Research Laboratory) in Canada, where the horizontal stress along the tunnel axis is the maximum principal stress.

Generally, deep underground projects have two distinct characters: high tectonic stresses and hard rock masses. However, most of the studies were trying to explain the mechanism of different failure modes of deep underground excavations from the perspective of stress, and the effect of heterogeneity of the rock mass on failure mode is often omitted. Observation of micro damage in heterogeneous material shows that the distribution of micro cracks changes from random to locally concentrated during the loading process, which eventually leads to macro failure. The formation and evolution of micro damage and the corresponding macroscopic failure modes followed have a close relation with the heterogeneity of rock material. In this paper, the effect of rock mass heterogeneity

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on failure mode and failure mechanism around deep underground excavations is studied by utilizing the advantages of two numerical codes called RFPA^{3D} and FLAC^{3D}.

Actually, a rock mass is a typical heterogeneous material. The micro-scale observations show that during the loading process, the distribution of micro-cracks changes from random to locally concentrated and eventually lead to failure on a macroscopic scale. The formation and development of the microscopic damage and the failure mode in macroscopic fractures followed have a close relation with the heterogeneity of the rock mass. In fact, the mine-by tunnel in Canada was excavated in intact granite with fine crystalline grain, the heterogeneity of which is relatively low. However, the zonal disintegration discovered in Dingji coal mine in China was formed in a jointed rock mass with medium to low strength, which is very heterogeneous. Until now, most of the studies on zonal disintegration have been trying to analyze the mechanism of rock mass failure and zonal disintegration from the aspect of stress and little attention has been paid on the effect of heterogeneity of the rock mass on failure mode on a macroscopic scale. Based on this consideration, in this paper, the effect of heterogeneity on failure mode and failure mechanism of rock around deep underground excavations under tri-axial stress is analyzed by utilizing the advantages of two numerical codes called RFPA^{3D} and FLAC^{3D}.

2. Effect of heterogeneity on failure mode of rock around deep underground openings

2.1. Simulation model

The RFPA3D code is a three dimensional finite element code based on damage mechanics and statistical theory. In this code, the material properties of each element are different form each other and are specified according to the Weibull distribution, which makes it capable of simulating the nonlinear behavior of distortion and failure of a rock mass. The heterogeneity of the numerical specimen, including the elastic modulus and compressive strength are assumed to conform to the Weibull distribution, as defined by the following probability density function:

$$f(u) = \frac{m}{u_0}\left(\frac{u}{u_0}\right)^{m-1} \exp\left[-\left(\frac{u}{u_0}\right)^{m}\right] \quad (1)$$

where u is the mechanical parameter of the element (such as strength or elastic modulus); the scale parameter u_0 is related to the average of the element parameters and the parameter m defines the shape of the distribution function. From the properties of the Weibull distribution, a larger value of m implies a more homogeneous material and vice versa. Therefore, the parameter m is called the homogeneity index.

The modified Mohr–Coulomb criterion with tension cut-off is adopted in this code, thus the characteristics of the brittle-plastic rock can be simulated. The damage threshold of tensile stress and shear stress is expressed as follows:

$$-\varepsilon_1 \geq kf_{c0}/E_0, \sigma_1 - \frac{1+\sin\phi}{1-\sin\phi}\sigma_3 \geq f_{c0} \quad (2)$$

where f_{c0} is the uniaxial compressive strength, E_0 the initial elastic modulus of element, k the tension–compression ratio, and ϕ the internal friction angle.

Before the stress reaches the damage threshold, the stress–strain relation for each element is elastic. Once one of the above criteria is satisfied, the damage begins. In elastic damage mechanics, the elastic modulus of an element degrades monotonically as damage evolves, and the elastic modulus of damaged material is expressed as follows:

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

where ω is the damage variable, E and E_0 the elastic modulus of damaged and undamaged elements respectively.

Here, four 3-D numerical models with different homogeneity indices of 3, 5, 10 and 30 are built by using RFPA^{3D} as shown in Fig. 2. Each model is 140 mm × 140 mm × 50 mm in size with a total element number of 980000. Displacement loads are applied in three directions along the negative axis of X, Y and Z at a value of 0.001 mm, 0.003 mm and 0.002 mm per step respectively. After a certain stress state is reached, a circular tunnel of 15 mm in diameter is excavated. Then the displacement loads are maintained until the whole model fails.

2.2. Results and discussion

Fig. 3 shows the progressive damage process of models with a different homogeneity index. Because the vertical displacement load is three times that of the horizontal displacement load perpendicular to the tunnel axis, most of the damages are concentrated at the two side walls. For a model with a low homogeneity index of 3 (model 1), initially, damages increase around tunnel side walls with no preferential distribution. Then more damaged elements

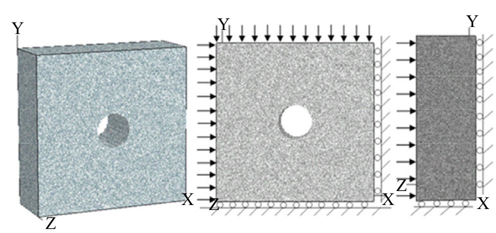
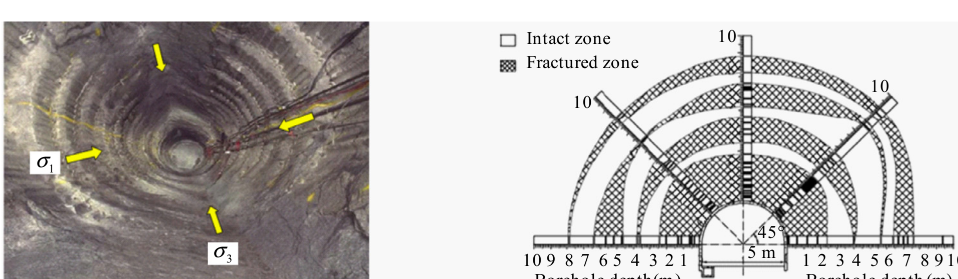


Fig. 2. Numerical model and its boundary condition.



(a) Final shape of v-shaped breakout notches in the (b) Zonal disintegration in deep roadway of Huainan

Fig. 1. Typical failure modes of deep underground excavations.