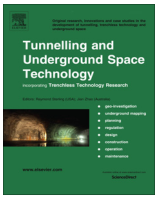
Tunnelling and Underground Space Technology 48 (2015) 1–10

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust



Mechanism of zonal disintegration around deep underground excavations under triaxial stress – Insight from numerical test

P. Jia *, W.C. Zhu

Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, Shenyang 110819, China
School of Resources & Civil Engineering, Northeastern University, Shenyang 110819, China

ARTICLE INFO

Article history:
Received 21 March 2014
Received in revised form 3 September 2014
Accepted 4 January 2015
Available online 21 February 2015

Keywords:
Zonal disintegration
Deep rock mass
Triaxial stress
Numerical test

ABSTRACT

The failure pattern and failure mechanism around deep underground excavations under tri-axial stress, in particular the zonal disintegration at different scales, were studied through three-dimensional numerical tests. It is found that the failure patterns of deep underground openings are obviously influenced by the triaxial stress. Zonal disintegration is a general failure mode of deep surrounding rock mass under high triaxial stress, where the alternate fracture zones and intact zones are formed by the intersection of the fully developed shear dominated fractures. The circular failure pattern of zonal disintegration is only a very specific failure pattern of zonal disintegration that is more likely to be formed when the horizontal stress in the direction of tunnel axis being the maximum principal stress. Sometimes the circular failure pattern of zonal disintegration is only the miss-judgment based on the limited borehole observations. Numerical results also denote that the heterogeneities of rock masses play a very important role on the scale of zonal disintegration.

1. Introduction

Zonal disintegration is a special kind of failure mode of rock mass around deep underground excavation, which is characterized by the alternate existence of fractured zones and relatively intact zones around tunnel and in front of the tunnel face (Shemyakin et al., 1986). This phenomenon was first noticed in 1970s by measuring the physical and mechanical parameters around a vertical tunnel at 200 m level. It was found that these parameters changed periodically away from tunnel boundary (Cloete and Jager, 1972). However, the phenomenon of zonal disintegration was paid little attention at that time until the rapid development of deep underground engineering such as mining and oil exploration was boomed. Zonal disintegration phenomenon has been observed more and more often and has aroused more attention from researchers in the rock mechanics field.

Because the failure pattern of zonal disintegration is quite different from the traditional recognition on excavation damaged zone, some researchers believe that this phenomenon announce the existence of another type of equilibrium process and stability type, thus can be taken as an evidence of non-linear theory (Prigogine and Stengers, 1996). Though many works have been done theoretically, experimentally and numerically (Cloete and Jager, 1972; Chen and Zhang, 2011; Jia et al., 2012; Odintsev, 1994; Qian et al., 2009; Wu et al., 2009a,b; Zhou and Bi, 2012), the debating on the mechanism of zonal disintegration has never been stopped.

One of the hotspot of the debate is whether zonal disintegration really exists. Owing to the fact that the zonal disintegration phenomenon cannot be observed directly, generally there are two ways that can be used to know its existence. One way is by drilling boreholes around tunnel, the fracture zones can be deduced from boreholes images; the other way is by measuring the physical mechanical parameters in the surrounding rock mass and analyzing its changing rules. Fig. 1 shows the zonal disintegration around a road way of Huainan mine in China deduced from digital images captured from five boreholes with borehole camera (Li et al., 2008). Fig. 2 shows the periodically variation of sound velocity and strain away from tunnel boundary, indicating the existence of alternate fractures zones and intact zones (He, 1991; Fang, 1996). However, the acquired data can only reflect local fractures around tunnel, thus the exact distribution of fracture and intact zones is hard to be known clearly. It seems that laboratory tests seem to be a good way to reproduce zonal disintegration.

Gu et al. (2008) reproduced the zonal disintegration shown in Fig. 3 by uniaxially loading a steel-drum – confined physical material with a round or U-shaped hole inside. They deemed that high stress in the direction of tunnel axis should be the reason of zonal disintegration. Based on their experiments, a series of uniaxial

---

* Corresponding author at: School of Resources & Civil Engineering, Northeastern University, Shenyang 110819, China. Tel.: +86 24 83691102.
E-mail address: jiapeng@mail.neu.edu.cn (P. Jia).

http://dx.doi.org/10.1016/j.tust.2015.01.005
0886-7798/

compression tests on confined hole-containing cylinder models were carried out to study the failure mechanism of zonal disintegration. However, these tests cannot take the triaxial stress condition in deep rock mass into account, thus being difficult to understand its mechanism in real case.

Some researchers believe that the location, number and size of fractured and intact zones depend significantly on the unloading rate and dynamic-mechanical parameters of deep rock masses (Zhou and Bi, 2012; Zhou et al., 2009a,b), but they cannot explain why zonal disintegration can occur when non-blasting excavation methods are used. Attempts were also made by Odintsev (1994) and Wu et al. (2009a,b) to give the initiation criteria of zonal disintegration by simplifying the 3-D problem of tunnel excavation as a plain strain problem, but the conclusions were not quite suitable for describing the complex failure mechanism of deep rock mass under high triaxial stress conditions. In term of this, Chen and Zhang (2011) conducted a real triaxial model test on a block of similar material model containing a U-shaped tunnel with total size of 0.6 m × 0.6 m × 0.6 m. Due to the high cost and difficulties in adjusting parameters in triaxial models, only one specific triaxial stress state (the stress in the direction of hole axis is being the maximum principal stress) is adopted in his test.

The other hotspot debate is the mechanism of zonal disintegration. Odintsev (1994) proposed that zonal disintegration is an alternation of zones of unconnected and connected mass containing closed splitting cracks in the region of hypercritical deformation. However, Zhou et al. (2009a,b) deemed that zonal disintegration is induced by the dynamic unloading disturbance of excavation. Wu et al. (2009a,b) believed that zonal disintegration is the split failure of rock mass occurred under large tangential stress and small radial stress, and can be caused by creeping failure of rock mass in the process of development of plastic zones. Qian et al. (2009) numerically simulated the failure process of the diversion tunnels of Jinping II Hydropower Station of China as a two dimensional problem and found that the slip-line zonal fractures were generated around diversion tunnels. Jia et al. (2012) numerically analyzed the parallel fractures around deep underground openings in different scale from onion-skin fractures, spalling failure to zonal disintegration, and found that under larger multi-axial stress, especially under a higher horizontal stress along tunnel axis, zonal disintegration can be motivated from the split failure of spalling or slabbing at the trace of logarithmic spiral line from the free surface of tunnel boundary into deeper surrounding rock mass, however only fixed boundary condition was considered. Zuo et al. (2013) numerically studied the failure mode of deep underground openings under horizontal and vertical load respectively under a fixed boundary condition, but he did not take the effect of triaxial stress into account. Li et al. (2013) numerically studied zonal disintegration by using FLAC3D by simplifying the vertical and horizontal stress as hydrostatic stress, however the effect of different triaxial stress cannot be considered due to technical difficulties in his model.

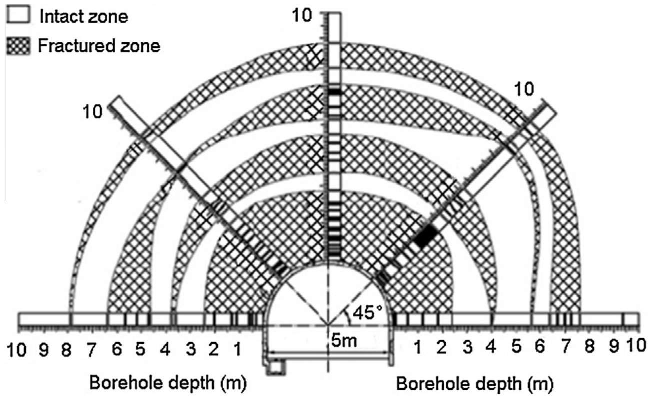


Fig. 1. Zonal disintegration monitored around deep roadway of Huainan mine in China (Li et al., 2008).

Due to the high cost, time consuming, and technical difficulties, the effect of triaxial stress on zonal disintegration was rarely be considered. Although many numerical studies have been made, for most numerical methods, the progressive failure process of rock mass can hardly be realized. In this work, we focus our study on how zonal disintegration develops under different triaxial stress conditions as well as its failure mechanism. By using a three-dimensional numerical code called Realistic Failure Process Analysis (RFPA^{3D}), which is capable of simulating the progressive failure process of rock-like material of heterogeneity, the existence of zonal disintegration induced by excavation under triaxial stress was first verified; then the effect of triaxial stress on zonal disintegration and the failure mechanism were studied; finally, the reason for existence of different scale of zonal disintegration were discussed. The aim of this paper was to shed some light on the stability control of deep underground excavation.

2. About RFPA^{3D}

The RFPA^{3D} 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 Weibull distribution, which makes it capable to simulate the nonlinear behavior of distortion and failure of 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:

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

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 characteristics of the brittle-plastic rock can be simulated. The damage threshold of tensile stress and shear stress is expressed as follows:

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

where ε_1 is the maximum principal strain, σ_1 and σ_3 are the maximum and minimum principal stress respectively. f_{c0} is the uniaxial compressive strength, E_0 is the initial elastic modulus, k is the ratio between tensile and compressive strength, ϕ is the internal friction angle.

Before loading, the meso-scopic elements are under elastic condition thus can be expressed by the elastic modulus and Poisson's ratio, and the stress–strain relation for each element is elastic. Upon the stress one of the above damage thresholds are 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:

$$E = (1-\omega)E_0 \tag{3}$$

where ω is the damage variable ranging from 0 to 1. E and E_0 are the elastic modulus of damaged and undamaged elements, respectively.