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Failure mechanism and numerical simulation of zonal disintegration around a deep tunnel under high stress

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ABSTRACT

The zonal disintegration phenomena in deep rock mass will appear with the increase of underground engineering depth which is widely different from shallow cavern. In order to reveal the formation mechanism of zonal disintegration, the geomechanical model test and numerical simulation of zonal disintegration are carried out respectively. Taking the deep tunnel of Dingji coal mine in China's Huainan coal mine as engineering background, a 3D geomechanical model test is carried out relying on the high stress 3D loading test system. The zonal disintegration phenomenon is observed, and the oscillation law of displacement and strain are measured. Based on the strain gradient theory and continuum damage mechanics, the zonal disintegration elastic damage-softening model is established. The relationship between rock failure and energy dissipation is analyzed. According to the strain energy density theory, the zonal disintegration energy damage failure criterion based on strain gradient is established. A numerical analysis method for zonal disintegration is proposed, the zonal disintegration calculation program is developed based on a commercial finite element code. The results of numerical simulation and the 3D geomechanical model test are basically consistent.

1. Introduction

With the rapid development of the world economy, the shallow mineral resources of the earth are gradually depleted, and the mining depth is deeper and deeper. At the same time, the needs of human survival and the exploration of the unknown world are constantly expanding the underground space. At present, in many engineering fields, such as mining engineering, hydropower engineering, transportation engineering and national defense project, the deformation and failure of deep rock mass are involved. The deformation and failure mode of deep rock mass is very different from that of shallow rock mass, which shows obvious discontinuous and nonlinear behavior, such as zonal disintegration, rock burst, large deformation and so on. The zonal disintegration refers to the alternation phenomenon of the rupture zone and non-rupture zone in the deep rock mass, as shown in Fig. 1.

The zonal disintegration has been observed in many deep cavern projects by many kinds of physical exploration methods. In 1980, two South African scholars, Adams and Jager,[1] discovered the periodic rupture phenomenon in South African 2300 m gold deposits. Using the resistivity instrument, Shemyakin[2] detected zonal disintegration in the Taimyrskii deep mine. Using borehole television, Li[3] detected zonal disintegration in China's Huainan coal mine.

The zonal disintegration of deep cavern is a nonlinear failure phenomenon, which is quite different from the failure mode of shallow cavity, this has stimulated research interest of many scholars. Shemyakin[4] considered that the fracture zone is attributed to splitting failure caused by caused by higher tangential compressive stress of rock mass. Based on the theory of non-equilibrium thermodynamics, Guzev and Paroshin[5] proposed a non Euclidean continuum model. Using the model, the stress distribution of circular cavern was analyzed. Based on the non-equilibrium thermodynamic principle, Metlov and Morozov[6] explained the formation mechanism of zonal disintegration in surrounding rock. The evolution process from elastic stage to zonal disintegration was described. Qian and Zhou[7–9] have done a lot of research work on zonal disintegration. Based on free energy density, equilibrium equation and incompatible deformation condition, a new model was proposed. Using the above model, they obtained the peak and trough alternating stress field of deep circular tunnel, and thought that the volatility of stress field leads to zonal disintegration. Wang[10] proposed a constitutive model which can describe the dynamic evolution, expansion and shear slip deformation of deep rock mass. Using

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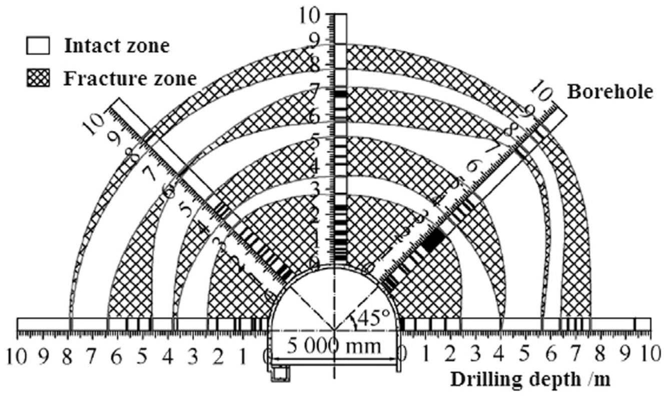

Fig. 1. Distribution of cracked zones in Huainan mine of China.

this model, the dynamic simulation calculation of characteristic science in deep rock mass was realized. Using the internal variable gradient theory, Qi[11] studied the zonal disintegration of deep tunnel.

Shemyakin[12] carried out the 2-D and 3-D equivalent material model test, and the zonal disintegration of surrounding rock has been observed. By means of model test, Gu[13] proved that zonal disintegration will appear in the surrounding rock under the higher axial pressure. Using cement mortar as a similar material, Yuan and Gu[14] carried out the zonal disintegration model test of deep rock mass, and alternate rupture zones and non-rupture zones were observed (Fig. 2), and they believed that higher axial pressure is the main reason of zonal disintegration.

Using the method of elastic damage mechanics, Li and Feng[15] described the post-peak mechanical properties of rock. The excavation of underground cavern was regarded as a dynamic process, the Flac3D numerical code was used to simulate zonal disintegration in the surrounding deep tunnel rock. Tao and Li[16] believed that the dynamic properties of rock conformed to continuous cap model. Using LS-DYNA finite element software, they carried out zonal disintegration numerical simulation study under dynamic loading conditions. They pointed out that static stress gradient and dynamic loading were the two prerequisites for the far field fracture zone. Zhu and Wang[17] believed that static mechanics theory is difficult to explain zonal disintegration in deep rock mass, and it should be studied by means of the dynamic knowledge. Using 3-D RFPA and high performance computer, the formation process of zonal disintegration in cubic specimen with a circular hole under axial loading condition was studied by Jia and Yang[18]. They pointed out that the three dimensional effect should be considered in the study of zonal disintegration.

To sum up, although the zonal disintegration has been proved by many kinds of testing methods in the field of engineering. And the great progress has been made in theoretical research, laboratory experiment and numerical simulation. But so far, the theoretical method is still needed to be further improved, there is not a widely accepted theoretical explanation for zonal disintegration; because of the lack of reliable theoretical basis and numerical simulation methods, the further research for numerical simulation is also needed. At present, the zonal disintegration in deep cavern is still a hot and difficult problem, the formation mechanism and numerical simulation of zonal disintegration are especially worth to be further studied.

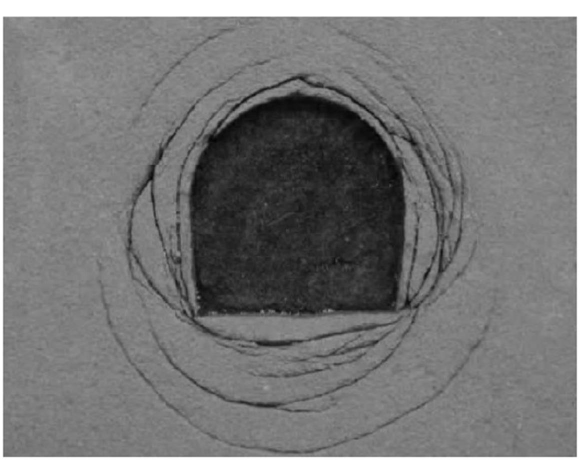

Fig. 2. Zonal disintegration phenomena obtained by model test.

In this paper, the 3D geomechanical model test for zonal disintegration is introduced firstly, the distribution of fracture zone and the variation law of radial displacement and radial strain around the tunnel are given. Based on the strain gradient theory and continuum damage mechanics, the damage softening model for zonal disintegration is established. According to the theory of strain energy density, the energy damage criterion for zonal disintegration is proposed. In order to consider the strain gradient effect in the numerical simulation, the high order hexahedral element is constructed using Hermite interpolation function, and the shape function and stiffness matrix of the element are derived. The numerical analysis method for zonal disintegration is proposed, the corresponding calculation program is developed based on ABAQUS platform. The results of numerical simulation and model test are basically consistent. The reliability of the damage softening model and the numerical analysis method for zonal disintegration is proved. Finally, based on the theoretical analysis and numerical simulation, the formation mechanism of zonal disintegration in deep cavern is elaborated.

2. Three dimensional geomechanical model test for zonal disintegration in deep rock mass

2.1. Model test procedure

The engineering prototype of 3D geomechanical model test is the deep roadway of Dingji Coal Mine in Huainan mining area of China. The buried depth of roadway is 910 m, the lithology is mainly Permian sandstone. The high ground stress field formed by the combination of self-weight stress and tectonic stress, the axial horizontal stress is the maximum principal stress.

The geometric similarity ratio and stress similar ratio of model test are all 1/50. According to the similarity principle and the physical and mechanical parameters of rock, using iron crystal sand cementitious geotechnical similar material, through lots of material proportion tests and corresponding mechanical parameters tests, the physical and mechanical parameters of similar material (Table 1) and the proportion of similar materials are obtained. In the similar material, the mass ratio of iron powder, barite powder and quartz sand is 1: 1.2: 0.38. The concentration of rosin alcohol solution is 9.5%. The weight of rosin alcohol solution is 5% of the similar material total weight.

The shape of geomechanical model is a cube, and its side length is 0.6 m. The shape of model tunnel is circular, and its diameter is 0.1 m. The X direction of geomechanical model is parallel to tunnel axis, the Y direction is perpendicular to tunnel axis, the Z direction is vertical. The vertical stress (σ_z) of the model tunnel is self weight stress, the horizontal ground stress (σ_y) perpendicular to tunnel axis is 1.5 times vertical stress, the horizontal stress (σ_x) parallel to tunnel axis is the maximum principal stress, its value is 2 times the compressive strength of similar materials.

The geomechanical model is made by the method of stratified compaction. In order to observe zonal disintegration phenomenon effectively, a variety of measuring elements are arranged around model tunnel at intervals. These measuring elements include: resistance strain gauge and grating scale multi-point displacement meter. The layout of the model monitoring section is shown in Fig. 3, the arrangement of the measuring element is shown in Fig. 4.

The high stress three-dimensional loading test system has been