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Mechanism of zonal disintegration phenomenon (ZDP) and model test validation

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ABSTRACT

The zonal disintegration phenomenon (ZDP) is investigated by proposing a criterion based on fracture mechanics. Accordingly, the mechanism is revealed to be the circulation of the fracture of the elasto-plastic boundary caused by the peak SIF (Stress Intensity Factor) and the constant formation of a "new" plastic boundary. Consequently, the reason ZDP occurs in deep caverns is also interpreted based on this theory. In addition, a formula is proposed to predict and determine the post-mortem features of ZDP, including the numbers (N) and sizes (r) of the fractured zones. The subsequent sensitivity analysis shows that the impact factors are the geo-stress and parameters of the rock mass. The variation laws of the post-mortem feature versus these impact factors are also determined. A 3-D geo-mechanical model test is conducted based on an analogous material. A deep tunnel in the PANJI coal mine, where zonal disintegration is observed, serves as the prototype engineering project. This model presents the forming process of ZDP. The criterion and post-mortem features proposed by the formula are validated through the model test. Furthermore, the results confirm that the wavy deformation law can be used to predict the ZDP.

1. Introduction

A series of deep caverns with embedded depths of more than 1000 m have recently been explored worldwide. Two examples include the Jinping II Hydropower Station in China and the Witwatersrand gold mine in South Africa. The depth of these caverns could induce a unique cavern rupture called the "zonal disintegration phenomenon (ZDP)". The ZDP occurs when a "fractured zone and non-fractured zone occur alternately around deep caverns during the excavation in the deep rock masses" [1]. This unique failure was first observed by Adams [3] using a bore periscope at an embedded depth of 2000 m in the Witwatersrand gold mine. It was subsequently reported in many deep caverns, occurring with the use of all types of geophysical methods and devices. For example, it was studied in the Taimyrskii deep mine in Russia by Shemyakin et al. using a resistivity meter [1]. Their subsequent research eliminated explosions as the cause of the ZDP [4–6]. In China, it was found using a borehole camera exploration device in the Huainan coal mines [7] and then in the Suncun and Liangzhuang mines [8]. This unique failure mode could result in a major disaster during the excavation of deep rock masses [2].

The ZDP has been the focus of recent investigations. This is mainly because it is one of the characteristics of deep rock masses that is distinct from those occurring in shallow masses. According to traditional concepts, the surrounding rock mass around a shallow cavern will be divided into fractured, plastic and elastic regions from the periphery of the tunnel to infinity. This is totally different from the engineering response and post-mortem features observed from the ZDP in deep caverns. Many different methods have attempted to interpret the ZDP. Malan and Spottiswoode [9] analyzed the relationship between the shock bump and the ZDP in the surrounding rocks of a mining field. Zhou and Qian [10–12] conducted a series of studies to investigate the dynamical excavation of a deep cavern to determine the forming mechanism, the residual strength and the forming time of fractured zones. Various elastic-plastic theories [13,14] have been adopted to interpret the phenomenon. Moreover, non-traditional theories such as the Hamiltonian time-domain variation [15] and non-Euclidean models [16–18] were utilized and applied to attempt to interpret the mechanism. Due to computer technology developments, numerical simulations have also been adopted to simulate this phenomenon.

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For example, Wang et al. [19,20] separately adopted the strain-softening heterogeneous constitutive model and the continuum grain-interface-matrix model to simulate the ZDP. Some commercial software applications, such as RFPA [21], FLAC [22] and AUTODYN [23], were improved to conduct numerical simulations.

These previous studies have contributed a great deal in interpreting the mechanism of the ZDP. However, with the exception of a few qualitative descriptions, the forming conditions and failure modes of the ZDP have not yet been convincingly explained. Moreover, various arguments about the characteristics of the ZDP still persist. For example, Borzykh [24] believed that the fractured zones comprise a group of plastic slippage lines after the deep rock mass yields to plasticity, while the other group is in the radial direction of the tunnel. On the contrary, Oparin and Kurlenya [25–27] reported that the fractured zone is the concentric circle of the excavated tunnel, and they also provided the relationships among the radii of the fractured zones. Knowing the features of the ZDP is vital for ensuring the safety of a deep tunnel. For example, the location of the disintegration zones prior to their formation is used to prevent them and protect the deep cavern. Therefore, further research on the ZDP, such as the forming mechanism, evolution laws and especially the failure pattern is needed.

The purpose of this paper is to reveal the criterion, post-mortem features and impact factors of the ZDP. First, a theoretical criterion based on the fracture mechanics was proposed to interpret the forming conditions and failure mode of the ZDP. Second, a 3D model is presented to examine this criterion. The fractured pattern and morphology of the ZDP were found to be concentric circles. Finally, the morphology is validated by comparing the theoretical analysis to the test results. The impact factors that influence the features of the ZDP are determined to be mechanical parameters and the geo-condition. The deformation law for the ZDP is proved to be an indicator for the ZDP. A formula is given to predict the number of fractured zones and the ratio of the interval of disintegration zones.

2. Mechanism analyses of the ZDP

2.1. Cracks surrounding the cavern

Fig. 1 shows the morphology of the surrounding rock mass, with abundant joints, fissures and fractures at different scales. These discontinuities will multiply and extend with the stress redistribution induced by the cavern excavation. Many fractures are present, but the largest one needs to be studied. This is because the driving force of fracture expansion is in direct ratio to the length of the fractures. However, different from the rock specimen, crack extensions in the surrounding rocks will be influenced by the cavern. This influence can be modeled as semi-infinite when the fracture begins and the ratio of its length to the cavern radius is small enough [28].

Generally, for a collapsed cavern, the long and short half axes are separately assumed to be a and b. Hence the load is accordingly assumed to be P_0 and λP_0. If the rock mass is elastic and has not become plastic after the excavation, the fracture can be assumed to be circular for the purpose of simplification, with a radius of (Fig. 2)

$$R_c = \frac{2ab^2}{a^2 + b^2} + d \tag{1}$$

Then, the stress intensity factor (SIF) and of the fracture affected by the cavern can be expressed as [28]

$$K_1 = \frac{2\sqrt{\pi}}{\sqrt{R_c \sin\theta}(3 - \cos\theta)}\left[(F + \Delta F)\frac{3\cos\theta - 1}{2\pi} - (\sigma_\theta + \Delta\sigma_\theta)R_c \sin\theta \cos\frac{\theta}{2}\right] \tag{2}$$

wherein $F + \Delta F = 2a\overline{\beta}(\sigma_r + \Delta\sigma_r)$, $\overline{\beta} = \frac{2}{3\pi}$, $R = a + d$, $\sigma_\theta + \Delta\sigma_\theta$ is the tangential stress and $\sigma_r + \Delta\sigma_r$ is the radial stress of the surrounding rock mass.

2.2. The shallow buried tunnel

The stress distribution in a rock mass of a shallow buried tunnel is already known and can be expressed as [29]

$$\left.\begin{aligned} \sigma_\theta + \Delta\sigma_\theta &= P_0 \cdot \left[1 - \tfrac{a^2}{(a+d)^2}\right] = P_0 \cdot \left[1 - \tfrac{a^2}{r^2}\right] \\ \sigma_r + \Delta\sigma_r &= P_0 \cdot \left[1 + \tfrac{a^2}{(a+d)^2}\right] = P_0 \cdot \left[1 + \tfrac{a^2}{r^2}\right] \end{aligned}\right\} \tag{3}$$

Substituting formula (3) into formula (2), we then obtain

$$K_1(r) = \frac{2P_0\sqrt{\pi}}{\sqrt{r\sin\theta}(3 - \cos\theta)}\left\{\left[1 + \frac{a^2}{r^2}\right]\frac{2a(3\cos\theta - 1)}{3\pi^2} - \left[1 - \frac{a^2}{r^2}\right] r\sin\theta\cos\frac{\theta}{2}\right\} \tag{4}$$

Formula (9) shows that the SIF (Stress Intensity Factor) is a function of the radius of the circular fracture, i.e., the displacement from the fracture to the center of the cavern.

Taking the derivative of the SIF, we then have

$$\begin{aligned} K_1(r)' = &-\frac{2a(3\cos\theta - 1)}{3\pi^2}\left(\frac{1}{2}r^{-\frac{3}{2}} + \frac{5}{2}a^2 r^{-\frac{7}{2}}\right) \\ &- \sin\theta\cos\frac{\theta}{2}\left(\frac{1}{2}r^{-\frac{1}{2}} + \frac{3}{2}a^2 r^{-\frac{5}{2}}\right) \end{aligned}$$

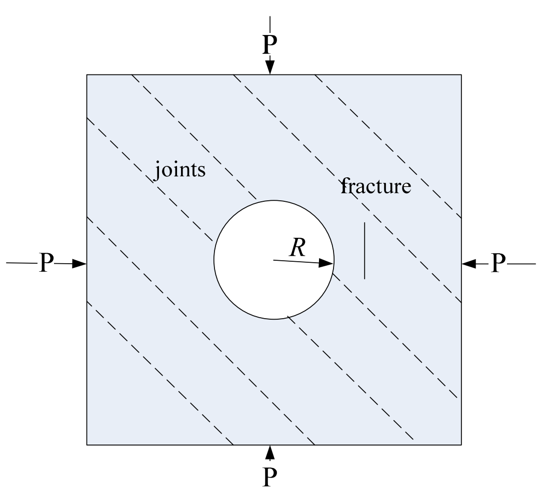

Fig. 1. The scheme of the crack distribution in enclosing rocks.

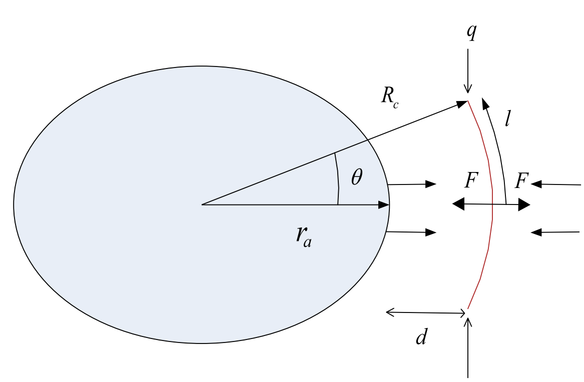

Fig. 2. A circular arc crack affected by an elliptical opening.