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THE EFFECTS OF THREE-DIMENSIONAL PENNY-SHAPED CRACKS ON ZONAL DISINTEGRATION OF THE SURROUNDING ROCK MASSES AROUND A DEEP CIRCULAR TUNNEL**

Xiaoping Zhou[1,2] **Qihu Qian**[3,4*] **Hanfei Song**[1,2]

([1]*School of Civil Engineering, Chongqing University, Chongqing* 400045*, China*)
([2]*State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing* 400045*, China*)
([3]*Engineering Institute of National Defense Engineering, PLA University of Science and Technology, Nanjing* 210007*, China*)
([4]*State Key Laboratory of Disaster Prevention & Mitigation of Explosion & Impact, PLA University of Science and Technology, Nanjing* 210007*, China*)

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ABSTRACT In this study, it was assumed that three-dimensional penny-shaped cracks existed in deep rock masses. A new non-Euclidean model was established, in which the effects of penny-shaped cracks and axial in-situ stress on zonal disintegration of deep rock masses were taken into account. Based on the non-Euclidean model, the stress intensity factors at tips of the penny-shaped cracks were determined. The strain energy density factor was applied to investigate the occurrence of fractured zones. It was observed from the numerical results that the magnitude and location of fractured zones were sensitive to micro- and macro-mechanical parameters, as well as the value of in-situ stress. The numerical results were in good agreement with the experimental data.

KEY WORDS deep rock masses containing penny-shaped cracks, the non-Euclidean model, axial in-situ stress, fractured zones, zonal disintegration phenomenon, deep circular tunnel

I. INTRODUCTION

Although it hasn't been observed in shallow rock engineering applications before, zonal disintegration phenomenon occurs in the surrounding rock masses around deep tunnels, which has drawn the attentions of many researchers[1–13]. Some researchers tried to study the zonal disintegration phenomenon using the classic elastoplastic model[5,6], which however, could not clearly explain the phenomenon. Other researchers tried to apply the non-Euclidean continuum model[7–11], fracture mechanics[12,13] and numerical methods[14] to reveal the zonal disintegration mechanism. Nevertheless, in the available literature, only the zonal disintegration phenomenon of deep rock masses containing two-dimensional penetrating cracks was investigated. In fact, cracks existed in rock masses are not two-dimensional but

* Corresponding author. E-mail: 277230437@qq.com
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three-dimensional, such as the 3-D joints and penny-shaped cracks. It was found from experimental observations that different from the nucleation, growth and coalescence of two-dimensional cracks, those of three-dimensional penny-shaped cracks obviously affected zonal disintegration of deep rock masses.

The effects of three-dimensional penny-shaped cracks and axial in-situ stress on the zonal disintegration haven't been taken into account in the available literature[7–14]. Therefore, it is significant to study such effects on zonal disintegration of the surrounding rock masses around deep circular tunnels.

In the present study, magnitude and location of non-fractured and fractured zones in deep rock masses containing penny-shaped cracks were investigated, as well as the stress fields of the surrounding rock masses around a deep circular tunnel.

II. THE STRESS FIELDS OF THE SURROUNDING ROCK MASSES

In this study, it is assumed that a deep circular tunnel with radius r_0 is subjected to the axial in-situ stress p_z, and the horizontal and vertical in-situ stresses σ_∞, as shown in Fig.1. The assumption of the axial normal strain ε_z not equaling zero leads to a non-plane-strain problem. Moreover, the discontinuous and incompatible deformations of rock-like material are considered using an incompatible strain tensor in the geometric equations. The internal space of rock-like material after deformation is treated as a non-Euclidean one[7–11]. The stress fields of the surrounding rock masses around a deep circular tunnel can be written as follows[9]:

$$\sigma_r = \left[\frac{p_z + 2\sigma_\infty - E\varepsilon_0}{2\,(1+\nu)}\right]\left(1 - \frac{r_0^2}{r^2}\right) - \frac{E}{2\rho^{3/2}(1-\nu^2)r}[AJ_1(\rho^{1/2}r) + BN_1(\rho^{1/2}r) + CK_1(\rho^{1/2}r)] \quad (1)$$

$$\begin{aligned}\sigma_\theta = &\left[\frac{p_z + 2\sigma_\infty - E\varepsilon_0}{2\,(1+\nu)}\right]\left(1 + \frac{r_0^2}{r^2}\right) - \frac{E}{2\rho(1-\nu^2)}[AJ_0(\rho^{1/2}r) + BN_0(\rho^{1/2}r) - CK_0(\rho^{1/2}r)]\\ &+ \frac{E}{2\rho^{3/2}(1-\nu^2)r}[AJ_1(\rho^{1/2}r) + BN_1(\rho^{1/2}r) + CK_1(\rho^{1/2}r)]\end{aligned} \quad (2)$$

$$\sigma_z = \left[\frac{\nu\,(p_z + 2\sigma_\infty) + E\varepsilon_0}{1+\nu}\right] - \frac{\nu E}{2\rho(1-\nu^2)}[AJ_0(\rho^{1/2}r) + BN_0(\rho^{1/2}r) - CK_0(\rho^{1/2}r)] \quad (3)$$

where

$$\rho^2 = E/[2q(1-\nu)];\ A = (C/2)\pi\sqrt{\rho}r_0[K_0(\sqrt{\rho}r_0)N_1(\sqrt{\rho}r_0) - K_1(\sqrt{\rho}r_0)N_0(\sqrt{\rho}r_0)]$$
$$B = (C/2)\pi\sqrt{\rho}r_0[K_0(\sqrt{\rho}r_0)J_1(\sqrt{\rho}r_0) - K_1(\sqrt{\rho}r_0)J_0(\sqrt{\rho}r_0)]$$

And C coincides with the Wronskian of the linearly independent solutions J_0 and N_0; J_0, N_0 and K_0 are zero-order Bessel, Neumann, and MacDonald cylindrical functions, respectively. E is Young's modulus, ν is Poisson's ratio, p_z is the axial in-situ stress, ε_0 is the axial normal strain before excavation, q is the fitting parameter of the model determined upon experimental data, σ_∞ is hydrostatic in situ stress, and r_0 is radius of the circular tunnel.

III. EFFECTS OF PENNY-SHAPED CRACKS ON ZONAL DISINTEGRATION

In this study, the deep rock masses containing a set of the parallel penny-shaped cracks are isotropic and linear elastic. All cracks are assumed to be penny-shaped with the same radius of a in their initial states before loading. The spacing between penny-shaped cracks is $2d$; the dip of preexisting penny-shaped cracks is θ; and the orientation of preexisting penny-shaped cracks is ϕ.

First the a-th single penny-shaped crack in an isotropic body uniformly loaded from far field (Fig.2) is considered. The global coordinate system $(ox_1x_2x_3)$ and its corresponding local coordinate system $(ox_1'x_2'x_3')$ are established, as shown in Fig.2, in which the x_2'-axis is parallel to the normal vector of the microcrack n, and the x_3'-axis is coplanar with the x_1-axis and the x_3-axis. Then, the orientation of the microcrack can be expressed as (θ, ϕ).

The stresses in the local coordinate system $(ox_1'x_2'x_3')$ are given by[15]

$$\sigma_{ij}' = g_{ik}'g_{jl}'\sigma_{kl} \quad (4)$$