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Analytical investigation for stress measurement with the rheological stress recovery method in deep soft rock

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ABSTRACT

Due to the difficulty and weakness of current stress measurement methods in deep soft rock, a new rheological stress recovery method of the determination of the three-dimensional (3D) stress tensor is proposed. It is supposed that rock stresses will recovery gradually with time and can be measured by embedding transducers into the borehole. In order to explore the applicability and accuracy of this method, analytical solutions are developed for stress measurement with the rheological stress recovery method in a viscoelastic surrounding rock, the rheological properties of which are depicted as both the Burger's model and a 3-parameter solid model. In such conditions, explicit analytical expressions for predicting time-dependent pressures on the transducer are derived. A parametric analysis is then adopted to investigate the influences of the grout solidification time and the mechanical properties of the grout layer. The results indicate that this method is suitable for stress measurement in deep soft rock, the characteristics of which are soft, fractured and subjected to high geo-stress.

1. Introduction

In-situ stress is one of the most important parameters for designing stable underground structures and improving mining methods in deep soft rock. Rock stresses originate from gravity and tectonic forces and can only be inferred by drilling a borehole, making a slot and coring the rock [1]. A large number of stress measuring methods have been developed and a detailed summary of these techniques can be found in previous works [2–4]. These methods for determining in-situ stresses have been divided into Borehole Techniques (e.g., over-coring, hydraulic fracturing and borehole breakouts) and Core-Based Methods (e.g., anelastic strain recovery, Kaiser effect) [5].

However, in recent years, with the decrease of shallow coal resources in China, most of the key collieries have mined deep coal seams, the surrounding rocks of which are soft and fragmentized. In the prior art, limitations and measurement errors exist and effective testing is very difficult. Hydraulic Fracturing (HF) can only determine the maximal and minimal principle stresses in a plane vertical to the borehole and is limited in highly anisotropic and fractured rock due to the assumption of continuous, linear elastic and isotropic rocks [6–8]. Borehole relief methods, which are subdivided into over-coring of cells in pilot holes, over-coring of borehole-bottom cells and borehole slotting [9–12], can be strongly influenced by the stress path, constitutive law and associated parameters [4]. In addition, it is ineffective in areas with extremely high geo-stress due to rock core disking [13].

Other stress measuring methods such as borehole breakout and Kaiser effect [14,15], which estimate rock stresses based on the phenomenon relevant to stresses, have relatively low reliability and are controversial as a method to determine in-situ stress. Anelastic Strain Recovery (ASR) method [16] requires orientated rock cores and is affected by a lot of factors (e.g., temperature variation, dehydration of samples, accurate orientation). Therefore, it is important to develop a new method to measure in-situ stress in deep soft rock.

A large number of field monitoring and laboratory tests [17,18] have shown that the rheological properties of soft rocks are very significant under high geo-stress. Even for a hard rock mass that is cut by several joints and fractures, creep deformation can also attain considerable magnitude [19]. Thus, a borehole will shrink gradually to be closed under high geo-stress due to the rheological characteristic of weak rocks and the rock stress will return to the initial stress state over time. Based on this, stress measurement with a rheological stress recovery method is proposed. It is supposed that pressure transducers are embedded in the borehole and rock stresses on the pressure transducers will recover gradu-

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ally and eventually tend to be stable due to the rheological characteristics of surrounding rocks. In this study, after a brief description of stress measurement with the rheological stress recovery method, the measuring process is analyzed by analytical solutions to explore the applicability and accuracy of this method.

2. Description of the rheological stress recovery method

The stress state of a certain point contains six independent stress components and one sensing face of a pressure transducer can only measure one normal stress. Thus, the calculation of the stress tensor needs to measure six normal stresses in different directions. A spatial coordinate system *oxyz* is established by taking normal directions of three mutually perpendicular sensing faces as directions of coordinate axes, and the x', y', z' axis are normal directions of the other three sensing faces. $\sigma_x, \sigma_y, \sigma_z, \sigma'_x, \sigma'_y, \sigma'_z$ are normal stresses measured by each sensing face respectively. The stress state $(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx})$ of the test point can be calculated through Eq. (1).

$$\begin{cases} \sigma'_x = l_1^2\sigma_x + m_1^2\sigma_y + n_1^2\sigma_z + 2l_1m_1\tau_{xy} + 2m_1n_1\tau_{yz} + 2n_1l_1\tau_{zx} \\ \sigma'_y = l_2^2\sigma_x + m_2^2\sigma_y + n_2^2\sigma_z + 2l_2m_2\tau_{xy} + 2m_2n_2\tau_{yz} + 2n_2l_2\tau_{yz} \\ \sigma'_z = l_3^2\sigma_x + m_3^2\sigma_y + n_3^2\sigma_z + 2l_3m_3\tau_{xy} + 2m_3n_3\tau_{yz} + 2n_3l_3\tau_{yz} \end{cases} \tag{1}$$

where τ_{xy}, τ_{yz}, τ_{xz} are shear stress components; l_1, l_2, l_3 respectively represent direction cosines between x', y', z' axis and x axis; m_1, m_2, m_3 respectively represent direction cosines between x', y', z' axis and y axis and n_1, n_2, n_3 respectively represent direction cosines between x', y', z' axis and the z axis.

The method for measuring the stress in deep soft rocks based on the rheological stress recovery principle comprises the following steps (Fig. 1): (1) A borehole is drilled as far as the test point in the surrounding rock of a soft rock tunnel; (2) Stress transducers are fixed on a connecting rod, and sent to the test point; a direction cosine of any two sensing faces in the normal direction is recorded and is not 1; a normal stress measuring device is mounted on each sensing face and connected with a data logger outside the borehole through long cables; (3) Grouting is carried out in the borehole, and the borehole is sealed after being entirely filled; and (4) after the grout has solidified, pressure values are continually read from the data logger and six stress values are substituted into the testing principle formula (Eq. (1)) after the values are stable, so as to obtain the rock stress at the test point.

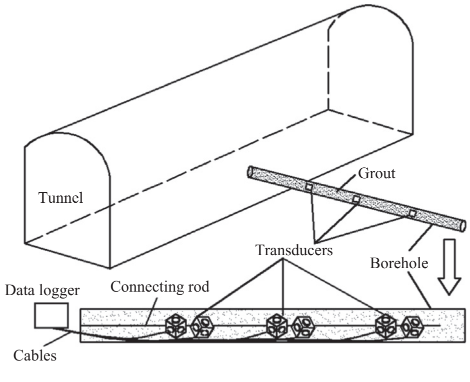

Fig. 1. Sketch of the stress measurement process with rheological stress recovery method.

3. Definition of the problem

In this paper, a two-dimensional (2D) model of the stress measurement process is conducted to determine the recovery stress on the pressure transducer. The transducer, which is adhered to the borehole by the elastic grout layer, is thought to be hollow and elastic. The cross-sections of the transducer, grout layer and the borehole are circular and concentric, as shown in Fig. 2. The interfaces between the rock and the grout layer and between the grout layer and the transducer are assumed to be smooth. The surrounding rocks are homogeneous, isotropic and linearly viscoelastic and the lateral pressure coefficient is λ.

Regarding the above assumptions, the problem is considered as a 2D infinite viscoelastic plane subjected to a biaxial stress, which treats a geometrically similar problem with tunnel linings in circular tunnels [20,21]. The process of stress measurement can be divided into two stages: during the first stage, spanning from borehole excavation until the time at $t = t_0$, pressure of the surrounding rock is released and there is no pressure on the grout layer or the transducer. The second stage spans from the time of the solidification of the grout, at $t = t_0$, onwards. The contact pressures between the rock and the grout layer and between the grout layer and the transducer, which will vary with time, are assumed as $p(t)$ and $q(t)$, respectively.

For such a biaxial plane strain condition, a cylindrical coordinate system (r, θ, z) is employed and the in-situ stress at infinity $(r = \infty)$ can be written as follows (Eq. (2)):

$$\begin{cases} \sigma_r = \frac{P}{2}[(1+\lambda) + (1-\lambda)\cos 2\theta] \\ \sigma_\theta = \frac{P}{2}[(1+\lambda) - (1-\lambda)\cos 2\theta] \\ \tau_{r\theta} = -\frac{P}{2}(1-\lambda)\sin 2\theta \end{cases} \tag{2}$$

where σ_r is the radial stress of the rock, σ_θ is the hoop stress of the rock, $\tau_{r\theta}$ is the shear stress of the rock and P is the vertical in-situ stress.

The in-situ stress can be divided into two parts: a uniform part and a non-uniform part. Correspondingly, the contact pressures on the interfaces can also be divided into uniform and non-uniform parts:

$$p(t) = p_0(t) + p_1(t)\cos 2\theta \tag{3}$$

$$q(t) = q_0(t) + q_1(t)\cos 2\theta \tag{4}$$

where $p_0(t)$ and $q_0(t)$ are contact stresses under uniform in-situ stress, $p_1(t)\cos 2\theta$ and $q_1(t)\cos 2\theta$ are contact stresses under non-uniform in-situ stress.

After the grout has solidified ($t > t_0$), the boundary condition for this problem is

$$u_{rc}(r_0, t) = u_r(r_0, t) \quad \text{and} \quad u_{rT}(r_1, t) = u_{rc}(r_1, t) \tag{5}$$

where u_r, u_{rc}, u_{rT} are the radial displacements in the rock, the grout layer and the transducer, respectively; r_0 is the radius of the borehole and r_1 is the external radius of the transducer.

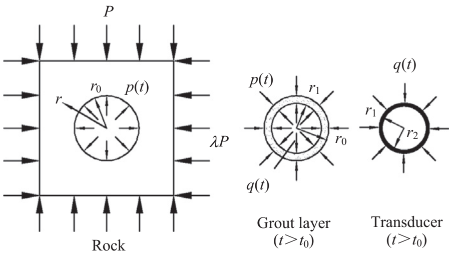

Fig. 2. Illustration of the radii of the grout layer and the transducer.

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