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An Estimation Method of Stress in Soft Rock Based on In-situ Measured Stress in Hard Rock

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Abstract: The law of variation of deep rock stress in gravitational and tectonic stress fields is analyzed based on the Hoek-Brown strength criterion. In the gravitational stress field, the rocks in the shallow area are in an elastic state and the deep, relatively soft rock may be in a plastic state. However, in the tectonic stress field, the relatively soft rock in the shallow area is in a plastic state and the deep rock in an elastic state. A method is proposed to estimate stress values in coal and soft rock based on in-situ measurements of hard rock. Our estimation method relates to the type of stress field and stress state. The equations of rock stress in various stress states are presented for the elastic, plastic and critical states. The critical state is a special stress state, which indicates the conversion of the elastic to the plastic state in the gravitational stress field and the conversion of the plastic to the elastic state in the tectonic stress field. Two cases studies show that the estimation method is feasible.

Key words: rock stress; gravity stress; tectonic stress; critical depth; estimation method

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1 Introduction

The demand for energy increases rapidly in China with the development of the economy. Therefore, rock bolting and fully mechanized top-coal caving methods should be popularized in coal mines to improve their production efficiency. Rock stress plays a key role in the application of these methods in coal mines and has been an important topic debated largely in both engineering geology and rock mechanics all over the world. Although much research in this area has been done both at home and abroad, at present in-situ stress measurements are still the primary means to estimate rock stress[1–3]. Hydraulic fracturing and stress-relief methods are the two main means of in situ stress measurement[4]. However, the cost of using these methods is very high and so it is impractical to measure rock stresses at different depths. In practice, only a few in-situ measured stresses are used in engineering designs, even in the design of key projects. It should be noted that a few measured stress values in coal mines cannot reflect the entire stress field. In addition, only the stress in hard rock can be measured by hydraulic fracturing and stress-relief methods while the stress in coal seams and soft rock cannot be measured at all. In fact, merely the stability of coal and soft rock is a troublesome problem which, up to now, has not been adequately solved, seriously hampering safe production in coal mines[5].

The field of rock stress is not uniform due to various important factors. In spite of considerable debate about these factors, there are some common viewpoints about them[6–7]. Rock stress is affected by some factors, such as surface topography, geological structures and lithology[8]. Points of view about the formation mechanism of natural rock stress are, on the whole, identical. There are two key factors causing stress in rock, of which one is the gravitational stress resulting from the weight of rocks themselves and the other is tectonic stress induced by the activity of the earth crust. In other words, the stress field at any point is assumed to be comprised of gravitational and tectonic components[9–10]. The gravitational com-

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ponent is assumed to be vertical and the principal stress, while the tectonic component is assumed to act entirely on the horizontal plane far afield.

We propose a simplified method for estimating rock stress by taking the above mentioned situations into consideration. In this method, the stress of soft rock is calculated based on the in-situ measured stress of hard rock. For those coal mines where not enough stress data can be obtained due to cost or other factors, the rock stress calculated by this method can be for reference. In the following discourse, the estimation method in gravitational and tectonic stress fields will, respectively, be introduced.

2 Gravitational Stress Field

A great deal of in-situ measured results demonstrate that vertical stress approximately equals its own weight of overburden rock, i.e., gravitational stress is the maximum principal stress in the gravitational stress field.

2.1 Isotropic rock

Strictly speaking, isotropic rock does not exist. In practice, however, a large number of rocks can be considered isotropic. In the gravitational stress field, rock in the shallow area behaves elastic with little stress; rock stress becomes larger with increased depth. If the rocks are buried deep enough, the rock will become plastic, i.e., it is in a natural plastic state [11]. The depth indicating the conversion to a natural plastic state from the elastic state is defined as the critical depth, denoted by H_{cr}. The rock above this critical depth behaves as if it is elastic and the rock below it behaves as if it is plastic. It is to be noted that the critical depth of different rocks varies, as is shown below. The calculation method of the critical depth H_{cr} is as follows.

At depth h, the stress components (σ_v, σ_H, σ_h) of linearly elastic and isotropic rock can be written as

$$\begin{cases} \sigma_v = \gamma \cdot h \\ \sigma_H = \dfrac{\nu}{1-\nu}\sigma_v \\ \sigma_h = \sigma_H \end{cases} \quad (1)$$

where σ_v is the vertical stress, σ_h and σ_H are the minimum and maximum principal stresses in the horizontal direction, h is the buried depth of rock, ν the Poisson ratio for rock, and γ the average unit density of overburden rock which equals 0.025–0.027 MPa/m for most rocks.

At the critical depth H_{cr}, where $h=H_{cr}$, the stress components can be expressed as

$$\sigma_v = \gamma \cdot H_{cr}, \quad \sigma_H = \sigma_h = \frac{\nu}{1-\nu}\gamma \cdot H_{cr} \quad (2)$$

Note that the rock at the critical depth starts to become plastic given the definition of critical depth H_{cr} so that the stress components should satisfy the Hoek-Brown yield criterion. That is

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^{\ 2}} \quad (3)$$

where σ_3 and σ_1 are the minimum and maximum principal stresses, σ_c is the uniaxial compression strength of rock; m and s are rock structure constants, obtained from the table of constants proposed by Hoek-Brown.

In the gravitational field, the following expressions can easily be obtained:

$$\sigma_v = \sigma_1, \quad \sigma_H = \sigma_h = \sigma_3 \quad (4)$$

Combining equation (2) with equations (3) and (4), the critical depth H_{cr} can be expressed as:

$$H_{cr} = \frac{m\lambda + \sqrt{(m\lambda)^2 + 4s(1-\lambda)^2}}{2\gamma(1-\lambda)^2} \quad (5)$$

where λ is the lateral pressure coefficient, i.e. $\lambda = \dfrac{\nu}{1-\nu}$. In equation (5), the critical depth H_{cr} relates to rock parameters (λ, m, s) and so the critical depth H_{cr} of different rocks varies, showing that rock structure and lithology have an enormous effect on rock stress.

As presented in Fig. 1, the rock over the critical depth H_{cr} behaves as if it was elastic and the rock below the critical depth becomes plastic in the gravitational stress field. The equations for calculating rock stress can be decided by comparing the critical depth H_{cr} with h, the depth of the rock (Fig. 1).

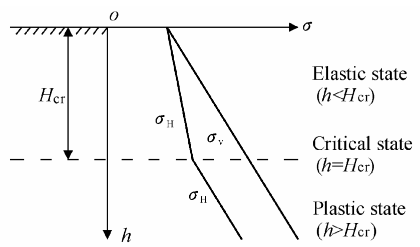

Fig. 1 Rock stress state in a gravitational stress field

If $h \leqslant H_{cr}$, i.e., above the critical depth, the rock becomes elastic and the rock stress components can be calculated by equation (1). When $h>H_{cr}$, i.e., below the critical depth, the rock becomes plastic and the rock stress should satisfy the Hoek-Brown criterion, i.e. equation (3), assuming that the rock is elastic perfectly plastic. By combining equation (5) with equations (2), (3) and (4), the rock stress components below the critical depth H_{cr} can be expressed as.

$$\begin{cases} \sigma_v = \gamma \cdot h & (h > H_{cr}) \\ \sigma_h = \sigma_v + \dfrac{1}{2}m\sigma_c - \sqrt{m\sigma_c\sigma_v + \dfrac{1}{4}m^2\sigma_c^{\ 2} + s\sigma_c^{\ 2}} \\ \sigma_H = \sigma_h \end{cases} \quad (6)$$