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Criterion of local energy release rate of gob instability in deep mines considering unloading stress path

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ABSTRACT

The stress path characteristics of surrounding rock in the formation of gob were analyzed and the unloading was solved. Taking Chengchao Iron Mine as the engineering background, the model for analyzing the instability of deep gob was established based on the mechanism of stress relief in deep mining. The energy evolution law was analyzed by introducing the local energy release rate index (*LERR*), and the energy criterion of the instability of surrounding rock was established based on the cusp catastrophe theory. The results show that the evolution equation of the local energy release of the surrounding rock is a quartic function with one unknown and the release rate increases gradually during the mining process. The calculation results show that the gob is stable. The *LERR* per unit volume of the bottom structure is relatively smaller which means that the stability is better. The *LERR* distribution showed that there was main energy release in the horizontal direction and energy concentration in the vertical direction which meets the characteristics of deep mining. In summary, this model could effectively calculate the stability of surrounding rock in the formation of gob. The *LERR* could reflect the dynamic process of energy release, transfer and dissipation and that provided an important reference for the study of the stability of deep mined out area.

1. Introduction

Compared with ground engineering, the original state of an underground rock mass is not in an absolute equilibrium state, but in relative equilibrium. The stress state of the rock mass is three-dimensional, and a large amount of energy is stored in the rock. In fact, the formation of gob is accompanied by the release and transfer of the stress in a certain direction. The stress state of the rock changes dramatically from three-dimensional to two-dimensional, even a uniaxial state. When the change of stress exceeds the rock strength, the gob will destabilize. The instability of the gob is caused by stress release which is called unloading [1–4].

Stability analysis mainly focuses on shallow gob. The influence factors of stability and failure mechanisms of gob are qualitatively analyzed and the evolution law of stress, displacement and plastic zones are revealed from a macro point of view [5–8].

Based on catastrophe theory, Zhao established the strength reduction method of stability analysis of overlapping roof of a gob [9]. The safety thickness of overlapping roof was studied, and the vertical displacement sequence of the overlapping roof and the catastrophe model of reduction coefficient were established. Li studied extensively the instability mechanism of the pillar-roof system and derived the instability mechanism based on plate-shell and nonlinear dynamics theory [10]. Tulu studied the influence of overlying strata thickness and span on the pillar stress and provided the basis for the design of gob pillar through theoretical analysis and numerical simulation [11]. Kripakov simulated the whole destabilization process of gob using the ADINA method and studied the instability mechanism of gob [12].

With increases in mining depth, the instability mechanism and the stability characteristics of gob would be significantly different due to the rapid growth of stress and the complexity of the occurrence environment.

Firstly, the damage form of rock transforms gradually from brittle fracture to ductile fracture, which is the reason that the gob can maintain stability after larger deformation of rock. This means that the stable standards of gob in shallow mines are no longer suitable for the gob in deep mines.

Secondly, the stability of gob in shallow mines is analyzed and evaluated using stress, strain, plastic zones, etc., but after entering

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into the deep stage, there is a great amount of elastic energy stored in the rock due to the high pressure. Mining will cause a sharp energy release which may lead to an instant burst of rock, but stress is less than the rock strength. Since the traditional indicators are not suitable for evaluation of rock stability, it is necessary to introduce new research indicators to accurately obtain the stability mechanism and characteristics of gob [13].

2. Unloading process during the formation of gob and numerical method

2.1. Process and calculation of unloading

Underground mining is actually a process of unloading. It can be seen from rock mechanics experimental test results that rock strength is often higher under triaxial loading, but the unloading causes a rapid deterioration of the rock strength. In general, the stress change includes loading and unloading in the process of underground mining. The stress state of the surrounding rock is shown in Fig. 1.

Actually, the formation of gob is the process of appearance and disappearance of unbalanced forces, so the unloading force is a kind of unbalanced force. The unloading force can be obtained by computing the unbalanced force. The unloading force is the nodal unbalanced force in the finite element method [14]. Taking the triangular element as an example, the force at each node is shown in Fig. 2.

The force of the triangular nodal satisfies the relationship which can be expressed as:

$$\{F\}_e = \{F_{ix}, F_{iy}, F_{jx}, F_{jy}, F_{mx}, F_{my}\}^T = [K]_e\{\delta\}_e \tag{1}$$

where {F}e is the nodal force; $[K]_e$ is the element stiffness matrix.

Then, based on elastic mechanics, the following equation can be obtained:

$$\begin{aligned}[K]_e\{\delta\}_e &= t \cdot \Delta_e \cdot [B]^T \cdot [D] \cdot [B]\{\delta\}_e = t \cdot \Delta_e \cdot [B]^T \cdot [S]\{\delta\}_e \\ &= t \cdot \Delta_e \cdot [B]^T \cdot \{\sigma\}_e\end{aligned} \tag{2}$$

where $\varDelta_e$ is the area of the triangle which can be expressed as:

$$\Delta_e = \frac{1}{2}\begin{bmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_m & y_m \end{bmatrix} \tag{3}$$

$[D]$ is the element elasticity matrix and $[B]$ is a geometric matrix. They can be expressed as:

$$[D] = \frac{E}{1-\mu^2}\begin{vmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & (1-\mu)/2 \end{vmatrix} \tag{4}$$

$$[B] = \frac{1}{2\Delta_e}\begin{vmatrix} b_i & 0 & b_j & 0 & b_m & 0 \\ 0 & c_i & 0 & c_j & 0 & b_m \\ c_i & b_i & c_j & b_j & c_m & b_m \end{vmatrix} \tag{5}$$

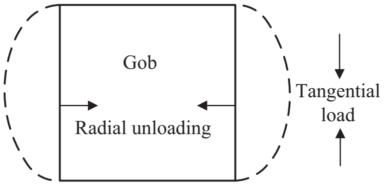

Fig. 1. Stress state of surrounding rock during the formation of gob.

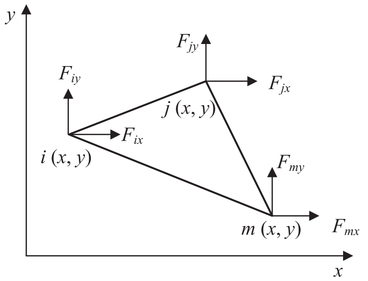

Fig. 2. Diagrams of force of triangular element.

where E is the rock elastic modulus and μ is a Poisson's ratio. Other parameters satisfy the following relationships which can be expressed as: $b_i = y_j - y_m$, $b_j = y_m - y_i$, $b_m = y_i - y_j$, $c_i = x_m - y_j$, $c_j = x_i - x_m$, $c_m = x_j - x_i$.

The element stress on the center of gravity is $\{\sigma\}_e$ can be expressed as:

$$\{\sigma\}_e = \{\sigma_x, \sigma_y, \tau_z\}^T \tag{6}$$

Substituting Eqs. (5) and (4) into Eq. (2), the following equation can be obtained as:

$$[F_{ix}, F_{iy}, F_{jx}, F_{jy}, F_{mx}, F_{my}]^T = t \cdot \begin{vmatrix} b_i & 0 & b_j & 0 & b_m & 0 \\ 0 & c_i & 0 & c_j & 0 & b_m \\ c_i & b_i & c_j & b_j & c_m & b_m \end{vmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{pmatrix} \tag{7}$$

Adding all the nodal forces together, the unbalanced force can be obtained as:

$$\begin{cases} F_{sx} = \sum\limits_e F_{sx}^e \\ F_{sy} = \sum\limits_e F_{sy}^e \end{cases} \tag{8}$$

Obviously, the sum of the nodal force of the unexploited region is zero while the sum of nodal forces on the boundary of the mining region is not zero. This means that an unbalanced force (the unloading force on the mining region boundary) appears.

2.2. Numerical simulation of unloading

A computer program was developed based on the method in the previous section. The calculation procedures include the following steps:

(1) To build the model which contains the mining area, then to mesh the model. The mining area can be meshed fine and modeled independently according to the mining sequence.
(2) To apply the stress and displacement boundary conditions and initialize the ground stress, then to calculate the initial nodal stress (σ_0) of elements.
(3) To mine the ore in the mining region and calculate all the nodal stresses (σ'). Before carrying out the addition operation, the mining disturbed zone (MDZ) should be determined. The stress and displacement of nodes in the MDZ are added together. Then the unloading stress and displacement are obtained as:

$$\sigma_1 = \sigma_0 + \sigma' \tag{9}$$

There are generally many mining steps which means multiple calculations of unloading. The unloading stress of any step is the previous nodal stress coupled with the nodal stress which can be expressed as:

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