PREDICTION OF BLOCK CAVING RATE USING SUBCRITICAL CRACK GROWING VELOCITY①

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ABSTRACT Block caving is a productive method of mining without drilling and blasting, whose output of ore is determined by the caving process of orebody. Therefore a method to predict the caving of orebody using the priniciple of crack growing rate was developed. With the method the orebody caving rate of Tongkuangyu copper mine in China has been predicted.

Key words subcritical crack growth double torsion testing block caving rate block caving

1 INTRODUCTION

Block caving is a mass mining method of sustained production at relatively low cost, which is applicable only to large orebodies. When the temporary pillar remained during undercut excavation are removed, failure and progresive collapse of the undercut crown occur. It is noted that factors considered in evaluating the caving potential of an orebody include the pre-mining state of stress, the frequency of joints and other fracture zone, and the mechanical properties of the rock mass. The key issue to be addressed when considering the use of block caving is the cavability of the orebody. It is generally considered that, the ability of a block to cave is a function of its strength in tension or shear stress conditions, the in-situ stress field, the geometry and the mechanics properties of the discontinuities in the orebody. Based on these factors, the cavability of the orebody is predicted with certain undercut span, boundary slots and boundary mass weakening[1].

This productive method is used in Tongkuangyu(TKY) mine in north of China, the main rocks are grano diorite and quartzite with brittle and hard properties and there are developed joints in the mine. In order to study the collapsing laws of the orebody without drilling and blasting, simulative model experiments had been done. The experiments indicated that if the area of undercut in the model has been large enough cracks in the simulative material would open and grow. In an interval of time, some cracks in the material grow with high speed, the extended cracks penetrate together with joints to cut a part of simulative material apart from the model and make a paroxysm of caving of simulative material[2]. Based on the experiments, it can be seen that the caving of orebody is a fracture process, the cavability of orebody is related with time. The laws of orebody caving with time is called as block caving rate here. The prediction of block caving rate is based on a developement of the prediction of caving ability. The simulative experiments showd that the caving rate of orebody can be predicted employing subcritical crack growth concept of rock fracture mechanics. With the priniciple the caving rate of orebody is predicted for TKY mine.

2 EXPERIMENTAL

2.1 *Theoretical consideration*

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The subcritical crack growth is a process of stress damage of material. If the stress intensity factor at crack tip is greater than the critical value K_{ISOC} which is less than the fracture toughness K_{IC}, crack begins to grow with low velocity. To obtain crack growing rate and fracture toughness double torsion sample, which has constant stress intensity factor at the crack tip, were used[3,4]. The tests were conducted with constant displacement or constant displacement rate control.

It is well known that the stress intensity factor at crack tip of double torsion sample and the displacement at the load acting point can be expressed respectively as:

$$K_I = AP \quad (1)$$

$$y = PBa \quad (2)$$

where A and B are constant value related to elastic properties and size of sample, P is load and a is the length of crack of the double torsion sample. From Eq. (2) the rate of displacement $\mathrm{d}y/\mathrm{d}t$ can be derived:

$$\frac{\mathrm{d}y}{\mathrm{d}t} = Ba\frac{\mathrm{d}P}{\mathrm{d}t} + BP\frac{\mathrm{d}a}{\mathrm{d}t} \quad (3)$$

From Eq. (3) the subcritical growing rate of crack $\mathrm{d}a/\mathrm{d}t$ can be obtained conveniently if the tests were controlled with constant $\mathrm{d}y/\mathrm{d}t$ or constant y. It is known that if $\mathrm{d}y/\mathrm{d}t$ is a constant, the load P keeps constant too during the crack growing[5], so the growing rate of crack can be expressed as following respectively:

$$v = \frac{\mathrm{d}a}{\mathrm{d}t} = \frac{1}{BP}\frac{\mathrm{d}y}{\mathrm{d}t} \quad (4)$$

or $$v = -\frac{a}{P}\frac{\mathrm{d}P}{\mathrm{d}t} = -\frac{y}{P^2B}\frac{\mathrm{d}P}{\mathrm{d}t} \quad (5)$$

2.2 *Experiment*

The double torsion specimens had been tested with constant displacement or constant displacement rate controlling for the typical rock samples as grano-diorite and quartzite of KTY mine. The displacement rate $\mathrm{d}y/\mathrm{d}t$ is controlled at 0.5 mm/min. The obtained rates of subcritical crack growing with the two methods were in good agreement. It is known from the results that $\lg v$ and stress intensity factor $\lg K_I$ has linear relation as that reported before[6,7]:

$$\lg v = a + b\lg K_I \quad (6)$$

where a and b are constant values, the formula can be written as:

$$v = AK_I^n \quad (7)$$

After regressing to the experiment results, the constant values for the main copper ore grano-diorite in TKY mine were obtained as following:

$$A = 10^{-674}\ \mathrm{m/s}$$

$$n = 105.1$$

Simultaneously, the fracture toughness of grano-diorite was obtained as 2.68 MN/m$^{3/2}$, and the critical value of stress intensity factor as crack begining growth K_{ISOC} is 0.86~0.94 K_{IC}.

3 DETERMIMATION OF CAVING DURATION USING ROCK FRACTURE MECHANICS

Assuming, if the area of undercut in orebody is large enough, some cracks in the undercut crown open and grow progressively only by tension stress. Since the rock mass in TKY mine is brittle and hard, it can be supposed that the resistances during cracks growing can be ignored, so the interval of time between crack begining growth to failure is related with the crack growing rate only. Supposing the cracks in TKY mine are penny shaped, so the interval of time from cracks starting growing to failure can be expressed by the subcritical growing rate of crack:

$$t = \int_{a_i}^{a_C}\frac{\mathrm{d}a}{v} \quad (8)$$

where a_i —the initial radius of disc crack; a_C —the critical radius of disc crack; v —the subcritical crack growing rate.

It is known that the stress intensity factor can be expressed with the stress at the crack tip and the raduis, a, of penny shaped crack:

$$K_I = 2\sigma\sqrt{a/\pi} \quad (9)$$

From Eqs. (7), (8) and (9) there is:

$$t = \frac{\pi}{2A\sigma^2(n-2)}\left[\frac{1}{K_{Ii}^{n-2}} - \frac{1}{K_{IC}^{n-2}}\right] \quad (10)$$

where K_{Ii} is the initial stress intensity factor of crack when no crack growth had been appeared. For the relation of fracture toughness and tension strength, the stress intensity factor can be expressed as:

$$K_{\mathrm{I}i} = (\sigma/\sigma_t)K_{\mathrm{IC}} \quad (11)$$

where σ_t is tension strength of rock sample, it is 6.1 MPa for grano-diorite sample of TKY mine. From Eqs. (10), (11) and that $(\sigma/\sigma_t) < 1$, $n = 105.1$, the interval of time t can be expressed approximately:

$$t = \frac{\pi}{2A\sigma^n(n-2)}(\sigma_t/K_{\mathrm{IC}})^{n-2} \quad (12)$$

Substituting the relative constant values into the formula, the interval of time for TKY mine's ore is

$$t = 1.02 \times 10^{709}/\sigma^{105.1} \quad (13)$$

where the unit of t is second and that of σ is Pa. From the formula it is known that the interval of time between two caving of orebody is a function of stress acting on the crack only, if the stress intensity factor at crack tip K_I is greater than K_{ISOC}.

4 PREDICTION OF BLOCK CAVING RATE FOR TKY MINE

Essentially, the prediction of orebody caving rate is to determine the area of undercut and the way of boundary slots and boundary mass weakening when orebody caves continuously. Eq. (13) showed that if a critical tension stress is given, an interval of time can be determined by the end of the interval at that the crack extends with high speed. The extended cracks run through together with joints in orebody and lead a part of ore to be cut off from orebody, and the ore will collapse itself under the action of gravity.

For block caving problem, it is usually known that the stress condition in undercut crown can be evaluated by numerical analysis method, so the surface of caved ore can be determined conveniently if a critical stress has been given. Supposing that there is a maximum interval of time in which orebody may collapse under the action of critical stress, from Eq. (13) the critical tension stress can be calculated with the maximum interval of time. It is known from experience that if rock mass or orebody does not collapse in three days, the rockmass will be considered as stable relatively. Thus seventy-two hours is selected as the maximum interval of time between two cavings for TKY mine by ignoring slight step of orebody caving in practice. Substituting the interval of time seventy-two hours into Eq. (13), the relative critical stress is obtained reversely. Assuming the critical stress is exactly the yield stress, the caved surface in orebody can be found. So the prediction of block caving rate of orebody is realized in the way.

Combining the laws and results of experiments and theory analysis, the prediction of orebody caving rate can be carried out with computer finally. Since the mechanical model of block caving is very large, three dimension Boundary Element Method is used as the numerical analysis method to calculate the stresses and displacements for TKY mine. The mechanical properties of jointed rock mass is determined by effective constitutive equation considering the properties of rock samples, the geometry and properties of joints in the rock mass or orebody[8, 9]. Comparing the critical stress related with the interval of time and the stresses analysed with 3-D BEM, a curved surface can be enclosed in orebody in which the ore may collapse in the interval of time. For the 5th orebody of TKY mine, predictions of block caving rate of the orebody had been made for different area of undercut and boundary weakening before the orebody was mined. The predicted results show that while the area of undercut arrives 4 000 m^2 without boundary weakening, the orebody begins to collapse continously, and the output of ore is about 4 000 t a day. If the undercut area increases to 6 500 m^2, it is shown from the predicted results that the orebody will cave effectively and periodically, the output of ore can arrive at about 23 000 t a day without any weakening in the orebody. Corresponding to the outputs of 4 000 t and 23 000 t ore, the insitu measument area of undercut is 3 500 m^2 and 5 800 m^2 respectively without any boundary weakening. The other predicted results such as heights and areas of caved region of the orebody are also in good agreement with in-situ measument results. Guided with the predicted results, no boundary weakening is used up to now in the mine, and the orebody caves normally as predicted. In the engineering point of view, the predicted method is accepatable.

5 CONCLUSION

Block caving method is used in the mine with developed joints, the caving of orebody is induced by subcritical growing of crack in ore and the action of joints in orebody, it is a fracture process related with time which can be simulated by combining the subcritical growing rate of crack in ore and numerical analysis method. The subcritical crack growing rate of rock can be tested with double torsion testing method effectively and conveniently. As an application of rock fracture mechanics in ming engineering, the caving rate of orebody of TKY mine is predicted with the subcritical crack growth of the orebody. Comparing the predicted results and in-situ measument results, it can be considered that the predicting method is useful and preferable to the prediction of cavability for block caving mining.

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(*From page 13*) position, the pressure and the temperature of the system. Not all of the granitic magmas may bring about the liquid separation at any conditions. The dominant oxides of the granitic magmas such as SiO_2, Al_2O_3, Fe_2O_3, FeO, CaO, MgO, etc. do not excert a significant or apparent influence on the liquid separation. The contents of the volatile components such as F or Cl and alkaline metal elements such as Li , Na, and K could excert an important influence on the liquid separation.

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