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Stability of a coal pillar for strip mining based on an elastic-plastic analysis

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1. Introduction

There is a large amount of coal left unmined under surface structures, water bodies, and railways (referred to as the "three-body") in China. Coal mining under "three-body" has become a major problem in the mining field.[1] The key problem of mining under "three-body" is to control overburden strata and surface movements. At present, the mining methods under "three-body" are strip mining, backfilling mining method, room and pillar mining, grouting of bed separations, harmonic mining, etc.[1] As for strip mining, coal reserve is divided into regular strips that are mined one in every other strip. The strips left behind, called strip pillars, are designed to support the overburden, prevent surface subsidence and protect the surface structures and ecological environment. Therefore, the strip mining is widely used in China coalmines.[2–4] In the strip mining, the most important task is to maintain the stability of coal pillars. Because the safety mining is controlled by the stability of coal pillars, many methods to study the pillar stability have been proposed.

Generally, these methods can be divided into three types, which are the theoretical method,[5–8] the numerical simulation method[9–13] and the engineering experience method.[14–18] The theoretical method can provide one theoretical equation for the width of the coal pillar. Therefore, it can be used simply and practically. However, to obtain and solve the complicated theoretical equation, some mechanical assumptions should be applied. The numerical simulation method simulates the pillar and its surrounding rock mass by the numerical simulation software. It can obtain the distribution law of the stress and strain in the coal pillar and its surrounding rock mass, nevertheless it's results rely on the suitable mechanical parameters, which cannot be obtained easily. For the engineering experience method, the empirical formulae for the coal pillar width generally can be obtained by the statistical analysis approaches based on the practical engineering experience. However, the empirical formulae can only be used in the certain engineering conditions, thus the generalization of the engineering experience method is generally restricted.

Because of their simplicity and practicality, theoretical methods are the most commonly used to analyze the stability of coal pillars. Of the theoretical methods, the limiting equilibrium method is the most suitable and has been widely studied. In this approach, the stability of one small slice element in the coal pillar is selected and analyzed using the limiting equilibrium method; the width of the non-elastic zone for the coal pillar can then be obtained. Therefore, the stability of coal pillar can be determined. However, the limiting equilibrium method can only analyze the non-elastic zone of the coal pillar. To study the stability of the strip coal pillar comprehensively, based on the theories of the elastic-plastic mechanics and the previous studies of the limiting equilibrium method, one new method to analyze the stability of the strip coal pillar is

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proposed. At last, through the application in one real engineering example, the new method is verified. And the affections of the width of coal pillar and the width of mining strip on the stability of the strip coal pillar are all analyzed. Moreover, the effects of two mining conditions for the coal pillar, which are mining out at both sides and mining out at single side, on the stability of coal pillar are also analyzed. At last, through the numerical simulation study, the theoretical results have also been verified.

2. Computational model

In the strip mining, one individual mining strip can be described by the model of the infinite laminated anisotropic plate with a rectangular hole.

The previous studies[19] show that, the stress at the tip of the rectangular hole is similar to that of the ellipse hole when the ratio of the mining strip width to its height and the distance of the computational point to the tip of the hole are all large enough. Moreover, the effect of anisotropy on the stress at the tip of the ellipse hole is very little, especially when the mining strip height is small. Therefore, the model of the infinite laminated anisotropic plate with a rectangular hole can be simplified to the model of the infinite isotropic plate with a ellipse hole, which is as shown in Fig. 1.

3. Theoretical analysis

3.1. Mining out at single side of coal pillar

The simplified mechanical model can be solved by the complex function method of the elastic mechanics. The tangential stress along the x-axis is,[20]

$$\sigma_z = \frac{q}{2(m\xi^2-1)}\left\{\frac{1}{(m-\xi^2)(m\xi^2-1)}[\xi^2[\xi^2\left(m-1-2m^2-m^3\right) + m\xi^4 + m^2 + 3m - 1] - 1] + (2+m)\xi^2 + 1\right\} \quad (1)$$

where $\xi = [a + r - \sqrt{2ar + r^2 + b^2}]/(a-b)$, $m = (a-b)/(a+b)$, a is the half width of mining strip, b is the half height of mining strip, r is the distance of the computational point to the tip of the hole, and q is the vertical overburden pressure.

Because Eq. (1) is very complicated, it is very hard to use in practice. To analyze the stress of coal pillar, Eq. (1) must be simplified. Previous studies[21] showed that, when the mining depth and the mining width are all lager than the mining height very much, the effect of the mining strip height b can be ignored. Therefore, supposing $b=0$, Eq. (1) can be simplified as follows,

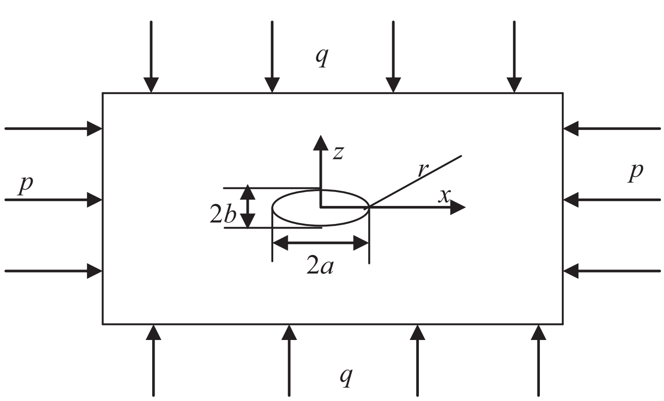

Fig. 1. Mechanical model of the infinite isotropic plate with a ellipse hole.

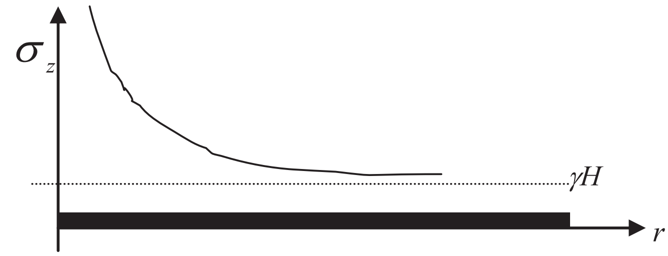

Fig. 2. Distribution of the vertical stress in the coal pillar mining out at single side.

$$\sigma_z = \frac{q(a+r)}{\sqrt{r(r+2a)}} \quad (2)$$

Through Eq. (2), the distribution of vertical stress in the coal pillar mining out at single side can be obtained as shown in Fig. 2.

Generally, for the high stress at the edge of coal pillar, the coal pillar will enter the plastic state. And thus, the stress at the edge of coal pillar will decrease. The reduction of stress will extent from the edge to the inner of coal pillar, until the stress can be beard by the coal pillar.

At this moment, the width of non-elastic zone for the coal pillar can be described as follows,[19]

$$r_0 = a\left[\frac{1}{\sqrt{1-(q/P)^2}} - 1\right] \quad (3)$$

where P is the support pressure at the edge of coal pillar.

Generally, the non-elastic zone which is created is non-stable, because it does not satisfy the limit equilibrium condition. To satisfy the limit equilibrium condition, the non-elastic zone will extend to the inner of coal pillar.

When the limit equilibrium condition is satisfied, the distribution of vertical stress in the coal pillar can be shown as in Fig. 3. In Fig. 3, r_p is the ultimate width of the non-elastic zone, and r_1 is the width of the loose zone for the coal pillar. Those all can be obtained by the limit equilibrium method.

In this study, based on the previous studies,[22] the ultimate width of the non-elastic zone can be described as follows,

$$r_p = \frac{1}{\xi}\ \ln\left\{\frac{1}{\sigma_c^*}\left[P - \eta\left(\exp\ \frac{\sigma_c - \sigma_c^*}{\eta} - 1\right)\right]\right\} \quad (4)$$

where σ_c^* is the residual single compression strength of the coal material, $\xi = f_1 k_p/b$, $\eta = M_0 S_t/2f_1 k_p$, f_1 is the friction coefficient between the coal pillar with the roof and floor, $K_p = (1+\sin\ \varphi)/(1-\sin\ \varphi)$, ϕ is the internal friction angle of the coal material, M_0 is the soften modulus of the coal material, and S_t is the strain gradient of the coal material in the plastic zone.

The width of the loose zone can be described as follows[22]:

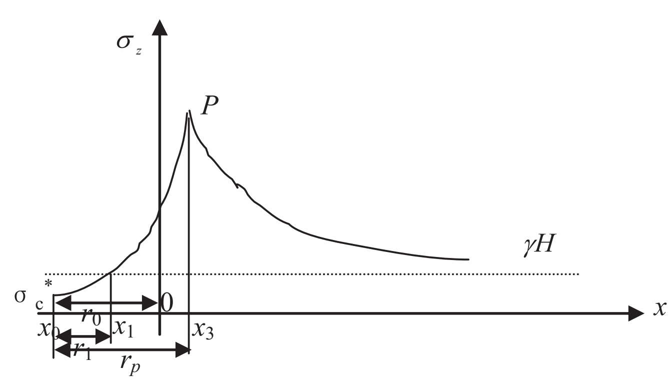

Fig. 3. Distribution of the vertical stress for the coal pillar in limit equilibrium state.