International Journal of Mining Science and Technology 25 (2015) 133–138

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Study on first caving fracture mechanism of overlying roof rock in steep thick coal seam

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ARTICLE INFO

Article history:
Received 2 March 2014
Received in revised form 15 April 2014
Accepted 15 July 2014
Available online 7 February 2015

Keywords:
Steep
Mining field
Initial fracture interval
Thin plate theory
Coal pressure monitoring

ABSTRACT

Based on the elastic plate theory, a mechanical model of thin plate for the first caving of overlying roof rock in steep mining face was established. The analytical solution of the deflection and stress distribution of roof rocks was obtained. According to the specific geological conditions of the 5-103 panel in Shanxi, the failure of roof rocks and the influence of seam dip on it during the exploitation were theoretically investigated. Meanwhile, the first caving characteristics of the overlying rock in the steep coal seam were investigated based on its stress contour. The results show that the dip angle has a distinct influence on the caving interval and the first caving interval for the 5-103 panel is 37 m in theory. Finally, a systematic monitoring on the behavior of rock pressures was conducted. The measured results agree well with the theoretical prediction, which provides a good reference for practical steep coal seam mining.

1. Introduction

As the domestic demand for coals increases in China, the exploitation of various coal resources of high quality is a long-term task among which the coal mining technology for steep coal seams is of great significance. There is, so far, no consensus achieved as to the definition of a steep coal seam. It is generally accepted that seams with dips of 35–55° [1–3] are defined as steep coal seams. The coal seams with a dip angle larger than 35° account for 17% of the coal reserves in China. The exploitation of large inclined coal seams will enhance the reserves of renewable sources and has caught increasing attention [4–7]. The steep coal seam is anisotropic due to the coal and rock sedimentation structures. The larger the dip is, the more significant is its anisotropy. It is obvious that the overlying strata movement differs from that of flat seams under the sloping component of gravity after the exploitation of the inclined seam. The failure range and shape of overlying strata not only depend on the goaf area, lithology and combination of roof and floor rocks, but also directly related to the dip angle of coal seams [8–11].

In order to theoretically investigate the fracture mechanism of the overlying roof rock with large inclinations, this paper establishes the mechanical model of the first caving of steeply inclined overlying roof rock based on the theory of elastic thin plate in the context of a practical steep coal mining project of 5-103 panel in Shanxi province in China. The first caving characteristics of the roof rock under various dip angles of coal seams are studied. The theoretical model is validated against the on-site monitoring of the mine pressure.

2. Summary of geology

The geological reserves of a steep mining field in Shanxi reaches 2.1 billion tons with a workable reserve of 1.06 billion tons. The coking coal of high quality was the main component of the coal source. The fully mechanized natural caving mining technology was used in the steep thick coal seam. The seam of panel 5-103 was No. 5 seam. The ground elevation was 1150–1296 m and that of the panel was 695–786 m. The average thickness of the #5 seam was 6.3 m with dip angles of 18–26°and 22° on average. The panel face length was laid out along the seam dip. The face length, strike length and mining height were 165 m, 1734 m and 6.3 m, respectively. The panel 5-103 coal seams have a complicated structure due to its joint development. Three layers of carbonaceous mudstone exist in the middle of the seam. The seam is stable with a uniform thickness. The properties of the roof and floor of the panel face are listed in Table 1.

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http://dx.doi.org/10.1016/j.ijmst.2014.11.013
2095-2686/

3. Analysis of first caving characteristics of overlying roof rock in the steep thick coal seam

3.1. Mechanical model

Fig. 1 illustrates the mechanical model of an elastic thin plate with four edges clamped for simulating the overlying roof rock in steep coal seams. The load applied on the inclined rock can be resolved into the normal stress and tangential stress. The solution of the deflection of the thin plate can be obtained using the Ritzi method in the elastic shell mechanics theory [12–16].

Assume the function of deflection of the roof rock as:

$$w=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}c_{mn}\left(1-\cos\frac{2\pi mx}{a}\right)\left(1-\cos\frac{2\pi ny}{b}\right) \tag{1}$$

where a and b are the panel's face and strike lengths, respectively; and c_{mn} the undetermined coefficient. According to the theory of elastic plate mechanics, the potential energy of deformation for a thin plate with four edges clamped is given as:

$$\begin{aligned}U&=\frac{Eh^3}{24(1-\mu^2)}\int\int_s\left(\nabla^2w\right)^2dxdy\\&=\frac{\pi^2Eh^3}{6(1-\mu^2)}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}c_{mn}^2\left(\frac{3bm^4}{a^3}+\frac{3an^4}{b^3}+\frac{2m^2n^2}{a^2b^2}\right)\end{aligned} \tag{2}$$

where E is the elasticity modulus, GPa; μ the Poisson's ratio of the roof stratum; h the thickness, m; and s the area of the roof stratum, m^2.

The work done by the external load $q(x)$ on the roof rock is:

$$\begin{aligned}W&=\int\int_s q\cos\alpha w dxdy+\frac{1}{2}\int\int_s q\sin\alpha y\left(\frac{\partial w}{\partial y}\right)^2dxdy\\&=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}c_{mn}q\cos\alpha ab+\frac{q\sin\alpha a\pi^2}{2b}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}c_{mn}^2n^2\end{aligned} \tag{3}$$

Then, the potential energy of the roof rock can be expressed as:

$$\begin{aligned}\prod=U-W=&\frac{\pi^2Eh^3}{6(1-\mu^2)}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}c_{mn}^2\left(\frac{3bm^4}{a^3}+\frac{3an^4}{b^3}+\frac{2m^2n^2}{a^2b^2}\right)\\&-\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}c_{mn}q\cos\alpha ab-\frac{q\sin\alpha a\pi^2}{2b}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}c_{mn}^2n^2\end{aligned} \tag{4}$$

Based on the principle of minimum potential energy $\partial\prod/\partial c_{mn}=0$, the undetermined coefficient c_{mn} can be calculated as:

$$c_{mn}=\frac{q\cos\alpha}{\frac{4\pi^2Eh^3}{12\left(1-\mu^2\right)}\left(\frac{3m^4}{a^4}+\frac{3n^4}{b^4}+\frac{2m^2n^2}{a^3b^3}\right)-\frac{q\sin\alpha\pi^2n^2}{b^2}} \tag{5}$$

Substitution of Eq. (5) into Eq. (1) yields the deflection function of the roof rock as:

$$w=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{q\cos\alpha}{\frac{4\pi^2Eh^3}{12\left(1-\mu^2\right)}\left(\frac{3m^4}{a^4}+\frac{3n^4}{b^4}+\frac{2m^2n^2}{a^3b^3}\right)-\frac{q\sin\alpha\pi^2n^2}{b^2}}\left(1-\cos\frac{2\pi mx}{a}\right)\left(1-\cos\frac{2\pi ny}{b}\right) \tag{6}$$

3.2. Deformation of overlying roof rock

According to stratigraphic column of panel 5-103 and basic physical and mechanical properties of rocks, the thickness of the roof stratum, elasticity modulus and rock weight are h = 10 m, E = 20 GPa, q = 11.25 MPa, respectively. Fig. 2 illustrates the deflection surface of the roof rock in a coal seam with a dip angle of 25° when the face advances a distance of b = 10 m, 20 m, 30 m and 40 m. Fig. 3 shows the variation of the maximum roof deflection against the face advance distances. It can be seen that the roof is subjected to non-uniformly distributed loads due to the seam inclination. The maximum deflection occurs just below the middle of the panel center. As the face advance distance and load increases, causing increases in roof deflection. It is evident from Fig. 3 that the smaller the seam dip is, the greater influence the advance distance will be on the roof deflection. Moreover, with the increase of the coal seam dip, the normal stress of the load reduces and the influence of advance distance on the roof deflection also reduces.

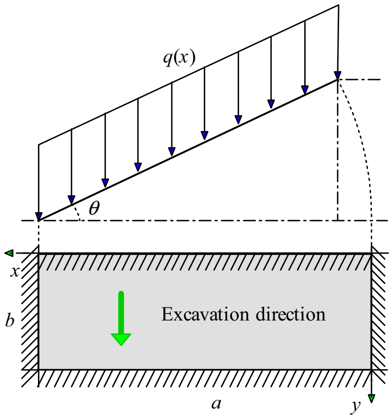

Fig. 1. Mechanical model of a clamped elastic thin plate for overlying roof rock in the steep coal seam.

3.3. First caving characteristics of overlying roof rocks

In order to study the first caving characteristics of the roof rocks and calculate the first caving distance of the coal seam roof, this paper proposes a method to determine the caving location of overlying roof rocks using the maximum tensile stress criterion. According to the theory of elasticity [17], the stress distribution in the roof strata can be obtained from its deflection equation as:

$$\sigma_x=-\frac{4\pi^2Ezq\cos\alpha}{(1-\mu^2)}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\left(\frac{m^2}{a^2}\cos\frac{2\pi mx}{a}\left(1-\cos\frac{2\pi ny}{b}\right)+\mu\frac{n^2}{b^2}\cos\frac{2\pi ny}{b}\left(1-\cos\frac{2\pi mx}{a}\right)\right)}{\frac{4\pi^2Eh^3}{12\left(1-\mu^2\right)}\left(\frac{3m^4}{a^4}+\frac{3n^4}{b^4}+\frac{2m^2n^2}{a^3b^3}\right)-\frac{q\sin\alpha\pi^2n^2}{b^2}} \tag{7}$$

$$\sigma_y=-\frac{4\pi^2q\cos\alpha Ez}{(1-\mu^2)}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\left(\frac{n^2}{b^2}\cos\frac{2\pi ny}{b}\left(1-\cos\frac{2\pi mx}{a}\right)+\mu\frac{m^2}{a^2}\cos\frac{2\pi mx}{a}\left(1-\cos\frac{2\pi ny}{b}\right)\right)}{\frac{4\pi^2Eh^3}{12(1-\mu^2)}\left(\frac{3m^4}{a^4}+\frac{3n^4}{b^4}+\frac{2m^2n^2}{a^3b^3}\right)-\frac{q\sin\alpha\pi^2n^2}{b^2}} \tag{8}$$

The stress distribution in the x and y directions of top and bottom (the coal seam top) surfaces of overlying roof rocks can be determined by Eqs. (7) and (8). Fig. 4 shows the stress contours of a coal seam with a dip angle of 25° and face advancing distance of 40 m (negative value compressive and positive value tensile).

Table 1
Characteristics of roof and floor rocks.

Roof/floor	Rock	Thickness (m)	Rock characteristic
Main roof	White sandstone	1.6–2.5	Light gray sandstone in medium size, hard, vertical crack, obvious contact, undeveloped joint, dip of 21°
Immediate roof	Mudstone	1.0–2.1	Black mudstone, bright band, low density, medium hard, brittle, developed joint, dip of 21°
Immediate floor	Mudstone	1.1–1.9	Black gray mudstone, dense, massive, main mineral component of mud, plant fossils, hard, developed joint, dip of 21°
Main floor	Sandstone	2.0–3.1	Gray white, main mineral component of quartz, carbonaceous fragments and streaks, undeveloped joint, dip of 19°