Research on failure characteristics of goaf floor in the inclined coal seam based on the fracture mechanics

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Abstract

Floor failure is the leading cause of mine water inrush after coal mining above the confined aquifer. Therefore, the prediction of floor failure depth is an important content of mine water prevention. The mining-induced failure depth and goaf floor characteristics are researched to grasp the goaf failure condition after the inclined coal seam mining with the theoretical analysis method. The inclined coal goaf floor's stress solving mechanics mode is set up based on the fracture mechanics theories. According to the Mohr–Coulomb criterion, the floor failure depth solving the equation is derived. With the theoretical analysis of the floor failure characteristics during the inclined coal seam mining, (1) the maximum failure depth of floor is nonlinear to the coal seam dip and the lateral pressure coefficient; the working face length, mining depth and floor cohesion positively correlate with the failure range; the floor cohesion is reversely proportional to the failure range. (2) There appears asymmetry in the layout of stress and plastic zones in the inclined coal goaf floor. Failure range and depth in-floor plastic zone increasingly enlarge when the coal face advances.

Keywords Fracture mechanics · Mohr–coulomb criterion · Inclined coal seam · Theoretical analysis method · Floor failure depth

1 Introduction

After the coal seam is mined, the rock strata stress in the goaf floor is redistributed. With the mining process, the stress successively goes through three stages of increase, decrease, and recovery, leading to the floor's deformation and failure, and finally forming a certain depth of rock strata failure zone, which seriously affects the coal mine production. Therefore, to realize the coal mine's safe and efficient production, it is of great practical significance to study the coal seam floor's failure characteristics.

In terms of theoretical calculation of goaf floor failure depth, Zhu et al. applied semi-infinite body theory of elastic mechanics, considering the effect supporting pressure exerts on the floor, and then established a mechanical model of coal floor [1–4]. Lu et al. treated limit equilibrium failure form of the floor under the supporting pressure as circular

slip, applying the slip-line field's applied theory to calculate the maximum floor failure depth [5–10]. Zhang et al. comprehensively analyzed the influential factors from floor failure, modified empirical formula for floor failure depth with multiple linear regression analysis, or orthogonal text analysis [11, 12]. In the aspect of floor failure field management, Zhang et al. confirmed the coal floor failure conditions by monitoring the deformation degrees of the strata in various depths under the coal floor [13–17]. Liu et al. applied the electrical detection technology to detect water flowing fracture changing rules in coal floor strata during mining progress and established dynamic evolution geo-electric model of water flowing fractures when floor mining [18–20]. In terms of simulation test of goaf floor failure, Guo et al. detected the floor failure evolution progress through simulation tests system for the mining floor [21–23]. In the aspect of floor failure numerical simulation, Liu et al. studied floor

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failure deformation characteristics during mining through numerical simulation softwares [24–26].

The distribution law and failure characteristics of floor stress after mining inclined coal seam are different from those of the horizontal coal seam. With the change of the coal seam's inclination, the normal stress perpendicular to the floor decreases, while the shear stress parallels to the floor increases, increasing the amplitude and intensity of the floor rock movement. However, the above results are mostly limited to the horizontal coal seam, and the research on inclined coal seam is relatively few, and the influence of tectonic stress is not considered in theoretical calculation. Therefore, it is necessary to study the characteristics of mining-induced deformation and failure of the floor in goaf of the inclined coal seam to provide the theoretical basis for floor confined water prevention, floor roadway valid location, gas prevention, and mining adjacent coal seam. Based on coal seam goaf as the research object, using the fracture mechanics theory, simplifying the post-harvest space to bi-directional compression II inclined crack, through the crack tip stress field, combined with Mohr–Coulomb criterion, floor damage depth is derived to solve the equation.

2 Solving model of floor stress in inclined coal seam goaf

Because the working face dip length is much longer than the mining width, the effect of mining height is ignored [27]. Within the limits of the mining face, because the variation of lateral pressure around the coal seam is small, the variation of gradient lateral pressure on both sides of the coal seam is ignored. With the advance of the working face, the goaf is gradually closed. After that, normal stress on goaf will not produce stress singularity. Type I stress intensity factor $K_I=0$, goaf stress state can be purely regarded as type II shearing crack. According to inclined coal mining characteristics, mined areas are simplified as bi-directional compression inclined crack, as shown in Fig. 1. Working face length in Fig. 1 is L ; under the combined action of vertical and lateral pressure, coal seam dip angle is α . Set up a rectangular coordinate system on floor strata and make x-axis parallel to strata direction and y-axis coincide with strata perpendicular.

According to the coordinate transformation of stress distribution, the stress state in goaf is shown as

$$\begin{cases} \sigma_{xx}^{\infty} = \sigma \cdot \sin^2 \alpha + \lambda \sigma \cdot \cos^2 \alpha \\ \sigma_{yy}^{\infty} = \sigma \cdot \cos^2 \alpha + \lambda \sigma \cdot \sin^2 \alpha \\ \tau_{xy}^{\infty} = (1 - \lambda) \sigma \cdot \sin \alpha \cdot \cos \alpha \end{cases} \quad (1)$$

In these equations, $\sigma_{xx}^{\infty}, \sigma_{yy}^{\infty}, \tau_{xy}^{\infty}$ is the far-field stress/MPa; σ is the vertical stress/MPa; λ is the coefficient of horizontal pressure; α is the coal seam dip angle/°.

Fig. 1 Mechanical model of inclined coal seam floor

Positive stress σ_N and shearing stress τ_N on goaf are shown as

$$\begin{cases} \sigma_N = \sigma_{yy}^{\infty} = \sigma \cdot \cos^2 \alpha + \lambda \sigma \cdot \sin^2 \alpha \\ \tau_N = \tau_{xy}^{\infty} = (1 - \lambda) \sigma \cdot \sin \alpha \cdot \cos \alpha \end{cases} \quad (2)$$

Thus, stress intensity factor on goaf tip is shown as

$$K_{II} = \tau_N \sqrt{\frac{\pi L}{2}} = [(1 - \lambda) \sigma \cdot \sin \alpha \cdot \cos \alpha] \sqrt{\frac{\pi L}{2}} \quad (3)$$

Near-field stress state on goaf tip is shown as

$$\begin{cases} \sigma_{xx}^c = -\frac{K_{II}}{\sqrt{2\pi r}} \sin\left(\frac{\theta}{2}\right) \left[2 + \cos\left(\frac{\theta}{2}\right) \cdot \cos\left(\frac{3\theta}{2}\right)\right] \\ \sigma_{yy}^c = \frac{K_{II}}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \cdot \sin\left(\frac{\theta}{2}\right) \cdot \cos\left(\frac{3\theta}{2}\right) \\ \tau_{xy}^c = \frac{K_{II}}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \left[1 - \sin\left(\frac{\theta}{2}\right) \cdot \sin\left(\frac{3\theta}{2}\right)\right] \end{cases} \quad (4)$$

In these equations, $\sigma_{xx}^c, \sigma_{yy}^c, \tau_{xy}^c$ is the near-field stress/MPa; r is the distance from stope tip/m; θ is the included angle between r and floor level/°.

According to the principle stress calculating equation in elastic mechanics, the principle stress is shown as

$$\begin{cases} \sigma_1 = \frac{K_{II}}{\sqrt{2\pi r}} \left[-\sin\left(\frac{\theta}{2}\right) + \sqrt{1 - \left(\frac{3}{4}\right) \sin^2 \theta} \right] \\ \sigma_3 = \frac{K_{II}}{\sqrt{2\pi r}} \left[-\sin\left(\frac{\theta}{2}\right) - \sqrt{1 - \left(\frac{3}{4}\right) \sin^2 \theta} \right] \end{cases} \quad (5)$$

Substitute the principle stress into the Mohr–Coulomb criterion, as shown in equation

$$\sigma_1 - [(1 + \sin\phi)/(1 - \sin\phi)]\sigma_3 = (2c \cdot \cos\phi)/(1 - \sin\phi) \quad (6)$$

According to Eq. (6), the failure range of goaf edge can be obtained

$$r' = \frac{L\gamma^2 H^2}{64c^2} \left[\frac{(1 - \lambda)\sin 2\alpha}{\cos\phi/(1 - \sin\phi)} \right]^2 \left[\left(\frac{1 + \sin\phi}{1 - \sin\phi} - 1 \right) \sin \frac{\theta}{2} + \left(\frac{1 + \sin\phi}{1 - \sin\phi} + 1 \right) \sqrt{1 - \frac{3}{4}\sin^2\theta} \right]^2 \quad (7)$$

In these equations, r' is the yield damage radius/m. γ is the average bulk density of the overlying strata/kN/m³. H is the mining depth/m. C is the floor cohesion/MPa. ϕ is the internal frictional angle of floor/°.

The damaging range is shown in Fig. 2. Set lower part of the inclined coal goaf as polar origin, use dimensionless r/r_0 to stand for yielding damage radius r and then r_0 is the yield size when $\theta = 0$. There appears asymmetry in the layout of plastic failure zones in the inclined coal floor.

The maximum failure depth $h = r \times \sin\theta'$ is shown as

$$h = \frac{L\gamma^2 H^2}{64c^2} \left[\frac{(1 - \lambda)\sin 2\alpha}{\cos\phi/(1 - \sin\phi)} \right]^2 \left[\left(\frac{1 + \sin\phi}{1 - \sin\phi} - 1 \right) \sin \frac{\theta}{2} + \left(\frac{1 + \sin\phi}{1 - \sin\phi} + 1 \right) \sqrt{1 - \frac{3}{4}\sin^2\theta} \right]^2 \sin\theta' \quad (8)$$

The distance between the floor maximum failure depth and working face $l = r \times \cos\theta'$ is shown as

$$l = \frac{L\gamma^2 H^2}{64c^2} \left[\frac{(1 - \lambda)\sin 2\alpha}{\cos\phi/(1 - \sin\phi)} \right]^2 \left[\left(\frac{1 + \sin\phi}{1 - \sin\phi} - 1 \right) \sin \frac{\theta}{2} + \left(\frac{1 + \sin\phi}{1 - \sin\phi} + 1 \right) \sqrt{1 - \frac{3}{4}\sin^2\theta} \right]^2 \cos\theta' \quad (9)$$

In these equations, θ' is the maximum failure angle of floor.

3 Engineering application

Take the working face 41,501 of HUAFENG Mine of the XINWEN Mining Industry as an example [28]. It focuses

on No.15 coal seam with dip angle 30°, maximum depth 475 m, minable thickness 2 m, working face strike length 800 m and working face length 100 m. Its direct floor is made of medium sandstone, about 6 m thick. Its hard floor is made of fine sandstone about 15 m. Solve floor failure depth with an average modulus method. The average modulus method takes elasticity modulus as the main parameter to calculate each floor's average thickness h_i' and transforms sliced floors into homogeneity-like floors. Solve contrastive analysis between homogeneity-like floor

failure depth and the original floor thickness to calculate the practical floor failure depth inversely.

Fig. 2 Failure range in inclined mining stope tip

$$h_i' = h_i \sqrt{\frac{E_i}{E_w}} \quad (10)$$

$$E_w = \frac{\sum_1^n h_i E_i}{\sum_1^n h_i} \quad (11)$$

In Eqs. (10) and (11), h_i' is the equivalent strata thickness of No. i floor/m; E_w is the elastic modulus weighted average/GPa; h_i is the original floor strata thickness of No. i floor/m; E_i is the floor elastic modulus/GPa.

We can figure out the floor strata average elastic modulus with the weighted average, which is 8 GPa. Similarly, the average cohesion force c_w is 4.7 MPa, and the average inner frictional angle ϕ_w is 32.7°. Working face 41,501-floor strata equivalent thickness is shown in Table 1.

Take the parameters $L = 100$ m, overlying strata average unit weight $\gamma = 27$ kN m⁻³, lower buried depth $H = 475$ m,

$c_w = 4.7$ MPa, $\varphi_w = 32.7^\circ$, $\lambda = 1.5$ [29] into Eq. (7). Use MATLAB to figure out equivalent failure depth in the lower part of goaf floor, which is 14.94 m, and the equivalent failure depth of fine sandstone is 9.34 m. Use Eq. (10) to reversely figure out the practical failure depth of the fine sandstone, which is 9.12 m. Then, the practical floor failure depth is 15.12 m, which basically matches the field-measured failure depth 15.49 m [28].

4 Analysis of the influential factors from inclined coal seam goaf floor failure

Based on Eq. (7), the inclined coal seam's yield failure zone size is influenced by factors such as working face length, mining depth, coal seam dip, coefficient of horizontal pressure, floor cohesion and internal frictional angle of the floor.

Take the parameters of the HUAFENG coal mine as an example. When other parameters remain the same, maximum floor failure depth varies with the change of coal seam dip angle, as shown in Fig. 3. With enlarging the dip angle, failure depth firstly increases and then begins to decrease. When the dip angle is 45° , failure depth reaches its peak value.

With the lateral pressure coefficient enlarging, failure depth firstly decrease and then begins to increase. When the floor tip is under hydrostatic pressure, the damage degree is low, as shown in Fig. 4.

When the internal frictional angle enlarges, the yielding range widens, and failure depth increases, as shown in Fig. 5.

As shown in Fig. 6, the working face length and mining depth positively correlate with the failure range; the floor cohesion is reversely proportional to the failure range.

Table 1 Working face floor equivalent thickness and other parameters

Floor strata	Elasticity modulus/GPa	Original thickness/m	Equivalent thickness/m	Cohesion/MPa	Friction/($^\circ$)
Middle sandstone	6.96	6	5.6	5.2	32
Fine sandstone	8.4	15	15.4	4.5	33

Fig. 3 Influence of the coal seam dip angle on floor failure depth

5 Summary and conclusion

- (1) Based on the fracture mechanics, establish an inclined floor stress solution model. According to the two-way compressed stress field of the goaf end and the Mohr–Coulomb criterion, derive the solution equation for the floor failure depth of inclined coal seam; the equation rationality is verified through examples.
- (2) The theoretical analysis of the floor failure characteristics shows that the plastic failure zones of inclined coal floor appear asymmetric distribution. Failure range and depth in-floor plastic zone gradually

Fig. 4 Influence of the lateral pressure on floor failure depth

Fig. 5 Influence of internal frictional angle on floor failure depth

Fig. 6 Influence of the mining depth, working face length and floor cohesion on floor failure depth

enlarge when the coal face advances. The maximum failure depth of the floor position lies in the part of the lower goaf.

- (3) Use the failure depth equation to analyze the floor failure factors. The inclined coal seam floor's failure

zone size is influenced by factors such as working face length, mining depth, coal seam dip, coefficient of horizontal pressure, floor cohesion, and internal frictional angle of the floor.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

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