Dip angle effect on the main roof first fracture and instability in a fully-mechanized workface of steeply dipping coal seams

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Abstract The study of fracture and instability mechanism of the main roof in steeply dipping coal seams (SDCS) workface is crucial to the proper choice of support type and control of stability of surrounding rock, as well as the safe and effective mining in the coal seam. Based on the established SDCS main roof model, this study derived the stress distribution in the main roof under linear load, analyzed the dip angle effect associated with the evolving stress of SDCS workface, and elaborated the sequential characteristics of the ground pressure mechanism. Besides, an inclined unstable structure model of the main roof based on deformation, fracturing, and rotating of the main roof in the SDCS workface was also proposed here, which explained the impacts of overburden rock’s key parameters on sliding and rotatory instability of rock mass. In light of the analysis of the movement rule of overburden rock and loading condition of support, it is found that, when the roof and floor in the workface are stable, the critical support resistance with the absence of sliding and rotating increases as the dip angle of coal seam increases, the roof is in the state of discontinuous movement due to its self-weight and overburden pressure. Support is affected by the discontinuous movement and moved along with the roof. The results of this study can be of theoretical reference to the control of SDCS.

Keywords Steeply dipping workface; Dip angle; Main roof; First fracture; Support resistance

1 Introduction

With a gradual reduction of coal resources and growing mining intensity, mining under complicated conditions has been increasing in recent years (Wu et al. 2014). In particular, steeply dipping coal seams (SDCS) are regarded as difficult for mining (Ye et al. 2017; Wu et al. 2010; Tu et al. 2019). However, with the development of fully-mechanized mining theories, advancing research of equipment, and improved management in the workface, SDCS with shallow depth has gradually become the main coal seam in western China’s mining areas. For example, the Sichuan Coal Industry Group Ltd. has succeeded in the trial mining in the Lvshuidong coal seam with a dip angle of 70°. The rock pressure pattern in the SDCS workface is influenced by a dip angle, which results in a significant difference from coal seam with a low dip angle during mining (Kang et al. 2002; Shi et al. 2018). The available pressure control and technology theories focused on horizontal coal seams and coal seams with a shallow dip...
angle cannot guide the safe and efficient mining in SDCS. At present, roof falling, flying gangue in workface, and hydraulic support sliding are the major disasters in SDCS mining (Shan et al. 2020; Hu et al. 2017) and are all directly related to roof stability. Therefore, the study of roof failure and movement is the prerequisite for safe and efficient mining in SDCS (Zhang et al. 2018; Das et al. 2017).

Numerous field test results proved that mining in SDCS caused roof weighting in different zones in the workface, and the ground pressure became abnormal. Studies of fracturing in different zones in the roof of the SDCS workface were conducted by different researchers and were focused on the failure, migration, and evolution law of the workface roof (Wang et al. 2015b). Several studies performed the analysis of the fracturing pattern of the main roof in the workface and the relationship between the support-surrounding rock (Jiang et al. 2014). Establish a mechanical model of stope roof based on elastic theory, analyze the evolution characteristics of basic roof fracture, and obtain fracture forms in different periods (Wang et al. 2016; Cui et al. 2019). Based on the hinged rock block model, the limit position of the rotation instability of the hinged structure is studied, and the unique instability mode of the shallow-buried thin bedrock roof and the method for determining the working resistance of the support are proposed (Wang et al. 2015a). Based on the theoretical model of inclined coal seam stope, the stress distribution characteristics and fracture mechanism of basic roof strata during mining are analyzed (Zhang et al. 2010; Yang et al. 2013).

Based on beam and plate models, numerous researchers systematically investigated the fracture and evolution law of a roof in a fully-mechanized workface, improved the understanding of the main roof's first fracture, and refined the surrounding rock control theory. However, due to the complex characteristics of mines' geological conditions, it is difficult to fully and accurately reflect the fracture evolution law of the roof during mining in the coal seam and further study the dip angle effect on the kinematic movement law of overburden rock is highly demanded. Therefore, based on available findings, this study utilized a theoretical analysis method and elaborated a mechanical model of the main roof in SDCS to investigate the effect of dip angle on the first fracture of the main roof in a fully-mechanized workface. Thus, it determined the key factors controlling the surrounding rock stability. The results in this study provide theoretical reference for the effective preventive measures in mining.

2 Assumptions of the main roof mechanical model

According to the assumption of a thin plate (or a slender body) in the elasticity theory (Yang et al. 2013), an elastic plate can be treated as a thin plate if the ratio between its thickness h and length of its shortest side l satisfies the following conditions:

\[
\frac{1}{100} \cdot \frac{1}{80} \leq \frac{h}{l} \leq \frac{1}{8} \cdot \frac{1}{5}
\]  

Below the first-fracture mining pressure in the longwall workface in SDCS is reached, the main roof can be regarded as a thin plate since its thickness and length satisfy the above equation.

Hard hanging roof zone appears in the goaf rear area after mining in the workface. Usually, the narrow coal pillar side and fault side are treated as simple boundaries. The solid coal side is treated as a clamped boundary (Jiang et al. 2014), where deflection and rotation are zero.

3. Rule of the first fracture of the main roof

3.1 Basic equations of thin plate

As mining advances from the open-off cut, the main roof's exposed area gradually increases, and fracturing happens when the stress reaches the stratum's ultimate strength. The main roof in the SDCS workface is supported by integrated coal before fracturing. Since the coal seam's dip angle is relatively large, the false and immediate roofs fall to the bottom of goaf as mining proceeds. Therefore, a mechanical model of the main roof in SDCS, as shown in Fig. 1, was elaborated in this study. Herein, the dip angle of the coal seam is \( \alpha \), the x-axis is directed along the workface strike with a length of \( a \), the y-axis is along the workface dip with a length of \( b \), and the z-axis is normal to the roof and has positive downward direction.

Due to the impact of dip angle, the load from overburden rock that acts on the roof can be simplified as \( P(y) \) that linearly changes along the dip (i.e., positive axis), which is expressed as:

\[
P(y) = P_0 - \gamma y \sin \alpha
\]  

where \( \gamma \) is the average unit weight of the overburden rock and \( P_0 \) is the overburden load in the roadway of workface. The later value, \( P_0 \), is decomposed into the force...
perpendicular to the roof denoted by $P_1 = P(y) \cos \alpha$
and the force parallel to the roof denoted by $P_2 = P(y) \sin \alpha$. Since the latter force component $P_2$
is much smaller than $P_1$ within the dip angle range under
study, its effect is neglected, and the deflection function of
the main roof under the linear overburden load is written as:

$$\omega_1 (x, y) = A_1 \left( y + \frac{b}{4} \right) \sin^2 \left( \frac{\pi x}{a} \right) \sin^2 \left( \frac{\pi y}{b} \right)$$

(3)

Fig. 1. Mechanical model of the main roof in SDCS

The following boundary conditions have to be satisfied:

$$(\omega_1)_{x=0,y} = 0 \quad (\omega_1)_{y=0,b} = 0$$

(4)

According to the principle of minimum potential
energy (Yang et al. 2013), the total potential energy of a
thin plate under the linear overburden load is:

$$E_p = \frac{D}{2} \int \int P_1 \omega_1 \, dx \, dy - \int \int P_1 \omega_1 \, dx \, dy$$

(5)

where $P_1$ is the overburden load perpendicular to the
roof, $\omega_1$ is the deflection function of the main roof
under linear overburden load, and $\mu$ is Poisson’s ratio.

Since $\frac{\partial E_p}{\partial A} = 0$, the deflection function coefficient
can be calculated by

$$A_1 = \frac{3}{16} \frac{P_0 \cos \alpha ab^2 - \frac{11}{96} \gamma \sin \alpha \cos \alpha ab^3}{D (1 - \mu) b \left( \frac{3 \pi^2}{8} + \frac{\pi^4}{10} - \frac{47 \pi^4}{120} \right)}$$

(6)

Substituting Eq (6) into Eq (3) yields the deflection function of the main roof with four fixed sides under the linear overburden load

$$\omega_1 (x, y) = \left( \frac{3}{16} \frac{P_0 \cos \alpha ab^2 - \frac{11}{96} \gamma \sin \alpha \cos ab^3}{D (1 - \mu) b} \left( \frac{3 \pi^2}{8} + \frac{\pi^4}{10} - \frac{47 \pi^4}{120} \right) \right)$$

(7)

where $D$ is the bending stiffness of the thin plate,

$$E \frac{h^3}{12(1 - \mu^2)}$$

is Poisson’s ratio.

Gangue filling in the goaf of SDCS is highly heterogeneous. Hence, the upper, middle, and bottom areas of the main roof have different stress states and kinematic movement patterns. It is assumed that falling gangue fills two-thirds of the total space of goaf of SDCS, the bottom area has good filling and is closer to the intact rock strength than the middle area, and the upper area has no filling, so a load of gangue filling on the main roof $P_g$ is derived as follows:

$$P_g = \frac{3 \gamma P_0}{2b} \left( 0 \leq y \leq \frac{2}{3} b \right)$$

(8)

According to the principle of minimum potential energy, the deflection function of the main roof under gangue filling is

$$\omega_2 (x, y) = \frac{96 a^3 b^3 P_g y}{D (1 - \mu) \pi^3 (535 b^4 + 363 a^2 b^2 + 315 a^4)}$$

(9)

Using Eqs. (7) and (9) to derive $\omega = \omega_1 - \omega_2$, one gets in the total deflection function of SDCS main roof under overburden pressure and gangue filling conditions.

3.2 Stress expression

Using $A_1$, the coefficient

$$A_g = \frac{96 a^3 b^3 P_g y}{D (1 - \mu) \pi^3 (535 b^4 + 363 a^2 b^2 + 315 a^4)}$$

and the relation between deflection and stress in the theory of thin elastic plate, stresses in the SDCS main roof can be derived as follows:
3.3 Stress distribution in the main roof

During mining in the coal seam, when the roof’s maximum tensile stress exceeds its tensile strength $\sigma_t$, the tensile fracture will occur (Zhao et al. 2019). According to Eq. (10), the distributions of $\sigma_x$ and $\sigma_y$ in the bottom floor were obtained and depicted in Fig. 2.

In Fig. 2(a), where $\sigma_x$ is the compressive stress ranging from 0 to 15 MPa and from 45 to 60 MPa. The tensile stress portion ranges from 15 to 45 MPa and is symmetrical along the advance direction of the workface. Meanwhile, in Fig. 2(b), $\sigma_y$ is the compressive stress ranging from 0 to 30 MPa and from 120 to 140 MPa. It keeps increasing the thin roof with the workface advance, while the upper area experiences compression $\rightarrow$ tension $\rightarrow$ compression, and shows asymmetry as a whole along the dip of workface.
While $\sigma_x$ reaches its peak value at $x = \frac{a}{2}$ and $y = 0.56$, $\sigma_y$ reaches its peak value at $x = \frac{a}{2}$ and $y = 0.58$. The maximum stress can be calculated as follows.

As observed, $\sigma_x > \sigma_y$. Hence, $\sigma_x$ is the main factor controlling the fracturing instability of the overburden rock, while the dip angle of the coal seam only changes the rock’s tensile stress (i.e., the ultimate span of workface). When the maximum tensile stress reaches the tensile strength limit at a certain point in the thin rock plate, the tensile fracture occurs, and gradually thin rock plate evolves into spatial surrounding rock structure.

Current studies show that when the tensile stress exceeds the shear stress, while the latter exceeds the compressive stress ($\sigma_{\text{tensile}} < \sigma_{\text{shear}} < \sigma_{\text{compressive}}$), the tensile or shear failure is likely to take place in stratum, and the failure pattern is determined by its tension and shear strengths as well as the stress within the stratum (Yang et al. 2015). Therefore, the analysis of distributions of principal stress and shear stress on the main roof is of great significance. Relations between the roof stress components and principal stress, as well as shear stress, are described by the following equations.

\[
\frac{\sigma_{\text{max}}}{\sigma_{\text{min}}} = \frac{\sigma_x + \sigma_y}{2} \pm \frac{\sqrt{(\sigma_x - \sigma_y)^2 + \tau_{xy}^2}}{2} \quad (13)
\]

\[
\tau_{\text{max}} = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \quad (14)
\]

Equations (13) and (14) determine the principal stresses $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$, and shear stress $\tau_{\text{max}}$ at any point in the thin floor where the four boundaries are fixed. The above stresses depend on the main roof’s thickness $h$ and length-to-width ratio, overburden pressure, and coal seam dip angle $\alpha$. Hence, the overburden load $P_0$ above the roadway of the workface can be any load that satisfies $P_0 \geq 0$, which is $P_0 \cos \alpha - \gamma \sin \alpha \cos \alpha \geq 0$. Here, $P_0 = 10\text{MPa}$, Poisson’s ratio of the main roof $\mu = 0.25$, the main roof elastic modulus $E = 30\text{GPa}$, the main roof thickness $h = 6\text{m}$, coal seam dip angle $\alpha = 40^\circ$, strike length of the main roof $a = 60\text{m}$, and dip length $b = 140\text{m}$. The principal stress distribution in the thin main roof is shown in Fig. 3.
Fig. 3. Neophogram of the principal stress in the main roof

It can be seen from Fig. 3 that the principal stresses $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ in the upper-middle zone of the main roof in SDCS longwall workface are positive, indicating that the top roof ($z = -\frac{h}{2}$) is compressed and the bottom roof is under tension. Meanwhile, $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ in the upper zone of upper boundary and left and right zones of vertical boundaries in suspense zone are negative, implying that the top roof ($z = -\frac{h}{2}$) is under tension, and the bottom roof is under compression. It shows that the bottom roof is under compression at three boundaries and tension in the middle zone, while the top roof is under tension at three boundaries and compression in the middle zone.

The maximum shear stress distribution in the main roof with the same parameters is depicted in Fig. 4. The maximum shear stress $\tau_{\text{max}}$ occurs periodically in the upper-middle zone of the main roof in the SDCS longwall workface as mining is advancing, and it is large in the middle but small on both sides. Since rock has a very low tensile strength, failure is likely to occur in the bottom roof's upper-middle zone. Both sides of the long boundaries of the top roof, as well as the upper zone of the short boundary, and the failure in the middle zone of the bottom roof will develop toward the long boundaries.

![Fig. 4. Neophogram of maximum shear stress of the main roof](image)

Using $\frac{\sigma_{\text{max}}}{\tau_{\text{min}}} = \eta$, the principal stresses $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ and the maximum shear stress $\tau_{\text{max}}$ in the main roof during the first weighing in coal seam with different dip angles were calculated, and the results are depicted in Fig. 4. Principal stresses $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ are non-linearly correlated with the dip angle $\alpha$, principal stress decreases as the dip angle $\alpha$ increases, and $\sigma_{\text{max}}$ reduces rapidly as dip angle increases in the range $30^\circ$–$50^\circ$. This implies that the dip angle had a strong impact on the roof stress in this range. Stresses $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ gradually become stable as the dip angle increases in the range $50^\circ$–$60^\circ$, meaning that the dip angle has a weak effect on the roof stress in this range. The maximum shear stress $\tau_{\text{max}}$ exhibits the same evolution trend as the dip angle increases. The principal stress variation rate is defined by $\eta$, which turns out to be constant, meaning that $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ have the same variation rates for the same dip angle increments.

![Fig. 4. Neophogram of maximum shear stress of the main roof](image)

### 4 Fracturing instability characteristics of the main roof

#### 4.1 Slip instability of the main roof

Asymmetrical mechanical characteristics of the SDCS workface, as well as dip strata movements, are resulted from the heterogeneous features of dip angle and angle, and the larger the dip angle is, the more distinct the asymmetrical features strata movement has (Hu et al. 2018). Strata movement undergoes “failure—falling—fracturing—settling—rotating” when exposed to complex stress state conditions.

As workface advances, the vertical and separation fractures occur in a certain range of overburden rock. The extrusion between rock blocks induces an asymmetrical hinged rock structure. It gradually develops into a macroscopic "shell" structure (Xie et al. 2009; Zhang et al. 2015; Xie et al. 2019). A typical rock block is subjected to the stress state shown in Fig. 6.
The hinged structure is framed into the Cartesian coordinate system and satisfies the following mechanical equilibrium equations:

\[
\begin{align*}
(R_1 + R_2) - q(x_1 + x_2)\cos \alpha &= 0 \\
\frac{q}{2}x_1^2 \cos \alpha - \frac{q}{2}x_1h \sin \alpha - (T + qx_2 \sin \alpha)h &= 0 \\
\frac{q}{2}(x_1 + x_2)^2 \cos \alpha - \frac{q}{2}(x_1 + x_2)h \sin \alpha - R_2(x_1 + x_2) &= 0
\end{align*}
\]

Solving these equations, one can derive shear stresses \( R_1 \) and \( R_2 \) and the extrusion stress \( T \):

\[
\begin{align*}
R_1 &= \frac{q(x_1 + x_2)\cos \alpha + qh \sin \alpha}{2} \\
R_2 &= \frac{q(x_1 + x_2)\cos \alpha - qh \sin \alpha}{2} \\
T &= \frac{qx_1^2 \cos \alpha}{2h} - \frac{qx_1 \cos \alpha}{2} - qx_2 \sin \alpha
\end{align*}
\]

where \( h \) is the main roof thickness, \( \alpha \) is the coal seam's dip angle, while \( x_1 \) and \( x_2 \) are the lengths of fractured rock blocks.

The slip instability occurs when the shear stress exceeds the extrusion stress in the rock block. Thus, the mechanical balance equation for the hinged structure should be satisfied to avoid slip instability, i.e.

\[
\frac{(x_1 + x_2)\cos \alpha + h \sin \alpha}{hx_1 \cos \alpha - h^2 x_1 \cos \alpha - 2h^2 x_2 \sin \alpha} \leq \tan \varphi
\]

where \( \varphi \) is the friction angle of the fractured rock block, which is usually taken as \( \varphi = 38° \sim 45° \), \( \tan \varphi = 0.8 \sim 1 \) (Zhou et al. 2019).

Lengths of hinged rock blocks are assumed to be the same, that is, \( x_1 = x_2 \). The ratio of shear stress \( R \) to extrusion stress \( T \) in the hinged area is defined as a slip coefficient \( \lambda \) derived as

\[
\lambda = \frac{2x_1 \cos \alpha + h \sin \alpha}{hx_1 \cos \alpha - hx_1 \cos \alpha - 2h^2 x_2 \sin \alpha}
\]

When the ratio of the hinged rock block's length to the thickness of the main roof is constant, the slip coefficient changes with the dip angle ranging from 20° to 70°, and the relationship is depicted in Fig. 7.
At constant dip angle $\alpha$ values, the slip coefficient’s evolution trend for the main roof thickness $h$ and length $l$ ranges of $5m < h < 15m$ and $10m < l < 30m$ is shown in Fig. 8.

When the hinged rock block is in the limit equilibrium, the sum of all moments is zero, i.e., $\sum M = 0$. Then:

$$T(h-a-\Delta) = \frac{q x^2 \cos \alpha - (h-a) q x \sin \alpha}{2}$$

where $a$ is the width of the hinged area of the rock block in the main roof, $\theta$ is the angle of rotation of the fractured rock block, and $x$ is the rock block length.

When $a$ is relatively small, we get:

$$2a = h - x \sin \theta$$

$$\Delta = x \sin \theta$$

Combining Eq (19) and (20) gives

$$\frac{2q x^2 \cos \alpha - q x \sin \alpha (h + x \sin \theta)}{2(h - x \sin \theta)}$$

(21)

According to the strength criterion for rocks, the hinged structure of the main roof has to satisfy the following condition if when rotatory instability is absent

$$\sigma e \geq \sigma p = \frac{2q x^2 \cos \alpha - q x \sin \alpha (h + x \sin \theta)}{(h - x \sin \theta)^2}$$

(22)

where $\theta$ is the angle of rotation of the fractured rock block, $\sigma e$ is the fractured rock block’s compressive strength, and $\sigma p$ is the extrusive strength between two adjacent rock blocks.

The rotatory coefficient $\xi$ is defined as the ratio of extrusive strength of the fractured rock block $\sigma p$ to the compressive strength $\sigma e$. Thus, the ultimate load $q$ that the rock block can bear is

$$q = \frac{\xi \sigma (h \cdot x \sin \theta)^2}{2x^2 \cos \alpha - x h \sin \alpha \cdot x^2 \sin \alpha \sin \theta}$$

When the roof beam is fractured, the ultimate load $q$ and tensile strength $\sigma i$ are related as follows:

$$q = \frac{\sigma}{\kappa (\frac{x}{h})}$$

(24)

where $\kappa$ value depends on the boundary conditions of the hinged rock block. Combining Eqs. (23) and (24) yields the following formulas:

$$\sin \theta = \frac{h}{x} \left[ h^2 \sigma \sin \alpha + \sqrt{h^2 \sigma^2 \sin^2 \alpha - 48h^2 \xi \sigma \sigma (h x \sin \alpha - x^2 \cos \alpha)}/12x \sigma \right]$$

$$\Delta = \frac{h^2 \sigma \sin \alpha + \sqrt{h^2 \sigma^2 \sin^2 \alpha - 48h^2 \xi \sigma \sigma (h x \sin \alpha - x^2 \cos \alpha)}}{12x \sigma}$$

(25)
The angle of rotation and settlement changed with dip angle, which is in the range [20, 70], and the relationship is displayed in Fig. 10. The angle of rotation is positively correlated with the dip angle, indicating that it increases with the dip angle. Equation (25) yields the hinged rock block Δ’s settlement. When the settlement of the hinged area of the fractured rock block exceeds Δ, rotatory instability takes place in the roof, and the larger is the dip angle, the more likely is this failure.

When the dip angle is constant, the relationships between the angle of rotation and thickness of the main roof, as well as the length of the rock block take the form, as shown in Fig. 11, where 2m<h<5m and 10m<x<30m. It can be seen from Fig. 11 that the angle of rotation θ grows with an increase of h and x by 1.4~4.3°/m and 0.25~0.69°/m, respectively. It shows that a change in thickness has a larger impact on the hinged structure. When the rotation angle reaches its minimum value depending on the allowable deformation, the deformation instability occurs (He et al. 2020; Ju et al. 2018). The rotation angle’s magnitude reflects the differences of overburden rock structure and its stability, thus exerting a significant effect on the support (Xie et al. 2020).

5. Analysis of the support stability

Hydraulic supports are critical in protecting the roof and the dynamic mechanical environment where surrounding rocks impact and constrain each other (Yang et al. 2019; Luo et al. 2019). The load magnitude, direction, and point of application to the support vary with the roof kinematic state changes. Therefore, determining the critical work resistance of support can ensure the particular mining requirements (Yang et al. 2018).

The mechanical model of a single inclined support is shown in Fig. 13, where the x-axis is upward positive and coincides with the workface dip, the y-axis is upward positive and normal to the x-axis, b and h are the support width and height, respectively, h1 is the height of the support center of gravity, x1 is the point of application of the normal load to the roof, x2 is the point of application of the normal load resultant to the floor, G is the support weight, P is the normal load of the roof acting on the support (support work resistance), f1 is the tangential load of the roof acting on the support (friction between roof and support), Fx is the floor tangential load on the support, f2 is the tangential load of the floor on the support (friction between support and floor), Pi−1 and Pi+1 are forces acting between two adjacent supports. During mining in SDCS, forces between adjacent supports are much smaller than friction between support and roof or floor, so forces between adjacent supports are assumed to be the same. The mechanical response of the support in the critical instability state was analyzed in detail.
sliding instability, the anti-sliding force should exceed the sliding force in support, which means

\[ f_1 + f_2 \geq G \sin \alpha \]  \hspace{1cm} (26)

Under the critical sliding instability state, the coefficients of friction between the roof, floor, and support can be expressed as

\[ f_1 = \mu_1 P \]  \hspace{1cm} (27)

\[ f_2 = \mu_2 (P + G \cos \alpha) \]  \hspace{1cm} (28)

According to Eqs. (26)-(28), the critical work resistance of a single support before sliding can be expressed as

\[ P_{\text{cr}} = \frac{G(\sin \alpha - \mu_2 \cos \alpha)}{\mu_1 + \mu_2} \]  \hspace{1cm} (29)

To avoid rotatory instability, the anti-rotating moment should exceed the turning moment, which means that

\[ \frac{b}{2} G \cos \alpha + P_{x_1} + f_{x_1} h \geq h G \sin \alpha + F_{x_2} x_2 \]  \hspace{1cm} (30)

During mining in the workface, the loading characteristics of the support, roof, and floor change with time due to the roof and floor movements. When the support work resistance \( P \) is applied to A ( \( x_z =0 \)), the resultant force of normal loads on the floor \( F_y \) has a point of application C ( \( x_z =0 \)), the support experiences the worst condition before non-rotatory instability. In this case, Eq. (30) can be reduced to the following form

\[ \frac{b}{2} G \cos \alpha + P_{x_1} + f_{x_1} h \geq h G \sin \alpha \]  \hspace{1cm} (31)

According to Eqs. (27)-(31), the critical work resistance for single support before rotating can be expressed as

\[ P_{x_1} = \frac{2h G \sin \alpha - b G \cos \alpha}{2b \mu_1} \]  \hspace{1cm} (32)

As a case study for the proposed method, the 12124 workface in the Pansidong coal was selected to investigate the impact of the dip angle of coal seam on the critical work resistance of support analyzed via Eqs. (29) and (32).

The 12124 workface in the Pansidong mine is fully-mechanized, with the average dip angle of the coal seam \( \alpha =40^\circ \). A ZZ7200/22/45 covering hydraulic support was adopted in the workface, the support width was 1.5 m, the height of the center of gravity of support \( h_1 = 2.25 \) m, the gravity of support was 176.4 kN, the coefficients of friction between support and roof/floor were equal ( \( \mu_1 = \mu_2 =0.25 \)). The relationship between the critical work resistance of support and the dip angle is shown in Fig. 13, where the dip angle ranges from 20° to 70°. It can be seen from Fig. 13 that before slip and rotation of the support, the critical work resistance of support was positively correlated with the dip angle of coal seam and, under the same dip angle, the critical slip work resistance of support exceeded its critical rotation work resistance.

Fig. 13. Relationship between the critical work resistance and dip angle of the coal seam

6. Conclusions

A mechanical model of the main roof under linear load in the SDCS longwall workface was proposed in this study, which made it possible to derive the main roof stresses. The results obtained show that the bottom floor had features of compression at three sides and tension on the middle part, whereas the top floor had tensile stresses at three sides and compressive stress in the middle area. The maximum shear stress \( \tau_{\text{max}} \) slightly exceeded the middle of workface and occurred periodically during the workface advance.

The main principal stresses \( \sigma_{\text{max}} \) and \( \sigma_{\text{min}} \) of the roof were nonlinearly correlated with the dip angle. When the dip angle increased in the range 30°-50°, \( \sigma_{\text{max}} \) and \( \sigma_{\text{min}} \) rapidly dropped; when the dip angle increases in the range 50°-60°, they gradually become stable. The same variations of the dip corresponded to the same variation rates of \( \sigma_{\text{max}} \) and \( \sigma_{\text{min}} \).

The mechanical model of the first-fracture rock block in the workface was established, based on which the effects of the dip angle of coal seam on the rock block instability were analyzed. The hinged rock block's anti-slip capacity was improved with an increase in dip
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angle, making the slip instability unlikely to occur. The critical dip angle of the fractured rock block was 57° when instability occurred. The possibility of slip instability of a fractured rock block workface increased as the thickness of the main roof and length of the rock block increased.

The critical work resistance of a support under non-sliding and non-rotating conditions was positively correlated with the coal seam’s dip angle. The critical work resistance under sliding condition exceeded that at rotating condition at the same dip angles of the coal seam.

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References


