Stability Analysis of “Support-Surrounding Rock” System for Fully Mechanized Longwall Mining in Steeply Dipping Coal Seams

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The key to safe and efficient longwall mining of steeply dipping seams lies in the stability control of the “support-surrounding rock” system. This study analyzes the difficulties encountered when controlling the stability of the support during the longwall mining process of steeply dipping coal seams in terms of the characteristics of the nonuniform filled-in gob using a combination of physical tests, theoretical analyses, and field measurements. Considering the floor as an elastic foundation, we built a “support-surrounding rock” mechanical model using data obtained on support-surrounding rock systems in different regions and the laws of support motion under different load conditions. Our findings are summarized as follows: first, depending on the angle of the coal seam, the caving gangue rolls (slide) downward along the inclined direction, resulting in the formation of a nonuniform filling zone in the deep gob where the lower, middle, and upper sections are filled, half-filled, and empty, respectively. In addition, an inverted triangular hollow surface is formed on the floor of the gob in the middle and upper sections behind the support. Furthermore, as the angle of the coal seam, length of the working face, and mining height increase, the characteristics of the nonuniform filled-in gob are enhanced. Second, we found that because of the gangue support, the “support-surrounding rock” system is relatively stable in the lower part of the working face; however, in the middle and upper sections of the working face, the contact method and loading characteristics of the support are more complicated, making stability control difficult. Third, the magnitude and direction of the load, action point, and mining height affect the stability of the support to varying degrees, with the tangential load and action position of the roof load having the most significant impacts on the stability of the support. Under loading by the roof, rotation and subsidence of the support inevitably occur, with gradually increasing amplitudes and effects on the intersupport and sliding forces. Finally, we found that overall stability can be achieved by adopting measures involving “sliding advancement of supports” and applying a “down-up” removal order. These research results serve as a significant reference and guidance for longwall mining applications.

1. Introduction

Steeply dipping coal seams are seams with angles from the horizontal in the range of 35°–55° [1, 2]. Such seams, which are recognized worldwide as being difficult to mine, are widely distributed throughout major mining areas in China, accounting for 10–20% and 5–8% of China’s coal reserves and output, respectively. More than 50% of the mines with steeply dipping coal seams occur in western China (e.g., Sichuan, Guizhou, Gansu, Xinjiang, Ningxia Provinces) [3]. The country’s long history of high-intensity mining has made coal reserves with “excellent” occurrence conditions increasingly rare, and many mines have had to resort to the mining of steeply dipping coal seams with relatively complicated occurrence conditions in the eastern and central mining areas (e.g., Shandong, Hebei, Anhui, and Shanxi Provinces) [4]. Thus, the mining of steeply dipping coal seams has become a major engineering problem in the development of China’s coal resources [5, 6].
The key to the safe and efficient longwall mining of steeply dipping coal seams is the effective control of surrounding rock [7]. In the mining of steeply dipping coal seams, the high coal seam angle makes the control of roof movement, support, and floor failure sliding extremely complicated [8–12]. This complexity changes the “support-surrounding rock” system of the working face from a “stable state” system in the conventional sense to an “unstable state” system. In general, the control extended to the support must not only control the roof through the working resistance but also, through the application of working resistance, the floor, and the control system itself. In recent years, a number of methods, including theoretical analysis, numerical calculation, simulation with physically similar materials, on-site monitoring, etc., have been developed to understand, for example, the migration law of surrounding rock and support loading characteristics [13–15], the coupling mechanism of the “support-surrounding rock” system [16, 17], the mechanism of variation and instability [18], and intersupport pushing and its cumulative effects under various mining methods (e.g., longwall mining of steeply dipping medium-thick coal seams, fully mechanized longwall caving of thick coal seams, coal seam group mining) [19, 20]. A range of determinate conditions for support stability and methods for calculating the critical working resistance of the support have been derived and many technical measures for the prevention of slipping of the hydraulic support have been proposed, with the results promoting the continuous progress of the control theory and technology for ensuring support stability in steeply dipping coal seam mining.

However, previous research on support stability has focused primarily on experiments and field monitoring, with some theoretical research done to primarily determine the working resistance of the support under critical rotating and sliding conditions based on support stability criteria constructed without consideration of floor deformation and the assumption that the floor is a rigid body. In the mining process of steeply dipping coal seams, the deformation and failure of roof has a complicated influence on the support, and the mechanical behaviors and states of the support in different areas will change significantly. Particularly, the roof deforms and breaks frequently and the support is prone to experiencing no load and unbalanced loads in the middle and upper areas along the inclined direction. In severe cases, paralysis of the support system caused by local support instability can easily induce large-scale surrounding rock disasters [21]. Therefore, it is particularly important to reveal the surrounding rock movement law of the longwall working face in steeply dipping coal seams and its response mechanism to the mechanical behavior of the support, and develop dynamic stability control measures for the support.

In this study, an analysis of the breaking and moving laws of the surrounding rock and the basic characteristics of the surrounding rock structure formed in the longwall mining of steeply dipping coal seams was conducted. Under the assumption that the floor is an elastic foundation, a mechanical model of the “support-surrounding rock” system and the behavioral response of the support under the roof load was derived. The results provide a theoretical reference value for solving the dynamic stability control of the “support-surrounding rock” system in the longwall mining of steeply dipping coal seams.

2. Background

2.1. Working Face. Working face 25221 of a coalmine (Xinjiang Coking Coal Group Ewirgol) is located in district 2 of the #5 coal seam. The working face is located to the west of ditch #15 and 153 m east of line 16. The surface is mountainous and filled with gullies. The working face has a long and narrow distribution from east to west. The mining elevation is +2047–2120 m, the strike length is 2098 m, and the inclined length is 100 m. The angle fluctuates within 36°–46° with an average of 45°. The coal bulk density is 1.35 t/m³. The coal seam is stable with a thickness of 3.58–9.77 m and an average thickness of 4.5 m. The hardness coefficient of the coal is 0.3–0.5.

2.2. Field Monitoring of Working Resistances. The mining processes at working face 25221 adopt a fully mechanized large-height mining method with the following process flow: cutting coal downward ⟶ clearing floating coal upward ⟶ pushing conveyor ⟶ moving support. According to the special geological conditions of the mine, the working resistance of the support was finally determined to be 6,500 kN; to counter this, 60 ZZ6500/22/48 shield supports and 3 ZZZ66500/22/48 transition supports were used. The rock pressure on the working face was observed with a KJ377 pressure dynamic detector. The #9, #29, and #47 supports in the inclined lower, middle, and upper areas, respectively, were monitored, with the monitoring results shown in Figure 1.

The following observations are made from the monitoring results:

1. The average working resistance of the #9 support is 3,505 kN, while the maximum working resistance during periodic weighting is 5,400 kN, with a standard deviation of 767.12 kN. The average working resistance and maximum working resistance during periodic weighting of the #29 support are 6,422 and 9,390 kN, respectively, with a standard deviation of 1,358.17 kN. The average working resistance and maximum working resistance during periodic weighting of the #47 support are 4,985 and 6,481 kN, respectively, with a standard deviation of 1,088.07 kN.

2. The load distributions on the front and back legs of the support are different in different areas. In the lower area, the load distribution on the front and back legs of the support is more uniform, and the load on the front leg is larger than that on the back leg. The load ratios of the back to the front legs are 90.9%, 85.71%, and 90% before, during, and after the periodic weighting, respectively, and the average load ratio is 88.87%. In the middle area, the load distribution on the front and back legs of the support is relatively uniform, and the load on the back leg is...
greater than that on the front leg. The load ratios of the back to the front legs are 105.15%, 108.57%, and 112.5% respectively, and the average load ratio is 108.74%. In the upper area, the load distribution on the front and back legs of the support is uneven, and the load on the back leg is much smaller than that on the front leg. The load ratios of the back to the front legs are 60.61%, 45.45%, and 47.62% respectively, and the average load ratio is 51.23%.

(3) There are obvious unbalanced load characteristics in the support on the working face. Along the inclined direction, the load has the basic characteristics of being the largest in the middle area. In the lower area of the working face, the amplitude of the load is essentially constant, and the “support-surrounding rock” system is relatively stable. In the middle and upper areas of the working face, the support is susceptible during periodic weighting to the impact of the roof. Some supports bear an extremely low load, which leads to a lack of elements in the “support-surrounding rock” system.

3. Interaction between Support and Surrounding Rock

Experiments with physically similar materials were conducted to study the deformation and failure of surrounding rock. A coal and rock layer histogram was used to reduce the coalmine to an experimental model with a geometric similarity ratio of 1:20. The physical and mechanical parameters of the coal and rock mass measured on-site were used to determine the proportions of the similar materials: 70–140 mesh quartz sand, coal ash, gypsum, and calcium carbonate. Water was added, and the materials were mixed evenly and placed in the model frame. A heavy object was used to compact the material to the required density. To represent the layers, 8–20 mesh mica powder was used. According to the law of similarity, the stress and strength similarity constant was 32, the time similarity constant was $20^{1/2}$, the bulk density similarity constant was 1.6, and the load similarity constant was 12800. The proportions of the similar materials are given in Table 1, and the model is shown in Figure 2.

3.1. Characteristics of Surrounding Rock Migration. The results revealed the following:

(1) The movement of the roof is asymmetrical. Generally, the displacement of the upper area is larger. The failure mode of the upper area is generally “tensile-shear” failure, and that of the lower area is generally “compression-shear” failure.

(2) Along the strike of the working face, the main roof will form articulated rock beam structures of different lengths in different areas. In the lower area of the working face, the gob is relatively full, the gangue filling body is dense, the main roof is longer, and the amount of sinking and rotation is small. The strength of the mining pressure is relatively small, and there is no obvious periodic characteristic. The caving of the roof in this area is inadequate, and there is no obvious “three-zone formation.” In the middle area of the working face, the gob is partially filled, and the length of broken main roof is relatively short; however, the broken main roof can also form an articulated rock beam structure. The amount of sinking and rotation is large. The strength of the mining pressure is relatively large and there is an obvious periodic characteristic. In the upper area of the working face, the gangue slides down along the inclined direction, and a hollow face is formed on the bottom of the gob behind the support. Affected by this, the surrounding rock migration space in this area is large and the articulated rock beam structure
cannot be formed. The strata caved sufficiently, and the "three zones" formed at a high level. Overall, the broken roof along the strike is deep and short in the upper area while shallow and long in the middle and lower areas. In the deep gob where the roof is fully caved, a nonuniform filling zone is formed with fully filled-in lower area, partially filled-in middle area, and empty in upper area. In the middle and upper areas of the gob along the inclined direction behind the support where the roof has not fully caved, an inverted triangular hollow face is formed.

(3) Along the inclined direction of working face, the gangue slip filling from the immediate roof shows characteristics ranging from dense to loose. The lumpiness of the gangue fillings in the lower part is graded, and the strength is high. The gangue in the middle and upper areas has a large block size, and the strength is poor. Masonry and antimasonry structures along the inclined direction formed when rotational deformation failure occurred in the main roof. In the upper area, gangue slides downward along the working face, forming an empty area in the upper corner. In the middle area, the rotated rock block acts on the support which causes the working resistance of the support to increase. The lower area is filled up after the immediate roof caves in. The roof migration space in this area is small, and the amount of rotation and subsidence is smaller than that of the middle and upper areas, which is shown in Figure 3.

3.2. Nonuniform Filling Characteristics of Caving Gangue

Combined with the above experimental results, it can be seen that, in the mining of a steeply dipping coal seam, the angle of the coal seam will be greater than the natural resting angle of the caving gangue, inducing the gangue to slide down to fill the lower area of the working face along the inclined direction, as shown by the black arrow in Figure 4. The portion of the main roof that caves in the middle and upper areas of the deep gob will also slide down, as shown by the red arrow in the figure. In the deep gob, a nonuniform filling zone in which the lower, middle, and upper areas are filled, half-filled, and empty, respectively, is formed, while an inverted triangular hollow face is formed on the floor in the middle and upper areas behind the support, as shown in Figure 4. It is seen that the filling characteristics of this gob will have, in addition to obvious asymmetric characteristics, anisotropy along the strike. These asymmetries lead to significant differences in the characteristics of the loading and failure movement of the surrounding rock and the interaction relationship between the "support-surrounding rock" system along the inclined and strike directions.

Figure 5 shows the filling characteristics of the gob behind the support. In the figure, the x-axis runs along the strike, while the y- and z-axes point downward along the inclined direction on the working face and upward along the vertical coal seam, respectively. The length of the working face (L), thickness of the coal seam (h0), thickness of the immediate roof (h1), inclined length of the rectangular area of the caving gangue filling body behind the support (a), inclined length of the triangular area of the caving gangue filling body behind the support (b), and inclined length of the inverted triangle in the middle and upper area behind the gob (c) are all given in meters; the angle of the coal seam (α), resting angle of the gangue (γ), and angle between the contact line of the support and the floor and the contact line of the gangue and the floor (β) are all given in degrees.

For convenience in obtaining a theoretical solution, it is assumed that the gob behind the support in the middle and lower areas is filled with caving gangue as an immediate roof rock block. From the filling characteristics of the gob behind the support shown in Figure 5, the relationship between the immediate roof caving gangue and the filling gangue can be described as

\[ kLh_1 \cdot l = a(h_0 + h_1) \cdot b(h_0 + h_1) \cdot 1, \]

where \( k \) is the bulking factor. From the geometric relationship shown in Figure 5, the inclined length, \( b \), of the triangular area of the gangue filling body behind the support is

\[ b = (h_0 + h_1)\cot(\alpha - \gamma). \]

Substituting Equation (2) into (1), the inclined length, \( a \), of the rectangular area of the gangue filling body in the gob behind the support can be expressed as

\[ a = \frac{Lh_1k}{h_0 + h_1} - \frac{(h_0 + h_1)}{2}\cot(\alpha - \gamma). \]

Similarly, the inclined length, \( c \), of the inverted triangle in the middle and upper area of the gob behind the support can be expressed as

\[ c = \frac{Lh_1k}{h_0 + h_1} + \frac{(h_0 + h_1)}{2}\cot(\alpha - \gamma). \]

From the geometric relationship between the gangue filling body and the hollow face in the inclined middle and upper areas in Figure 5, the angle, \( \beta \), between the contact line of the support and the floor and the contact line of the gangue and the floor can be expressed as

\[ \beta = \arctan\frac{\sin \alpha}{\tan \gamma}. \]
Figure 2: Test model. (a) Model. (b) Date collection system. (c) Support mode.

Figure 3: Characteristics of caving and filling of floor.
Figure 6 shows the influence of the coal seam angle and the length of the working face on the filling characteristics of the gob behind the support. The values of the remaining parameters used in the calculation have been marked in the figure, while the dashed lines and corresponding labels indicate the values of these parameters when the inclined length, $c$, of the hollow face is zero. It is seen from the figure that the size of the hollow face of the floor behind the support increases with the coal seam angle and the length of the working face.

An inspection of Figure 6(a) reveals that, when the angle of coal seam is slightly larger than the natural resting angle of the gangue, that is, when the angle is between $35$ and $38.5^\circ$, the rolling characteristics of the gangue do not manifest. In this case, the inclined length, $a$, of the rectangular area of the filling body and the inclined length, $c$, of the inverted triangle hollow face are both less than zero, and the gob tends to have an unfilled region in its lower area and no hollow face in its upper area. When the angle is between $38.5$ and $42.5^\circ$, the length of the working face is less than $75.5$ m, the mining height is less than $2.98$ m, and the thickness of the immediate roof is greater than $4.70$ m, while the inclined length, $a$, of the rectangular area of the filling body is greater than zero and the inclined length, $c$, of the inverted triangle hollow face is less than zero. In this case, there is a filled-in region in the lower area of the gob behind the support and no hollow face in the upper area. When the angle is greater than $42.5^\circ$, the length of the working face and mining height is greater than $75.5$ and $2.98$ m, respectively, and the thickness of the immediate roof is less than $4.70$ m. The values of $a$ and $c$ are both greater than zero, and the gob tends to have a filled-in region in its lower area and a hollow face in its upper area.

From Figure 6(b), it is seen that, when the angle of coal seam is $45^\circ$ and the length of the working face is less than
75.5 m, a filling region is formed in the lower area of the working face, while the resting face of the gangue is covered in the middle and upper parts of the gob. When the length of the working face is greater than 75.5 m, the values of a and c are both proportional L, the length of the working face.

It is seen that in the case of longwall mining of steeply dipping coal seams, the nonuniform filling characteristics of the caving gangue are closely related to factors such as coal seam angle and length of the working face; as these factors increase, the amplitude and severity of gangue rolling increases. The stability of the roof and floor in the lower part of the working face is enhanced by the support of gangue. As the working face advances, the main activity range of the roof and floor rock formations that are moved and destroyed is moved upward, the amplitude and severity of the roof and floor rock formations in the upper and middle areas of the working face increase, and the likelihood of floor damage slip and falling and rotation of the support and equipment falling increase sharply. The "support-surrounding rock" system is prone to dynamic instability during the advancement of the working face, which in turn can lead to failure of the surrounding rock.

3.3. Interaction Characteristics of "Support-Surrounding Rock". The interaction relationship of the "support-surrounding rock" system along the strike and inclined direction varies significantly with the nonuniform filling effect of the gangue, as shown in Figures 7 and 8. In the lower area of the working face, the gob is in a filled-in state in which there is a high filling density, limited space for migration of the surrounding rock, and minimal subsidence and rotational angles along the strike and inclined direction. In this region, an articulated rock beam structure can be formed in the strike direction. Nevertheless, because of the lateral rolling (sliding) movement of the caving gangue, the rear canopy of the support in the lower area is susceptible to the impact of the gangue.

In the middle area of the working face, the gob is in a half-filled state and the filling density is less than in the lower area. Although an articulated rock beam structure can still be formed along the strike following ejection of the main roof, its stability will be weaker than in the lower area. In addition, the increase of the space available for roof movement allows for large degrees of cut-off and rotation along the strike and inclined directions following breaking of the main roof. The support is susceptible to impact loads. The stability of the "support-surrounding rock" system is poor.

In the upper area of the working face, a small amount of gangue is filled into the gob. The load on the front leg is greater than that on the back leg, and the support is prone to "head down." The amplitude and severity of roof movement are both high, and the stability of the rock structure is poor. Following ejection of the main roof, the cut-off and rotation amplitudes along the strike and inclined directions are much larger than in the middle area and, as the working face advances, instabilities caused by rotation and the formation of an empty roof are extremely likely. In the upper and middle areas of the working face, there are complex interactions in the "support-surrounding rock" system, phenomena such as eccentric and no-loading of the supports and biting between supports are prominent, and it is difficult to control the stability of the supports.

When the movement state of the roof changes, the value, direction, and action point of the load on the support all change, and the support responds accordingly. When the support position changes, the interaction between the support and floor and the magnitude, direction, and point of action of the load on the support by the floor also change, as shown in Figure 9. It is seen that, in the mining of steeply dipping coal seams, when the roof movement state changes, the interaction between the support and surrounding rock changes accordingly. The "support-surrounding rock" system is in a constantly dynamic state of mutual interaction.
4. Mechanical Analysis of Movement
Law of Support

From the above analysis, it is seen that the support will move under the influence of roof movement. In the mining of a steeply dipping coal seam, the support moves along the inclined direction through subsidence, slip, and rotation and must be adjusted fundamentally or through coupling of the movement form to adapt to changes in external loads and constraints until it enters a new balanced state. Under the
assumption that the floor is elastic foundation, a mechanical model of the motion of the support along the inclined direction was established (Figure 10) [7].

In the figure, the y- and z-axes are aligned downward along the inclined and vertical direction of coal seam, respectively, and the reverse rotation of the support in the positive direction. The weight of the support (G), the height of the center of gravity of the support (Lc), normal load of the roof to the support, i.e., working resistance of the support (P), and tangential load of the roof to the support, i.e., the friction between the support and the roof (Fr), normal load of the floor to the support (Ff), working resistance of the support (G), the height and the reverse rotation of the support is in the positive direction. kD is the weight of the support (G), the height and the reverse rotation of the support is in the positive direction. The acting positions of the roof and floor loads (y0 and y1, respectively) are given in meters and the rotational angle of the support (φ) is given in degrees.

4.1. Mechanical Analysis of Support Sliding. The sliding force $F_{H}$ of the support under loading by the roof can be expressed as

$$F_{H} = F_{R} - \Delta S - G \sin(\alpha - \varphi),$$

where $\Delta S = S_{\text{down}} - S_{\text{up}}$ is the interaction force between supports in kN. When the sliding force $F_{H}$ is greater than the maximum static friction $F_{\text{Fmax}}$, the floor and the support slips. Here, we define the support sliding factor, $f$, as

$$f = \frac{F_{H}}{F_{\text{Fmax}}}.$$  

When the absolute value of $f$ is greater than one, the supports slide. During the sliding process, the force $\Delta S$ gradually increases, and the sliding force $F_{H}$ gradually decreases until the support reaches a new balanced state given by

$$F_{R} - \Delta S - G \sin(\alpha - \varphi) + F_{\text{Fmax}} = 0.$$  

4.2. Mechanical Analysis of Support Rotation. When the acting load on the support changes, the resultant force couple on the support to deviate from zero and the support rotates. During this rotation, the load acting on the floor and the adjacent support is adjusted spontaneously, and the resulting force couple gradually approaches zero until a new balanced state is reached. The rotational direction and amplitude are closely related to the load on the support, and the rotational dynamics can essentially be divided into nonlifting, upper-side lifting reverse, and lower-side lifting sequential rotation.

4.2.1. Nonlifting Rotation. When the resultant force couple on the support is small, the support rotates without lifting away from the center point (point O) of its base. In this state, the force-couple balanced equation for the new balanced state is

$$F_{N} \left( y_{1} - \frac{\epsilon}{2} \right) - \Delta Sh + L_{c}G \sin(\alpha - \varphi) - F_{R}h + P\left( \frac{\epsilon}{2} - y_{0} \right) = 0,$$

where $h$ and $\epsilon$ are the height and width, respectively, of the support in meters.

When the support rotates without lifting, the intensities of the forces contributing to the normal load applied by the floor to the support follow the “trapezoidal” distribution shown in Figures 9(a) and 9(b). According to the theory of elastic foundation, under this new balanced state the resultant force $F_{b}$ of the normal load of the floor and its acting position $y_{1}$ can be expressed as

$$F_{N} = -z_{O}k_{f}fe,$$

and

$$y_{1} = \frac{\epsilon z_{O} - \epsilon^{2} \sin \varphi}{12z_{O}}.$$  

respectively, where $z_{O}$ is the displacement of the center point of the support base in the $z$ direction in the new balanced state in meters, $f$ is the length of the support base in meters, and $k_{f}$ is the foundation coefficient of the floor in kNm$^{-3}$.

In this new balanced state, the loads $S_{\text{down}}$ and $S_{\text{up}}$ between the adjacent supports can be expressed as

$$S_{\text{down}} = \begin{cases} 0, & y_{O} - \Delta y_{A} \geq 0, \\ -K_{s}(y_{O} - \Delta y_{A}), & y_{O} - \Delta y_{A} < 0 \end{cases}$$

and

$$S_{\text{up}} = \begin{cases} 0, & y_{O} - \Delta y_{B} \geq 0, \\ -K_{s}(y_{O} - \Delta y_{B}), & y_{O} - \Delta y_{B} < 0 \end{cases}$$

respectively, where $K_{s}$ is the stiffness of the side guard Jack in kNm$^{-1}$, $y_{O}$ is the displacement of the midpoint of the support base along the $y$ direction in new balanced state in meters, $\Delta y_{A}$ and $\Delta y_{B}$ are displacements caused by rotation of the upper and lower boundaries, respectively, of the canopy of the support along the inclined direction in meters, which can be expressed as
\[ \Delta y_A = \Delta y_B = 2 \sqrt{\frac{e^2}{4} + h^2 \sin\left(\frac{\varphi}{2}\right) \cos\left(\frac{\varphi}{2} + \arctan \frac{e}{2h}\right)}. \] (14)

4.2.2. Upper-Side Lifting Reverse Rotation. When the total force couple to which the support is subjected is large and in a counterclockwise direction, the support rotates around the inclined lower boundary (point C) of its base, and the inclined upper boundary (point D) is lifted off. When the support reaches a new balanced state under this loaded and restrained state, the resultant force and resultant force couple of the support in the \( z \) direction are zero, that is:

\[ -F_N (e - y_1) - \Delta S h + G \sin (\alpha - \varphi) L_G - G \cos (\alpha - \varphi) \frac{e}{2} = 0 \]

\[ -F_R h - P (e - y_0) = 0. \] (22)

In this situation, the normal load of the floor to the support is triangular, as shown in Figure 9(d). According to the theory of elastic foundations, the resultant force \( F_N \) of the normal load and its acting position \( y_1 \) can be expressed as

\[ F_N = \frac{-z_D e k_0}{2 \sin \varphi}, \] (23)

and

\[ y_1 = \frac{-z_C}{3 \sin \varphi}, \] (24)

respectively, where \( z_C \) is the displacement in the \( z \) direction of the lower boundary of the support base in the new balanced state in meters. The acting loads \( S_{\text{down}} \) and \( S_{\text{up}} \) between the adjacent supports can be expressed as

\[ S_{\text{down}} = \begin{cases} 0, & \text{if } y_C - \Delta y_A \geq 0, \\ -K_S (y_C - \Delta y_A), & \text{if } y_C - \Delta y_A < 0, \end{cases} \] (18)

and

\[ S_{\text{up}} = \begin{cases} 0, & \text{if } y_C - \Delta y_B \leq 0, \\ -K_S (y_C - \Delta y_B), & \text{if } y_C - \Delta y_B > 0, \end{cases} \] (19)

respectively, where \( x_C \) is the displacement in the \( x \) direction of the lower boundary of the support base in the new balanced state in meters, and \( \Delta y_A \) and \( \Delta y_B \) can be expressed as

\[ \Delta y_A = h \sin \varphi, \] (20)

and

\[ \Delta y_B = 2 \sqrt{e^2 + h^2 \sin\left(\frac{\varphi}{2}\right) \sin\left(\frac{\varphi}{2} + \arctan \frac{h}{e}\right)}, \] (21)

respectively.

4.2.3. Lower-Side Lifting Sequential Rotation. When the total force couple to which the support is subjected is large and in a clockwise direction, the support rotates around the inclined upper boundary (point D) of its base and the inclined lower boundary (point C) of the base is lifted off. When the support reaches a new balanced state under this loaded and restrained state, the total force and resultant force couple of the support in the \( z \) direction are zero, that is:

\[ -F_N (e - y_1) - \Delta S h + G \sin (\alpha - \varphi) L_G - G \cos (\alpha - \varphi) \frac{e}{2} = 0 \]

\[ -F_R h - P (e - y_0) = 0. \] (22)

In this situation, the normal load of the floor to the support is triangular, as shown in Figure 9(d). According to the theory of elastic foundations, the resultant force \( F_N \) of the normal load and its acting position \( y_1 \) can be expressed as

\[ F_N = \frac{-z_D e k_0}{2 \sin \varphi}, \] (23)

and

\[ y_1 = e - \frac{z_D}{3 \sin \varphi}, \] (24)

respectively, where \( z_D \) is the displacement in the \( z \) direction of the lower boundary of the support base in the new balanced state in meters. In this new balanced state, the acting loads \( S_{\text{down}} \) and \( S_{\text{up}} \) between the adjacent supports can be expressed as

\[ S_{\text{down}} = \begin{cases} 0, & \text{if } y_D + \Delta y_A \geq 0, \\ -K_S (y_D + \Delta y_A), & \text{if } y_D + \Delta y_A < 0, \end{cases} \] (25)

and

\[ S_{\text{up}} = \begin{cases} 0, & \text{if } y_D + \Delta y_B \leq 0, \\ -K_S (y_D + \Delta y_B), & \text{if } y_D + \Delta y_B > 0, \end{cases} \] (26)

respectively, where \( y_D \) is the displacement in the \( y \) direction of the upper boundary of the support base in the new balanced state in meters. In the new balanced state, \( \Delta y_A \) and \( \Delta y_B \) can be expressed as

\[ \Delta y_A = -2 \sqrt{e^2 + h^2 \sin\left(\frac{\varphi}{2}\right) \sin\left(\frac{\varphi}{2} + \arctan \frac{h}{e}\right)}, \] (27)

and

\[ \Delta y_B = -h \sin \varphi, \] (28)

respectively.

4.3. Mechanical Analysis of Support Subsidence. As the working resistance of the support increases, the support sinks further. During the rotation and subsidence of the support, the resultant force and force couple of the support along the \( z \) direction gradually approach zero until a new balanced state is reached:

\[ F_N - P - G \cos (\alpha - \varphi) = 0. \] (29)
5. Case Study

In the following case, the influence of the roof load and mining height on the stability of the support is analyzed based on data obtained from working face 25221 of a coalmine. The values of the basic parameters used in the model analysis are listed in Table 2.

5.1. Influence of Roof Load on Stability of Support. Figures 11–13 show the influence of the load on the stability of the support at a mining height of 4 m. It is seen from the figure that changing the acting load of the roof on the support alters the moving state of the support, with the magnitude, direction, and action point of the roof load affecting the stability of the support to different degrees.

When the load on the roof is not eccentric and the support is not subjected to a tangential load (i.e., \( y_0 = e/2 \ m, \ F_R = 0 \ kN \)), the main force inducing sliding and rotation of the support is the component of gravity parallel to the inclined direction. As the working resistance, \( P \), increases, the support sinks further and the amount of subsidence \( z_A \) of the lower boundary of the support increases. However, the main force couple formed by the incline-parallel component of gravity, rotation angle \( \phi \), and the force \( \Delta S \) remain unchanged as \( P \) increases and, because the main force couple is small, \( \phi \) and \( \Delta S \) are also small. Similarly, the sliding force \( F_{11} \) remains unchanged even as the maximum static friction \( F_{\text{max}} \) between the support and floor gradually increases. As a result, the sliding factor \( f \) gradually decreases to a value much lower than one, which means that the support will not slide down or rotate without lifting from the original position, as shown in Figure 11.

If the roof load is not eccentric and the support is subjected to a tangential load, the main forces that induce support sliding and rotation include the component of gravity on the support and the tangential load, \( \ F_R \). As \( \ F_R \) is increased, the sliding force on the support, main force couple formed by the tangential load, rotation angle \( \phi \) of the support, acting force \( \Delta S \) between the supports, and amount of subsidence \( z_A \) at the lower boundary of the support base all gradually increase, while the sliding factor \( f \) of the support gradually decreases. As the tangential load of the roof evolves from \( \ F_R \) to \( -\ F_R \), the mode of support motion evolves from upper-side lifting with reversed rotation to lower-side lifting with sequential rotation, as shown in Figure 12. If the roof load is not eccentric and the support is subjected to a tangential load \( (y_0 = e/2 \ m, \ F_R = 1,200 \ kN) \), the working resistance can be increased to effectively enhance the stability of the support. By increasing the working resistance, the maximum static friction \( F_{\text{max}} \) can be increased, reducing the sliding factor \( f \) and the probability of support sliding, and the rotational force couple formed by the tangential load of the roof can be reduced, in turn reducing the rotational amplitude and the force between the supports.

If the support is not subjected to a tangential load from the roof and the load is eccentric, the main forces inducing support sliding and rotation are gravity and the normal load, respectively. As the degree of load eccentricity is increased, the main force couple formed by the working resistance, rotation angle \( \phi \), force between supports \( \Delta S \), and value of subsidence \( z_A \) of the lower boundary all gradually increase. At the same time, the component of gravity along the inclined direction of the support remains unchanged, while the support sliding factor \( f \) increases with the increase in \( \Delta S \). As the action position of the load \( y_0 \) evolves from zero to \( e \), the support dynamics change from upper-side lifting with reverse rotation to nonlifting rotation and finally to lower-side lifting with sequential rotation, as shown in Figure 13. It is seen from Figure 11 that, when the support is eccentrically loaded but not subject to the tangential load of the roof \( (y_0 = e/4 \ m, \ F_R = 0 \ kN) \), the enhancement of the working resistance increases the probability of support instability; however, even though the maximum static friction \( F_{\text{max}} \) increases, the probability of support sliding is reduced as the working resistance on the support increases.

5.2. Influence of Mining Height on Support Stability. Figure 14 shows the influence of mining height on the stability of the support at a support working resistance of 5,000 kN. The following observations are made from the figure:

1. If the support is not eccentrically loaded and not subject to the tangential load of the roof \( (y_0 = e/2 \ m, \ F_R = 0 \ kN) \), the main force causing rotation and sliding is the component of gravity along the inclined direction. As the mining height increases, the height of the center of gravity, main force couple formed by the component of gravity along the inclined direction, rotational angle \( \phi \), intersupport force \( \Delta S \), and displacement of the lower boundary of the base all increase. At the same time, the increase in the force \( \Delta S \) induced by increasing the mining height reduces both the sliding force and factor on the support.

2. If the support is not eccentrically loaded and subject to the tangential load of the roof \( (y_0 = e/2 \ m, \ F_R = 1,200 \ kN) \), the component of gravity along the inclined and the tangential load of the roof are the primary causes of rotation and sliding of the support. As the mining height increases, the force couple formed by the tangential load, component of gravity along the inclined direction, rotation angle \( \phi \), intersupport force \( \Delta S \), and displacement of the lower boundary of the base all increase, while the increase in \( \Delta S \) induced by increasing the mining height reduces the sliding force and factor on the support.

3. If the support is eccentrically loaded and not subject to the tangential load of the roof \( (y_0 = e/4 \ m, \ F_R = 0 \ kN) \), the primary force causing sliding is the component of gravity along the inclined while the primary forces causing rotation are the component of gravity along the inclined and the tangential load. As the mining height increases, the height of the center of gravity, intersupport force \( \Delta S \), and anti-rotational force couple formed by \( \Delta S \) increase, while the rotational angle and the amount of lower
boundary subsidence of the base decrease. At the same time, the enhancement of $\Delta S$ results in decreases in the sliding force and factor.

From the above analysis, it is seen that, in the mining of steeply dipping coal seams, the support will move with the roof and that the magnitude and direction of force, action

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**Table 2: Physical parameters used in the model.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Width of support</td>
<td>1.6 m</td>
</tr>
<tr>
<td>$c$</td>
<td>Length of support base</td>
<td>3 m</td>
</tr>
<tr>
<td>$h_0$</td>
<td>Height of support center of gravity</td>
<td>$h/2$ m</td>
</tr>
<tr>
<td>$G$</td>
<td>Weight of support</td>
<td>$15 \times 9.8$ kN</td>
</tr>
<tr>
<td>$k_0$</td>
<td>Foundation coefficient of floor</td>
<td>$1.0 \times 10^5$ kN/m$^3$</td>
</tr>
<tr>
<td>$P$</td>
<td>Setting load of support</td>
<td>5,000 kN</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>Coefficient of friction between support and roof</td>
<td>0.3</td>
</tr>
<tr>
<td>$\mu_2$</td>
<td>Coefficient of friction between support and floor</td>
<td>0.3</td>
</tr>
</tbody>
</table>

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**Figure 11:** Influence of working resistance on support stability ($h = 4$ m). (a) Influence of working resistance on support rotation. (b) Influence of working resistance on support sliding.

**Figure 12:** Influence of tangential load of roof on support stability ($h = 4$ m). (a) Influence of tangential load on support rotation. (b) Influence of tangential load on support sliding.
point, and mining height will affect the stability of the support to various extents. The tangential load and action position of the roof load have the most significant impact on the stability of the support and can affect both the amplitude and direction of motion of the support. Roof loading inevitably leads to rotation and subsidence of the support, with the force $\Delta S$ and the sliding force gradually increasing with the amplitudes of rotation and subsidence.

Stability control of the support should start with the optimization of the support structure and the mining process. The support structure must have an independent base adjustment frame, a side pushing device, reinforced side guard, and base lifting device. In particular, in the upper area of the working face, multiple supports should be connected by an oil cylinder to form an integral antiskip unit to improve the overall stability of the support system in the activity range. In terms of the optimization of the mining process, the main aim is to move the support, and the operation should be strictly in accordance with the working face mining process regulations. The “down-up” moving sequence with “less drop and quick pull” and a combination of the whole and part should be adopted to ensure that the stability of the support during the dropping and moving process is controlled. These laws of surrounding rock migration under the longwall mining of steeply dipping coal seams clarify the need for full-time pressure monitoring of the working face. In the event of a sudden increase in load or poor positioning, immediate measures should be taken to protect the roof and floor and adjust the support position.

Figure 13: Influence of action position of normal loading on support stability ($h = 4$ m). (a) Influence of action position on support rotation. (b) Influence of action position on support sliding.

Figure 14: Influence of mining height on support stability ($p = 5,000$ kN). (a) Influence of mining height on support rotation. (b) Influence of mining height on support sliding.
6. Conclusion

The key to safe and efficient longwall mining in steeply dipping coal seams is the effective control of surrounding rock by undertaking the challenging task of controlling the stability of the “support-surrounding rock” system. With the goal of reducing challenges to managing support stability in the longwall mining of steeply dipping coal seams, this study assessed the characteristics of nonuniform filling in the gob, the interactions within the “support-surrounding rock” system in different areas along the inclined direction, and the motion laws governing the support. The following findings were made:

(1) It was found that the filling characteristics of the gob have obvious asymmetries along the inclined and anisotropies along the strike. Depending on the angle of the coal seam, the gangue will roll (slide) downward along the inclined direction. In the deep gob, a nonuniform filling zone with lower, middle, and upper areas of compaction, filling, and hanging, respectively, is formed. In the middle and upper areas, an inverted triangular hollow face is formed on the floor behind the support. As the angle of the coal seam, length of the working face, and mining height increase, these characteristics of nonuniform filled-in gob formation are enhanced.

(2) In the lower area of working face, the gob is in a high-density filled-in state with limited space for surrounding rock migration and a relatively stable “support-surrounding rock” system. There is a complex interaction between the “support-surrounding rock” system in the upper and middle areas of the working face, in which the amplitude of roof movement is large, and the stability of the surrounding rock structure is poor. There are obvious phenomena of eccentric loading and no-loading of the supports and biting between supports, and it is difficult to control support stability. Under the influence of the movement of the roof, the supports will also move.

(3) The magnitude and direction of force on the support, action point, and mining height will affect support stability to different extents. The tangential load and acting position of the roof load affect the amplitude and direction of motion of the support, with a more significant impact on the stability of the support than other factors. Under roof loading, the support will inevitably rotate and subside with a gradually increasing amplitude that leads to a gradual increase in the inter-support and sliding forces.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

This paper is not under consideration at another journal but has been posted on Research Square (DOI: 10.21203/rs.3.rs-403141/v1).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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