Determination of working resistance based on movement type of the first subordinate key stratum in a fully mechanized face with large mining height

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Abstract
The increase in extraction height will increase the mining-induced overlying strata failure height. In this scenario, the strata pressure behavior is strong in a fully mechanized face with large mining height (FMFLMH), which frequently causes coal wall falls, roof falls, and hydraulic support failure accidents (e.g., support closure and hydraulic column damage). The key to solving these issues is to determine support's working resistance of the FMFLMH. In this paper, comprehensive theoretical analysis, numerical simulation, and field observation were applied to determine the support's working resistance in the FMFLMH based on movement type of the first subordinate key stratum (SKS 1). First, six kinds of movement types of SKS 1 in the FMFLMH are found and defined by theoretical analysis and numerical simulation, which are the direct caving movement type of cantilever structure (direct caving), the double-sided rotation movement type of cantilever structure (double-side rotation), the quadratic rotation movement type of cantilever structure (quadratic rotation), the alternative movement type of cantilever structure hinged structure (alternate hinged), the voussoir beam structure movement type (vousoir), and the short voussoir beam structure movement type (short vousoir), respectively. Besides, based on this, the support load calculation model of each movement type was established, and a formula for the support working resistance of each movement type was obtained. Finally, the correctness of the formulae for the support working resistance under six types of movement of SKS 1 were verified using measurement data from four FMFLMHs in China. These research results have important guiding significance for reasonable selection of support and ensuring safe mining of the FMFLMH.

Keywords
cantilever structure, first subordinate key stratum (SKS 1), fully mechanized face with large mining height (FMFLMH), hinged structure, support working resistance

1 | INTRODUCTION

Coal seams may be classified thick, moderate and thin. Thick-coal seam categorization differs among countries. Generally, a coal seam over 3.5 m thick is termed as a thick-coal seam in China, and China is rich in thick coal seam reserves, accounting for 44% of the total coal reserves.2-4 At present, the main mining methods of thick coal seams are fully mechanized.
mining technology with large mining height (FMMTLMH) and fully mechanized top coal caving mining. Although fully mechanized top coal caving mining has the advantages of high output and high efficiency, it has some disadvantages, such as increased risk of coal spontaneous combustion in the goaf, high dust concentration in the face, and a low coal recovery rate, compared with FMMTLMH.\textsuperscript{6-7} Moreover, field observations show that the coal recovery rate achieved using FMMTLMH is 10%-15% higher than with fully mechanized top coal caving mining.\textsuperscript{8,9} Therefore, in China FMMTLMH has become the common method for extracting thick coal seams whose thickness is less than 7.0 m as this method has lower roadway driving rate, and a high coal recovery rate among other advantages.\textsuperscript{10}

In recent years, FMMTLMH has been widely used in many large mining height mining areas in China; for example, various coal mines in Jincheng, Lu'an, Datong, Yangquan, Xingtai, Xuzhou, Yanzhou, Fuxin, and Shendong mining areas have successively adopted this mining technology.\textsuperscript{11} Although relatively popular, there is a lack of FMMTLMH-related theoretical research, which leads to frequent coal wall falls, roof falls, and hydraulic support failure accidents, which affect coal production and its efficiency.\textsuperscript{12-15} For example, as shown in Figure 1, a large number of support failure accidents (e.g., support closure and hydraulic leg damage) occurred during periodic weighting in FMFLMH8218 in Jinhuagong coal mine. This accident affected coal production for 81 days, and resulted in loss of 89.4 million yuan. Besides, as shown in Figure 2, coal wall and roof fall accidents occurred several times in FMFLMH3305 in Zhaozhuang coal mine during periodic weighting, which affected the safe and efficient mining of the working face. Many studies were performed on the aforementioned issues related to FMFLMH, and their results have indicated that the key to solving the aforementioned issues is to determine the support working resistance of the working face.\textsuperscript{16-19} In general, two determination methods are applied to determine support working resistance in an untapped longwall face: an empirical formula or a theoretical calculation. In the empirical formula method, empirical estimation formulae (Table 1), are used to calculate the support working resistance of the longwall faces with normal mining height\textsuperscript{20}; however, with the increase in extraction height, especially FMFLMH, determination of the support working resistance by empirical estimation cannot guarantee safe mining of the face.\textsuperscript{21,22} There are two reasons for this: first, as shown in Table 1, the calculated support working resistance according to empirical formulae used in China encompasses a range of values due to the large mining height of the coal seam, so it is difficult to determine an appropriate value of support working resistance. Second, the empirical formula method only considers the influence of longwall face mining height, without considering the influence of structural form and movement of overlying strata, which is clearly inappropriate, for example, FMFLMH1203 in the Daliuta coal mine, whose mining height is 4 m (support working resistance calculated by the empirical formula is 3500-7000 kN, assuming that the width of the support is 1.75 m and roof-control distance is 5 m), uses the rated working resistance of 3437 kN of support and guarantees the safe mining of face: however, FMFLMH88101 of the Kangjiatan coal mine whose mining height is also 4 m uses a rated working resistance of 9318 kN of support, but cannot guarantee safe mining of the face; consequently, roof fall and support failure accidents have occurred many times in this region. Therefore, many scholars have realized that the determination of support working resistance should take into account the structural form and movement type of overlying

\textbf{FIGURE 1} Photos of support closure and support damage in Jinhuagong coal mine\textsuperscript{19}: (A) support closure, people must squat to move forward; (B) damaged support leg

\textbf{FIGURE 2} Photos of roof and coal wall falls in Zhaozhuang coal mine: (A) immediate roof fall in the longwall face; (B) coal wall failure and coal spalling
strata in FMFLMH. In particular, the structural form and movement type of SKS 1, and many theoretical calculation models for the support load have been established to determine support working resistance in FMFLMH. For example, Gong and Jin established two calculation models of support working resistance under a voussoir beam structure and the cantilever structure of SKS 1 to determine working resistance in FMFLMH. Yan et al. point out that the roof strata are prone to forming the short cantilever structure of SKS 1 and the voussoir beam structure of SKS 2, and presented formulae for the support working resistance under this structural condition in FMFLMH. Guo et al. established four kinds of structural model by physical modeling, theoretical analysis, and field observation of the Longwall Top Coal Caving (LTCC) panel in consideration of the coincident movement of key strata (KS) and mining activities at the upper face in overburden strata. Finally, a method is proposed for calculating the working resistance of the support in the LTCC face, which is verified by monitoring the mining pressure in practice. The overlying subordinate key strata are divided into three structural models according to physical simulation and theoretical analysis in FMFLMH and the corresponding three types of calculation formulae for support working resistance are obtained by Ju and Xu; however, it is noticed that these calculation models for support load were mainly based on the structural form of SKS 1 in a specific coal mine, rarely considering the influence of movement type of SKS 1 on support load of the longwall face. In fact, although SKS 1 forms the same structural form, when it presents different movement types, which may impose different loads on the support of the longwall face. Therefore, the combination of theoretical analysis, numerical simulation, and field observation was applied in this work to investigate the movement type of SKS 1 in FMFLMH. Based on this, the calculation of support working resistance of each movement type of SKS 1 is obtained according to the corresponding calculation model for the support load. The authors hope that this study can guide engineers in the reasonable selection of hydraulic support of an FMFLMH to ensure safe, efficient mining.

In the mid-1990s, “Key Strata Theory” was proposed. This theory provides in-depth information about the progressive caving behavior of strata and its impacts on longwall operation. According to this theory, the stratum that controls the movement of the whole or part of overburden is defined as the key stratum (KS), that is, when the KS breaks, the whole or part of the overburden above the KS will subside simultaneously. To be more specific, the former is defined as primary key stratum (PKS), whereas the latter is defined as a subordinate key stratum (SKS). There may be more than one SKS in the overburden, whereas the PKS is unique in a specific longwall working face. The first subordinate key stratum is named SKS 1; the second subordinate key stratum is named SKS 2, etc., until the key stratum is reached (called PKS). The PKS movement controls the surface deformation and subsidence, and may damage surface infrastructure, however, strata pressure behavior is mainly determined by break and movement of SKS 1, which is also the main reason for the occurrence of coal wall falls, roof falls, and hydraulic failure accidents in the longwall face. The overlying strata structure of a longwall working face is depicted in Figure 3. The theory has been widely used and demonstrated in the mining industry in China, and this current work is also based on this theory.

2 | STRUCTURAL FORM AND MOVEMENT TYPE OF SKS 1 IN THE FMFLMH

2.1 | Structural form of SKS 1

In general, the caved zone height of the fully mechanized face is 2-4 times the mining height of the coal seam. The SKS 1 type generally presents a voussoir beam structure, as the caved height of overlying strata of the working face is relatively small under conditions of normal mining height (\(M < 3.5 \text{ m}\)); however, because the increase in mining height will lead to a larger caved height in overlying strata, SKS 1 may be located in the caved zone and it forms a cantilever structure in FMFLMH. In some cases, SKS 1 may also be located in the fractured zone and it forms a stable hinged structure. The structural form of SKS 1 varies depending on the connection between the allowable rotation and the maximum rotation of the broken block of SKS 1. The allowable rotation of the broken block of SKS 1 is the distance between SKS 1 and the immediate roof strata after caving and compaction; the maximum rotation of the broken block of SKS 1 is the maximum rotation of the broken block, which can form a stable hinged structure (Figure 4).

As seen in Figure 4, the allowable rotation of the broken block of SKS 1 \(\Delta\) can be calculated from:

\[
\Delta = M - (K_p - 1) \sum h
\]
where $M$ is the mining height (m), $K_p$ is the bulking factor of immediate roof strata, and $\sum h$ is the thickness of immediate roof strata (m).

According to Qian et al.\textsuperscript{20} the maximum rotation of the broken block of SKS 1 $\Delta_{\text{max}}$ is given by:

$$\Delta_{\text{max}} = h_1 - \sqrt{\frac{2\gamma l_1^2 (h_1 + \sum h_1)}{\eta\sigma_c}}$$  \hspace{1cm} (2)$$

where $h_1$ is the thickness of SKS 1 (m), $\gamma$ is unit weight of the stratum (kN/m$^3$), $l_1$ is the broken interval of SKS 1 (m), $\sum h_1$ is the thickness of strata between SKS 1 and SKS 2 (m), $\eta$ is the extrusion coefficient between the hanging block and the previous broken block of SKS 1, and $\sigma_c$ is the compressive strength of SKS 1 (MPa).

As illustrated in Figure 4, when the allowable rotation is greater than the maximum rotation of the broken block of SKS 1, SKS 1 will be located in the caved zone and forms a cantilever structure. Therefore, the condition needing to be satisfied for the formation of a cantilever structure for SKS 1 in FMFLNH is as follows:

$$M - (K_p - 1) \sum h > h_1 - \sqrt{\frac{2\gamma l_1^2 (h_1 + \sum h_1)}{\eta\sigma_c}}$$  \hspace{1cm} (3)$$

According to the moment balance (O) point, we can obtain:

$$T(h_1 - a - \Delta_{\text{max}}) = \frac{1}{2} l_1 (\Omega_1 + \Omega_2) = \frac{1}{2} \gamma l_1 (h_1 + \sum h_1)$$  \hspace{1cm} (1)$$

Due to the contact of blocks is the plastic hinge relation, according to Qian et al.\textsuperscript{20} we can obtain:

$$\Delta_{\text{max}} = \frac{1}{2} (h_1 - \Delta_{\text{max}})$$  \hspace{1cm} (2)$$

$$T = a\sigma_c = \frac{\sigma_c}{\pi}$$  \hspace{1cm} (3)$$

Therefore, combining (2) and (3) with (1), the maximum rotation of the broken block of SKS 1 $\Delta_{\text{max}}$ can be calculated as:

$$\Delta_{\text{max}} = h_1 - \sqrt{\frac{2\gamma l_1^2 (h_1 + \sum h_1)}{\eta\sigma_c}}$$

FIGURE 3 Overlying strata structure of longwall working face, I, the caved zone, II, the fractured zone, III, the bending zone.

FIGURE 4 Rotating locus of SKS 1 in FMFLNH.
Otherwise it will be located in the fractured zone and forms the stable hinged structure. So, the condition for formation of a stable hinged structure is:

$$M - (K_p - 1) \sum h \leq h_1 - \sqrt{\frac{2P_1^2 (h_1 + \sum h_1)}{\eta \sigma_c}}$$ \hspace{1cm} (4)

According to inequalities (3) and (4), we can know that if the mining height is larger and the horizon of SKS 1 is lower, the SKS 1 is more likely to be located in the caved zone and forms a cantilever structure, as shown in Figure 5A. On the contrary, it is more likely to be located in the fractured zone and forms a stable hinged structure, as shown in Figure 5B.

2.2 | Movement type of SKS 1

2.2.1 | Movement type of cantilever structure of SKS 1

From the foregoing analysis, we can know that when SKS 1 satisfies inequality (3), it will present a cycle of breakage movement with the cantilever structure, as shown in Figure 5A. If the falling position of the broken block is close to the hanging block which is going to break, only a little rotation is needed for the hanging block to connect with the broken block and form a temporary hinged structure. On the contrary, if the falling position of the broken block is far from the hanging block, the hanging block cannot connect with the broken block during its rotation, therefore, based on whether, or not, a hanging block has the possibility of making contact with the broken block to form a temporary hinged structure during rotation, SKS 1 can be divided into two motion models of the cantilever structure, as shown in Figure 6.

As shown in Figure 6A, the hanging block B of SKS 1 in the caved zone has no possibility of making contact with broken block A to form a temporary hinged structure after rotating through a certain angle: hanging block B can, or cannot, form a temporary hinged structure during rotation depending on whether, or not, it meets certain geometric conditions. Therefore, we can establish a computational model for judging whether hanging block B can form a temporary hinged structure as shown in Figure 7, according to the motion of broken block of SKS 1 as modeled in Figure 6.

Figure 7 shows the limit state at which hanging block B can form a temporary hinged structure; therefore, it can be seen that $\triangle MM'O$ is an isosceles triangle, $N$ is the midpoint of $M'M$ and $MN = h = \Delta$. Therefore, to prevent hanging block B from making contact with broken block A during rotation, the following geometric condition should be met:

$$h_1 < M - (K_p - 1) \sum h$$ \hspace{1cm} (5)

Similarly, for hanging block B to make contact with broken block A during rotation, the following geometric condition must be satisfied:

$$h_1 \geq M - (K_p - 1) \sum h$$ \hspace{1cm} (6)
From the aforementioned analysis, we can conclude that, when the cantilever structure of SKS 1 cannot form a temporary hinged structure during rotation, the broken block of SKS 1 will fall directly on the goaf. It can be defined as the direct caving movement type of a cantilever structure (direct caving). Besides, the condition to be satisfied for direct caving of SKS 1 should not only satisfy inequality (3), but also satisfy inequality (5), restated as (7), below:

\[ h_1 < M - (K_p - 1) \sum h \]  \hspace{1cm} \text{(7)}

As can be seen from inequality (7), the lower the thickness of SKS 1, the larger the mining height and the lower horizon of SKS 1 may favor direct caving of SKS 1 (Figure 8).

As illustrated in Figure 8, the detailed movement process of Direct Caving of SKS 1 is as follows: first, broken block B of SKS 1 forms a cantilever structure, second, broken block B rotates gradually and falls directly on the goaf as the longwall working face advances, and broken block B cannot make contact with previously broken block A to form a temporary hinged structure during rotation. Finally, broken block C forms a new cantilever structure. Similarly, the cantilever structure of SKS 1 can form a temporary hinged structure during rotation when both inequalities (3) and (6) are satisfied:

\[ M - (K_p - 1) \sum h \leq h_1 < M - (K_p - 1) \sum h + \sqrt{\frac{2\rho l^2_i (h_1 + \sum h_1)}{\eta\sigma_c}} \]  \hspace{1cm} \text{(8)}

As shown in Figure 6B, when the extraction speed of FMFLMH is normal or slow, the hanging block B of SKS 1 has enough time to rotate before the next hanging block of SKS 1 breaks, however, when the extraction speed of FMFLMH is rapid, before hanging block B of the temporary hinged structure falls on the goaf, the next broken hinging block also begins to rotate with it. Therefore, the different extraction speeds of FMFLMH will result in different types of movement in SKS 1. In addition, both the front hinged joint (O) and the rear hinged joint (M) of hanging block B of the temporary hinged structure may be destroyed during rotation. When the front hinged joint (O) of hanging block B is destroyed during rotation, hanging block B will rotate to the other side and fall simultaneously. On the contrary, when the rear hinged joint (M) of hanging block B is destroyed during rotation, it will continue to rotate in the same direction until it falls on the goaf. Hence, different break positions of hanging block B also will result in different movement types of SKS 1. Overall, the movement type of SKS 1 is mainly determined by the extraction speed at the working face and break positions of hanging block B, however, it is difficult to use theoretical analysis to obtain all movement types of SKS 1 which can form a temporary hinged structure during rotation. Therefore, UDEC is further applied to achieve all movement types of SKS 1 based on the aforementioned analysis.

**Determination of simulation parameters**

The simulated block geometric parameters are determined through the following three steps: first, LW15104 of Sijiazhuang coal mine was chosen as the basic model, whose mining conditions are as follows: it is operated in the 15# coal seam, the average cover depth is 450 m, the coal seam thickness is 4.3-7.1 m with an average depth of 5 m, and the dip angle is 3°-15° with an average angle of 7°. The stratigraphic column of LW15104 is shown in Figure 9. Second, parameters including thickness of immediate roof strata, the ratios of the thickness to the length of rock block in SKS 1 and SKS 2, thickness of soft strata between SKS 1 and SKS 2 were determined according to inequality (8). Finally, the working face advancing speed can be represented as calculation steps for the model after each advance of a certain distance in UDEC numerical calculations, namely, the faster the...
working face advanced, the fewer corresponding calculation steps for model after each advance over a certain distance. Therefore, several numerical simulation experiments have been solved to study the quantitative relationship between working face mining speed and calculation steps for model after each advancing a certain distance. Results showed that the working face advancing at normal speed is equivalent to calculating 10,000 steps of the model after each advance of 0.8 m and the working face advancing at a faster speed is equivalent to calculation of 5000 steps of the model after each advance of 0.8 m. Therefore, block geometric parameters in numerical calculation models have been determined as shown in Table 2. Strata block and contact parameters refer to the parameters in the literature in these models (Table 3). The parameters are obtained by laboratory test combination with numerical simulation inversion.

Model configuration

The Mohr–Coulomb constitutive relationship was used in the model; the model measured 200 m × 80 m, the horizontal displacement was constrained on the left and right boundaries of the model, and the vertical and horizontal displacements were fixed at the base. Based on the depth of the longwall face, the vertical stress imposed on upper boundary was calculated as 9.25 MPa with a stress gradient of 0.025 MPa/m. A 40-m-long region on both sides of the model was preserved

| NO. | Thickness (m) | Formation | Lithology |
|-----|--------------|-----------|-----------|
| 1   | 4            | Sandy mudstone |           |
| 2   | 4.5          | Mudstone   |           |
| 3   | 6            | Siltstone  |           |
| 4   | 6            | Sandy mudstone |       |
| 5   | 4.5          | Mudstone   |           |
| 6   | 1.4          | Sandy mudstone |       |
| 7   | 3.7          | Mudstone   |           |
| 8   | 0.8          | Mudstone   |           |
| 9   | 2            | Siltstone  |           |
| 10  | 3.3          | Sandy mudstone |       |
| 11  | 6            | Siltstone  |           |
| 12  | 6            | Mudstone   |           |
| 13  | 5            | Coal       |           |
| 14  | 7.5          | Sandy mudstone |       |
| 15  | 2.5          | Siltstone  |           |

FIGURE 9  Stratigraphic column of LW15104 of Shijiazhuang coal mine

| No. | Mining height (M/m) | Block thickness of immediate roof strata \((2b_i)/(m)\) | Block thickness of SKS 1 \((h_1)/(m)\) | Block thickness of between SKS 1 and SKS 2 \((\sum h_i)/(m)\) | Block thickness of SKS 2 \((h_2)/(m)\) | Block length of SKS 2 \((l_2)/(m)\) | Calculation steps after each advancing 0.8 m/step |
|-----|---------------------|-----------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1   | 6                   | 6                                             | 12                             | 6                               | 5                               | 15                             | 10,000                          |
| 2   | 6                   | 4                                             | 12                             | 6                               | 5                               | 15                             | 10,000                          |
| 3   | 6                   | 6                                             | 15                             | 10,000                          | 5000                            | 15                             | 5000                            |
to avoid boundary effects; the longwall length for each excavation cycle is 0.8 m in the model. We used the stress relief method to investigate the in situ stress; field measurement showed that the vertical stress was 11.25 MPa, the maximum principal stress was parallel to the longwall face advancing direction with a value of 14.4 MPa, and the minimum principal stress was 7.87 MPa. The in situ stress state was incorporated into the model, and the geometry and boundary conditions of model 1 are shown in Figure 10.

Numerical analysis
According to aforementioned analysis, and throughout the numerical simulation, three types of movement of SKS 1 are found when the temporary hinged structure of SKS 1 breaks.

1. Double-sided rotation movement type of cantilever structure, as shown in Figure 11: after slight rotation, the broken block B of SKS 1 connects with the previously broken block A and stops rotating, forming a temporary hinged structure. While as the face advances, broken block B starts to rotate to the other side and falls simultaneously on the goaf. Finally, a new cantilever structure is developed.

2. Quadratic rotation of a cantilever structure, as shown in Figure 12: after significant rotation, the broken block B of SKS 1 connects with previously broken block A and stops rotating, forming a temporary hinged structure. While as the face advances, the temporary hinged structure experiences unstable failure, the broken block B of SKS 1 starts to rotate for a second time in the same direction until falling on the goaf. Finally, a new cantilever structure is developed.

3. Alternate movement of a cantilever structure hinged structure, as shown in Figure 13; after slight rotation, the broken block B of SKS 1 connects with previously broken block A and stops rotating, forming a temporary hinged structure. While as the face advances, the hinged block number and hinged range of the hinged structure gradually increases until reaching the limit state and falls on the goaf. Finally, a new cantilever structure is developed.

2.2.2 Movement of the stable hinged structure of SKS 1
From the aforementioned analysis, it can be seen that when mining conditions of FMFLMH satisfy inequality (4), SKS 1 will be located in the fractured zone and forms a stable hinged structure: however, the stable hinged structure can form the type of movement associated with a hinged structure, which also depends on the ratio of the thickness to length of the broken block of SKS 1. When the ratio of the thickness to length of the broken block of SKS 1 is less than 0.5 (i.e., \( h_1/l_1 < 0.5 \)), SKS 1 will present a voussoir beam structure type of movement (Figure 14). On the contrary, when the ratio of the thickness to length of the broken block of SKS 1 is \( \geq 0.5 \) (i.e., \( h_1/l_1 \geq 0.5 \)), SKS 1 will present the short voussoir beam structure movement type, which is also called the step voussoir beam structure movement type, as the working face is prone to experiencing step subsidence (Figure 15). Therefore, based on the aforementioned analysis and in combination with (4), the condition governing voussoir formation is:

\[
M - (K_p - 1) \sum h + \sqrt{2\gamma \rho_1 \frac{h_1 + \sum h_i}{\eta \sigma_c}} \leq h_1 < \frac{l_1}{2}
\]  

(9)

Similarly, the forming condition of a short voussoir is:

\[
\]
**Figure 11** Double-side rotation movement: (A) cantilever structure; (B) temporary hinged structure; (C) cantilever rotates to the other side and falls; (D) new cantilever structure.

**Figure 12** Quadratic rotation movement: (A) cantilever structure; (B) first rotation and form a temporary hinged structure; (C) quadratic rotation in the same direction; (D) new cantilever structure.

**Figure 13** Alternate hinged movement: (A) cantilever structure; (B-D) hinged block number and hinged range of hinged structure gradually increase until reaching the limit state; (E) new cantilever structure.

**Figure 14** Schematic diagram of a voussoir: (A) voussoir beam structure; (B) new voussoir beam structure.
From the aforementioned analysis, SKS 1 of FMFLMH will form different movement types under different occurrence conditions thereof, and the different movement types will cause different strata pressure behavior of the face. Therefore, determination of the support working resistance in the FMFLMH should take the type of movement of SKS 1 into account, which can finally meet roof management requirements in field operations.

### 3.1 Determination of support working resistance of the cantilever structure of SKS 1

From the aforementioned theoretical analysis, the horizon of the cantilever structure of SKS 1 in FMFLMH is generally lower and relatively far from the adjacent SKS 2; the breaking of SKS 2 does not affect the break of SKS 1, therefore, in this case, the calculation of support working resistance of the cantilever structure of SKS 1 in the FMFLMH should be only based on the breakage and movement type of SKS 1 without considering the influence of SKS 2.

#### 3.1.1 Determination of support working resistance of direct caving and quadratic rotation

Figure 8 shows that the broken block of SKS 1 fell directly on the goaf after rupturing and losing its stability in direct caving.
movement, so the support load calculation model of direct caving is established (Figure 16A). According to the quadratic rotation of SKS 1 in Figure 12, the broken block of the cantilever structure first forms a temporary hinged structure after the broken block rotates a certain angle, then continues to rotate and deposits coal gangue into the goaf, so the support load calculation model of quadratic rotation is established (Figure 16B).

According to the calculation model (Figure 16), the support working resistance \( P \) should be calculated in two parts: one part is static load of immediate roof strata \( Q_1 \), and the other part is dynamic load of support due to the rotation of SKS 1 \( Q_2 \).

\[
P = Q_1 + Q_2
\]  
(11)

1. The static load from the immediate roof strata \( Q_1 \)

   As shown in Figure 16, the static load is equal to the weight of immediate roof strata, so \( Q_1 \) can be calculated as

\[
Q_1 = \gamma B \left( l_k + \frac{1}{2} \cot \alpha \sum h \right) \sum h
\]  
(12)

where \( B \) is the width of support (m), \( l_k \) is the roof-control distance of support (m), and \( \alpha \) is the caving angle of the immediate roof strata (°).

2. Dynamic load of support due to the rotation of SKS 1 \( Q_2 \)

   As illustrated in Figure 16B, assuming that there is no energy loss when the broken block makes contact with the previously broken block and forms a temporary hinged structure, and in combination with Figure 16A: after the block of SKS 1 breaks, it rotates from the horizontal position to the direction of mined-out area until crushing coal gangue in the goaf. The kinetic energy of the system during direct caving and quadratic rotation movement types is given as:

\[
\frac{Q_{KZ} l_1 \sin \theta_{max}}{2} - F' l_s \sin \theta_{max} = \frac{Q_{KZ} (v_2^2 - v_1^2)}{2g}
\]  
(13)

where \( Q_{KZ} \) is the weight of the broken block of SKS 1 and the soft strata controlled thereby (kN), \( F' \) is the force of the immediate roof strata on the SKS 1 (kN), \( l_s \) is the distance between resultant force point of the support and the coal wall (m).

\( Q_{KZ} \) is the weight of the SKS 1 and the soft strata controlled by SKS 1, which can be calculated as follows:

\[
Q_{KZ} = \gamma B l_1 \left( h_1 + \sum h_1 \right)
\]  
(14)

From the geometry:

\[
\sin \theta_{max} = \frac{M - (K_p - 1) \sum h}{l_1}
\]  
(15)

Due to the broken block being stationary before rotation, \( v_1 = 0 \), because the rotation of the broken block occupies a large volume during direct caving and quadratic rotation, it may impose a huge impulse load on the support when it forces coal gangue into the goaf, which can lead to damage of hydraulic supports. Therefore, to prevent the hydraulic supports from being damaged, and ensure safe production at the working face, the velocity of the broken block should be zero when broken block touches any coal gangue in the goaf, namely, \( v_2 = 0 \). In this case, force \( F' \) is the largest according to formula (13), and:

\[
v_1 = 0
\]  
(16)

\[
v_2 = 0
\]  
(17)

Assuming that the immediate roof strata are rigid, the force \( F \) of the SKS 1 to the immediate roof strata is all transferred to the support, namely:

\[
Q_2 = F = F'
\]  
(18)

Combining (14), (15), (16), (17), and (18) with (13), \( Q_2 \) is calculated as:

\[
Q_2 = \gamma B l_1^2 \left( h_1 + \sum h_1 \right)
\]  
(19)

Combining (12) and (19) with (11), the support working resistance \( P \) in direct caving and quadratic rotation is calculated as:

\[
P = \frac{Q_{KZ} l_1 \sin \theta_{max}}{2} + \frac{Q_{KZ} (v_2^2 - v_1^2)}{2g} + \gamma B l_1 \left( h_1 + \sum h_1 \right)
\]  
(20)

3.1.2 | Determination of support working resistance in double-side rotation

The aforementioned numerical simulation indicated that the broken block in double-side rotation of SKS 1 will form a temporary hinged structure after slight rotation and then stop rotating. While the face continues to advance, the broken block starts to rotate to the other side and slips vertically. Based on the whole movement process of SKS 1, the support load calculation model of double-side rotation is established (Figure 17).

As illustrated in Figure 17, when the broken block of SKS 1 forms a temporary hinged structure, the rotational sinkage of broken block is \( \Delta_1 \). While the face continues to advance, the broken block rotates to the other side and falls simultaneously until crushing onto coal gangue in the goaf. The sinkage of broken block of SKS 1 is \( \Delta_2 \) at this stage. Load \( P \) imposed on the support is:

\[
P = Q_1 + Q_2
\]  
(21)

where \( Q_1 \) is the static load of immediate roof strata and \( Q_2 \) is dynamic load of support due to the instability of SKS 1 and the soft strata controlled by SKS 1.

Dynamic impact is a complicated physical process as is its analysis, therefore, we simplify as follows: (a) The time...
between SKS 1 breaking and the soft strata controlled by SKS 1 breaking is 0. (b) There is no springback when the broken block of SKS 1 and the soft strata controlled by SKS 1 touch the immediate roof. (c) There is no dissipation of energy as sound or heat during impact. (d) We consider the immediate roof strata as a rigid body and the support as a spring.

As shown in Figure 17, based on the law of conservation of mechanical energy, gravitational potential energy $E_P$ of SKS 1, and the soft strata controlled by SKS 1 during impact are all transferred into support pillar shrinkage as stored elastic potential energy $E_G$, namely:

$$E_P = E_G$$  \hspace{1cm} (22)

When SKS 1 and the soft strata controlled by SKS 1 reach the lowest position, the shrinking potential energy is:

$$E_P = Q_{Kz} (\Delta_1 + \Delta_2)$$  \hspace{1cm} (23)

We considered the support as a spring, which obeys Hooke’s law, so the increasing potential energy $E_G$ of support column can be represented as:

$$E_G = Q_2 \Delta S$$  \hspace{1cm} (24)

According to the Figure 17, Equation 25 is obtained as follows:

$$\Delta_1 + \Delta_2 = M - (K_P - 1) \sum h$$  \hspace{1cm} (25)

Combining (14), (22), (23), and (24) with (25), $Q_2$ is calculated as:

$$Q_2 = \gamma B l_1 (h_1 + \sum h_1) \frac{[M - (K_P - 1) \sum h]}{\Delta S}$$  \hspace{1cm} (26)

Combining (12) and (21) with (26), $P$ is calculated as:

$$P = \gamma B \left( l_1 + \frac{1}{2} cot \alpha \sum h \right) \sum h + \frac{\gamma B l_1 (h_1 + \sum h_1) [M - (K_P - 1) \sum h]}{\Delta S}$$  \hspace{1cm} (27)

where $\Delta S$ is the limiting compression of the support column (m).

### 3.1.3 Determination of support working resistance of an alternate hinged structure

Figure 13 shows that hinged broken blocks number and hinged range of the hinged structure gradually increase until reaching the limiting hinged structure that then falls on the goaf as the longwall face advances. Based on the whole movement process of SKS 1, the support load calculation model for this alternate hinged structure is established (Figure 18).

According to the calculation model (Figure 18), the support working resistance $P$ of this movement type should be calculated in two parts: the static load from immediate roof strata $Q_1$, and the force needed to balance the limiting hinged structure of SKS 1 $P_{HI}$. Thus, $P$ is as follows:

$$P = Q_1 + P_{HI}$$  \hspace{1cm} (28)

Since the length of the limit hinged structure of SKS 1 is relatively long, at $n$ times the length of the broken interval of SKS 1, the formula for calculating the force $P_{HI}$ can be obtained by transforming the theoretical equation from the voussoir beam structure\(^2\) as follows:

$$P_{HI} = \left[ 2 - \frac{nl_1 \tan (\varphi_1 - \beta_1)}{2 (h_1 - \delta_1)} \right] Q_{Kg}$$  \hspace{1cm} (29)

Therefore, combining (12) and (28) with (29), the reasonable support working resistance $P$ of an alternate hinged structure is

$$P = \gamma B \left( l_1 + \frac{1}{2} cot \alpha \sum h \right) \sum h + \left[ 2 - \frac{nl_1 \tan (\varphi_1 - \beta_1)}{2 (h_1 - \delta_1)} \right] Q_{Kg}$$  \hspace{1cm} (30)
where $n$ is broken block number composition of the limit hinged structure, $\varphi_1$ and $\beta_1$ are the internal friction angle and broken angle of rock block of SKS 1, respectively, $\delta_1$ is the subsidence of SKS 1 (m), and $Q_{kg}$ is the total weight of the broken block of SKS 1 itself and its controlled soft strata (N/m).

### 3.2 Determination of Support Working Resistance of the Stable Hinged Structure of SKS 1

The aforementioned analysis indicated that SKS 1 is relatively far from the coal seam and relatively close to SKS 2 when SKS 1 is located in the fractured zone and forms a stable hinged structure, so the breaking of SKS 2 may influence the breaking of SKS 1. Therefore, the calculation of the support working resistance of the stable hinged structure of SKS 1 should be divided into two cases as follows: (a) The breaking of SKS 2 does not influence that of SKS 1, so the support working resistance should be calculated by only considering the influence of SKS 1; and (b) The breaking of SKS 2 influences that of SKS 1, so the support working resistance should be calculated by not only considering the influence of SKS 1; and (b) The breaking of SKS 2 does not influence that of SKS 1, so the support working resistance of SKS 1 should be divided into two cases as follows: (a) The breaking of SKS 2 does not influence that of SKS 1, so the support working resistance should be calculated by only considering the influence of SKS 1; and (b) The breaking of SKS 2 influences that of SKS 1, so the support working resistance of SKS 1 should be calculated by considering the influence of SKS 1; and (b) The breaking of SKS 2 does not influence that of SKS 1, so the support working resistance should be calculated by only considering the influence of SKS 1. Therefore, the calculation of the support working resistance of SKS 1 in addition to considering the two loads described earlier (i.e., $Q_1$ and $P_{H1}$) must also include the force $P_{H2}$ needed to balance the voussoir beam structure of SKS 2. Therefore, the support working resistance $P$ is as follows:

\[
P = Q_1 + P_{H1} + P_{H2}
\]

Combining (12), (32) with (33), the support working resistance $P$ of a voussoir is:

\[
P = \gamma B \left( l_k + \frac{1}{2} \cot \alpha \sum h \right) \left( 2 - \frac{l_1 \tan \left( \varphi_1 - \beta_1 \right)}{2 \left( h_1 - \delta_1 \right)} \right) Q_{kg} + \left( 2 - \frac{l_2 \tan \left( \varphi_2 - \beta_2 \right)}{2 \left( h_2 - \delta_2 \right)} \right) Q_{dg}
\]

where $h_2$ is the thickness of SKS 2 (m), $\delta_2$ is the subsidence of the hinged block of SKS 2 (m), $\varphi_2$ and $\beta_2$ are the internal friction angle and the broken angle of the rock block of SKS 2, respectively, $l_2$ is the broken interval of SKS 2 (m), and $Q_{dg}$ is the weight of the hinged block of SKS 2 and its controlled soft strata (N/m).

### 3.2.2 Determination of Support Working Resistance of a Short Voussoir

1. Case 1: when the breaking of SKS 2 does not influence that of SKS 1, the support load is calculated according to the theoretical equation derived from the voussoir beam structure, thus, the support working resistance $P$ of support is as follows:

\[
P = Q_1 + P_{H1}
\]

The force $P_{H1}$ can be calculated according to the theoretical equation from the voussoir beam structure as follows:

\[
P_{H1} = \frac{2 - \frac{l_1 \tan \left( \varphi_1 - \beta_1 \right)}{2 \left( h_1 - \delta_1 \right)}}{ \frac{2 - \frac{l_2 \tan \left( \varphi_2 - \beta_2 \right)}{2 \left( h_2 - \delta_2 \right)}} \right) Q_{kg}
\]

Therefore, combining (12) and (32) with (33), the support working resistance $P$ of a voussoir is:

\[
P = \gamma B \left( l_k + \frac{1}{2} \cot \alpha \sum h \right) \left( 2 - \frac{l_1 \tan \left( \varphi_1 - \beta_1 \right)}{2 \left( h_1 - \delta_1 \right)} \right) Q_{kg} + \left( 2 - \frac{l_2 \tan \left( \varphi_2 - \beta_2 \right)}{2 \left( h_2 - \delta_2 \right)} \right) Q_{dg}
\]

2. Case 2: when the breaking of SKS 2 influences that of SKS 1, the force $P_{H2}$ needed to balance the voussoir beam structure can be calculated according to the theoretical equation from the voussoir beam structure as follows:

\[
P_{H2} = \frac{2 - \frac{l_1 \tan \left( \varphi_1 - \beta_1 \right)}{2 \left( h_1 - \delta_1 \right)}}{ \frac{2 - \frac{l_2 \tan \left( \varphi_2 - \beta_2 \right)}{2 \left( h_2 - \delta_2 \right)}} \right) Q_{dg}
\]
according to the model in Figure 20A. The support working resistance \( P \) is calculated according to formula (36), where \( Q_1 \) is the static load from immediate roof strata, as shown in formula (12). The force \( P_{H1} \) can be calculated according to the theoretical equation derived from the short voussoir beam structure:\(^{20}\)

\[
P_{H1} = \frac{4i_1(1 - \sin \theta_{\text{max}})}{4i_1 + 2i_1 \sin \theta_{\text{max}} (\cos \theta_{\text{max}} - 2)} Q_kg
\]

where \( i_1 \) is the ratio of the thickness to length of the broken block of SKS 1, \( \theta_{\text{max}} \) is the limiting rotation angle of the broken block of SKS 1, which is generally between 8° and 12°.

Combining (12) and (32) with (38), the support working resistance \( P \) of a short voussoir is:

\[
P = \gamma B \left( l_k + \frac{1}{2} \cot \alpha \sum h \right) \sum h + \frac{4i_1(1 - \sin \theta_{\text{max}})}{4i_1 + 2i_1 \sin \theta_{\text{max}} (\cos \theta_{\text{max}} - 2)} Q_kg
\]

2. Case 2: when the breaking of SKS 2 influences that of SKS 1, the influence of SKS 2 should be considered when calculating the support working resistance, and the corresponding support working resistance calculation model is presented in Figure 20B. The support working resistance \( P \) is calculated according to formula (35), where \( Q_1 \) is the static load from the immediate roof strata, as given in formula (12), \( P_{H1} \) is as given by formula (38), \( P_{H2} \) is as given by formula (36), and therefore, the reasonable support working resistance \( P \) of a short voussoir is:

\[
P = \gamma B \left( l_k + \frac{1}{2} \cot \alpha \sum h \right) \sum h + \frac{4i_1(1 - \sin \theta_{\text{max}} - 3 \sin \theta_{\text{max}} - 2 \cos \theta_{\text{max}})}{4i_1 + 2i_1 \sin \theta_{\text{max}} (\cos \theta_{\text{max}} - 2)} Q_kg + \left[ \frac{2 - i_2 \tan (\varphi_p - \beta_1)}{2(b_2 - b_1)} \right] Q_dg
\]

4 | ENGINEERING VERIFICATION

To verify the correctness of the calculation formula of support working resistance of each movement type of SKS 1, 17 typical working faces with large mining height belonging to 16 coal mines in China have been selected for analysis. However, due to the limitation of article length, only four working faces were selected as representatives for analysis in detail in the paper. These are located in typical mining areas with large mining heights in China: LW1272(3) of Dingji coal mine, LW1611(3) of Zhangji coal mine, LW30101 of Hanglaiwan coal mine, and LW20110 of Yushuwan coal mine, respectively.

4.1 | Mining conditions

The Dingji and Zhangji coal mine are located in Fengtai County and the west of Panxie mining area of Huainan city, Anhui Province, respectively; Hanglaiwan coal mine is located in Shenmu County, Shanxi Province; Yushuwan coal mine is located in Yulin County, Shanxi Province. The basic mining conditions of their working faces are shown in

![FIGURE 19 Support load calculation model: a voussoir structure](image)

![FIGURE 20 Support load calculation model: a short voussoir](image)
4.2 Movement types in SKS 1

4.2.1 LW1272(3), Dingji coal mine

As can be seen in Figure 21A, for LW1272(3) the 4th fine sandstone is the first SKS (SKS 1) and the 10th sandy mudstone is the second SKS (SKS 2), which are determined according to “KS Theory”.20 According to the working face mining conditions, the following are determined: \( M = 5 \text{ m} \), \( \sum h = 1.6 \text{ m} \), \( h_1 = 4 \text{ m} \), and \( \sum h_1 = 4.4 \text{ m} \). In addition, the broken interval \( l_1 = 16.7 \text{ m} \) is obtained from field-monitoring data; the average swelling factor of the immediate roof strata \( K_p = 1.25 \) is obtained by calculating the volume ratio of the broken stone to the original stone in the immediate roof strata; the compressive strength of fine sandstone \( \sigma_c = 33.8 \text{ MPa} \) is derived from laboratory test data. By substituting the actual parameters of working face into the inequality (7), the left-hand side of inequality (7) is calculated to be 4 m, and the right-hand side is calculated to be 4.6 m. Thus, inequality (7) is satisfied. Therefore, the movement type of the 4th fine sandstone of SKS 1 is direct caving.

4.2.2 LW1611(3), Zhangji coal mine

According to the overlying roof lithology of LW1611(3) presented in Figure 21B, the 5th fine sandstone is the first SKS (SKS 1) and the 9th medium sandstone is the second SKS (SKS 2), which are determined according to “KS Theory.” Combining working face mining conditions and field-monitoring data, the following are determined: \( M = 6 \text{ m} \), \( \sum h = 6.2 \text{ m} \), \( h_1 = 5.5 \text{ m} \), \( \sum h_1 = 4.6 \text{ m} \), \( l_1 = 15.6 \text{ m} \), \( K_p = 1.24 \), and \( \sigma_c = 38 \text{ MPa} \). By substituting the actual parameters of the working face into inequality (8), the left-hand side of inequality (8) is calculated to be 4.55 m < 5 m, and the right-hand side is calculated to be 6.67 m. Thus, inequality (8) is satisfied. Therefore, after the cantilever structure of fine sandstone of SKS 1 breaks, it will form a temporary hinged structure.

To obtain the movement type of SKS 1 of LW1611(3), the load-monitoring data from the No. 85 support of LW1611(3) are selected for analysis (Figure 22). The mining speed is the normal extraction speed with a value of 5 m/d between 290 and 340 m from the face start line; however, as the geological conditions become simpler and given production requirements between 340 and 390 m from the face start line, the mining speed increases to 10 m/d.

As shown in Figure 22, five periodic weightings occur when the working face advances from 290 to 340 m with a...
normal extraction speed of 5 m/d, and the characteristics of the periodic weightings are consistent. Namely, at first, the working face starts bearing weight and this state lasts for a specific period, after which the support resistance sharply declines until the nonweighting state; however, after advancing a certain distance, the working face regains its load-bearing state until periodic weighting is over. It is obvious that the strata pressure behavior of the periodic weightings is in good agreement with double-side rotation and quadratic rotation movement. The strata pressure behavior during 3rd and 4th periodic weightings is more severe compared with that during the 1st, 2nd, and 5th periodic weightings, so the type of movement of SKS 1 of LW1611(3) during the 3rd and 4th periodic weightings is double-side rotation, and that of SKS 1 of LW1611(3) during the 1st, 2nd, and 5th periodic weightings is alternate hinged movement.

### 4.2.3 LW30101, Hanglaiwan coal mine

Based on the overlying roof lithology of LW30101 (Figure 21C), the 4th siltstone is the first SKS (SKS 1) and the 12th fine sandstone is the second SKS (SKS 2), which are determined according to “KS Theory”. Combining working face mining conditions and field-monitoring data, the following are determined:

\[
M = 5 \text{ m, } \sum h = 11 \text{ m, } h_1 = 12 \text{ m, } \sum h_1 = 47 \text{ m, } l_1 = 15.56 \text{ m, } K_p = 1.25, \text{ and } \sigma_c = 38.8 \text{ MPa.}
\]

By substituting the actual parameters of the working face into inequality (9), the left-hand side of inequality (9) is calculated to be 11.85 m < 12 m, and the right-hand side is calculated to be 12.3 m. Thus, inequality
4.2.4 | LW20110, Yushuwan coal mine

Based on the overlying roof lithology of LW20110 presented in Figure 21D, the 5th siltstone is the first SKS (SKS 1) and the 7th medium sandstone is the second SKS (SKS 2), which are determined according to “KS Theory”. Combining working face mining conditions and field-monitoring data, the following are determined: \( M = 5 \text{ m}, \) \( \Sigma h = 10 \text{ m}, \) \( h_1 = 9.2 \text{ m}, \) \( \Sigma h_1 = 2.9 \text{ m}, \) \( l_1 = 14.6 \text{ m}, \) \( K_p = 1.25, \) and \( \sigma_c = 33.8 \text{ MPa}. \) By substituting the actual parameters of the working face into inequality (10), we can see that inequality (10) is also satisfied. Therefore, the movement type of the 5th siltstone of SKS 1 is a short voussoir.

4.3 | Determination of support working resistance and validation of field-monitoring data

4.3.1 | LW1272(3), Dingji coal mine

The foregoing analytical results indicated that movement type of the 4th fine sandstone is direct caving, so the support working resistance should be calculated using calculation formula (20). According to the working face mining conditions, the following are determined: \( B = 1.75 \text{ m} \) and \( l_k = 5 \text{ m}. \) In addition, the caving angle of immediate roof strata \( \alpha = 60^\circ, \) as obtained by field measurement. Assuming that the distance between resultant force points of the support and the coal wall \( l_k \) is approximately equal to the half of the roof-control distance of each support (i.e., \( l_k = 2.5 \text{ m} \)), and by substituting these parameters and their values into formula (20), the support working resistance of LW1272(3) is calculated to be 12,809 kN.

To verify the correctness of the calculation result of the support working resistance of LW1272(3), the load-monitoring data from the No. 67 support are selected for analysis (Figure 23).

As seen in Figure 23, the average load on each support is about 9,759 kN during periodic weighting and is about 4,400 kN during nonperiodic weighting. The maximum load on a support of LW1272(3) reaches 10,230 kN, but it is less than the support working resistance of LW1272(3), which is calculated to be 12,809 kN according to formula (20). This confirms that choosing formula (20) to calculate the support working resistance is appropriate and safe when SKS 1 of the FMFLMH presents direct caving movement.

4.3.2 | LW1611(3), Zhangji coal mine

There are three types of movement of SKS 1 of LW1611(3) during the advance of the working face (quadratic rotation, double-side rotation, and alternate hinged movement, respectively): the previous analysis indicated that different movement types corresponded to different calculation formulae for support working resistance. Therefore, the support working
resistance of LW1611(3) should be the maximum of three support working resistances calculated using the corresponding three formulae for the three movement types of SKS 1, otherwise, it is not possible to ensure the safety of working face. Combining working face mining conditions and field-monitoring data, the following are determined:

\[ B = 1.75 \text{ m}, \quad l_k = 5.8 \text{ m}, \quad \alpha = 62^\circ, \quad l_s = 2.9 \text{ m}, \quad P_0 = 0.8P, \quad \text{and} \quad \theta = 5^\circ. \]

By substituting these mining parameters of face into the support working resistance calculation formula (20) for quadratic rotation, the support working resistance is calculated as 12 515 kN, which is greater than the maximum load (10 695 kN) on the support during the 1st, 2nd, and 5th periodic weightings. This indicates that choosing formula (20) to calculate the support working resistance is reasonable and safe when SKS 1 of FMFLMH undergoes quadratic rotation. The limiting compression of the support column of the ZY10800/30/65-type hydraulic support is \( \Delta S = 2.7 \text{ m}. \) By substituting these parameters into the support working resistance calculation formula (27) for double-side rotation, we find that the support working resistance is 13 420 kN, which is greater than the maximum load (9 753 kN) on each support during the 6th, 7th, and 8th periodic weightings. It also indicates that choosing formula (30) to calculate the support working resistance is reasonable and safe when SKS 1 of FMFLMH undergoes alternate hinged movement. Therefore, the support working resistance of LW1611(3) should not be less than 13 420 kN; however, LW1611(3) uses the ZY10800/30/65-type hydraulic support, whose rated working resistance is only 10 800 kN, which is less than 13 420 kN, therefore, the ZY10800/30/65-type hydraulic support cannot ensure safe mining of LW1611(3). As a result, massive supports failure accidents occur, such as sudden hydraulic support closure, hydraulic leg damage, etc. during the 3rd and 4th periodic weighting as the support load reaches 12 025 kN, as shown in Figure 22.

| Weighting no. | Weighting step (m) | Maximum support load during weighting (kN) | Dynamic load coefficient |
|---------------|-------------------|---------------------------------------------|--------------------------|
| 1             | 25                | 8355                                        | 1.15                     |
| 2             | 17                | 8526                                        | 1.17                     |
| 3             | 25                | 8823                                        | 1.21                     |
| 4             | 25                | 8640                                        | 1.19                     |
| 5             | 33                | 8697                                        | 1.20                     |
| 6             | 29                | 8469                                        | 1.16                     |
| 7             | 21                | 8810                                        | 1.21                     |
| 8             | 25                | 8765                                        | 1.21                     |
| 9             | 21                | 8651                                        | 1.19                     |
| The average value | 24.55            | 8637.33                                    | 1.19                     |

**Figure 23** Load curve: No. 67 support in LW1272(3)
4.3.3 LW30101, Hanglaiwan coal mine

Due to the movement of the 4th siltstone of SKS 1 being that of a voussoir, and \( h_2 = 24 \) m. By substituting the aforementioned parameters of the working face into inequality (31), it is clear that inequality (31) is not satisfied. Therefore, it can be deduced that the breaking of SKS 2 does not influence SKS 1; the support working resistance of LW30101 should thus be calculated according to formula (34). Combining working face mining conditions and our prior assumptions, the following are determined: \( B = 1.75 \) m, \( l_k = 5.2 \) m, \( \varphi_1 = 38.6^\circ \), \( \beta_1 = 0^\circ \), and \( \delta_1 = h_1/6 = 2 \) m. By substituting these parameters into formula (34), the support working resistance of LW30101 is calculated to be 9364 kN.

To verify the correctness of the calculated support working resistance of LW30101, load-monitoring data from the No. 83 support, located in the middle of the working face, are selected for analysis (Table 5).

As seen in Table 5, the periodic weighting step varies from 17 to 33 m with an average of 24.55 m; the dynamic load coefficient (the ratio of the average load of support during periodic weighting to the average load of support during nonperiodic weighting) of support varies from 1.15 to 1.21 with an average of 1.19. Both the periodic weighting step and dynamic load coefficient do not alternate between long/large and short/small. It verifies that the breaking of SKS 2 does not influence that of SKS 1 and the strata pressure behavior of the working face. In addition, the maximum support load of LW30101 is 8823 kN, which is less than the support working resistance of 9364 kN, as calculated by use of formula (34). This indicates that choosing formula (34) to determine the support working resistance is safe when the movement type of SKS 1 is a voussoir.

4.3.4 LW20110, Yushuwan coal mine

Due to the movement of the 5th siltstone of SKS 1 being that of a short voussoir, and \( h_2 = 21.9 \) m, by substituting these parameters of the working face into inequality (31), we see that inequality (31) is satisfied. Therefore, the breaking of SKS 2 exerts an influence on that of SKS 1; the support working resistance of LW20110 should be calculated according to formula (40). Combining working face mining conditions and our prior assumptions, the following are determined: \( B = 1.75 \) m, \( l_k = 5.2 \) m, \( \alpha = 60^\circ \), \( \theta_{\text{max}} = 10^\circ \), \( \varphi_2 = 38.6^\circ \), \( \beta_2 = 0^\circ \), and \( \delta_2 = h_2/6 = 3.65 \) m. By substituting these parameters into formula (40), the support working resistance of LW20110 is calculated to be 7862 kN.

To verify the correctness of the calculated support working resistance of LW20110, load-monitoring data from the No. 53 support are selected for analysis (Figure 24 and Table 6).

As seen in Figure 24 and Table 6, the field-monitoring data from the No. 53 support show that both the periodic weighting step and dynamic load coefficient present periodic change between long/large and short/small, and the short weighting step is accompanied by a large dynamic load coefficient. This verifies that the breaking of SKS 2 exerts an influence on that of SKS 1 and the strata pressure behavior of the working face. The longer periodic weighting step varies from 12.1 to 14.2 m, with an average with 13.1 m, and the smaller dynamic load coefficient varies from 1.35 to 1.46, with an average with 1.42, which corresponds to the breaking of SKS 1. The shorter periodic weighting step varies from 7.9 to 8.2 m with an average with 8.07 m and the larger dynamic load coefficient varies from 1.61 to 1.69 with an average of 1.66, and this corresponds to the two adjacent, simultaneous

| Weighting no. | Weighting step (m) | Support load during weighting (kN) | Dynamic load coefficient |
|---------------|-------------------|-----------------------------------|--------------------------|
| 1             | 12.1              | 5661.0                            | 1.44                     |
| 2             | 8.1               | 6318.0                            | 1.61                     |
| 3             | 14.2              | 5315.0                            | 1.35                     |
| 4             | 7.9               | 6640.0                            | 1.69                     |
| 5             | 13.0              | 5735.7                            | 1.46                     |
| 6             | 8.2               | 6561.3                            | 1.67                     |

FIGURE 24 Load curve: No. 53 support in LW20110
SKS breaks resulting from breaking the upper SKS 2. The maximum support load of LW20110 is 6720 kN, which is less than the support working resistance of 7862 kN, as calculated by use of formula (40). This indicates that choosing formula (40) to determine the support working resistance is safe when the movement type of SKS 1 is a short voussoir and the breaking of SKS 2 exerts an influence on that of SKS 1.

5 | DISCUSSION

In this work, comprehensive theoretical analysis, field observations, and numerical simulations were used to investigate the types of movement of SKS 1 in the FMFLMH, and, based thereon, formulae giving the support working resistance for all types of movement of SKS 1 were obtained. Nowadays, there are two main methods used to determine the support working resistance in an untapped working face; the empirical formula method and the theoretical calculation method. The empirical formulae are as listed in Table 1, and the theoretical calculation formula is given in Equation 34: this is the most widely used method in China and is deduced according to the voussoir beam structure proposed by Chinese Academician Qian. To compare the calculated values of support working resistance of various movement types of SKS 1 according to the corresponding formulae from the present research, with those from the aforementioned empirical formula (entry labeled China, Table 1) and theoretical calculation formula (34) in FMFLMH, which is more reasonable, the four FMFLMHs are selected for calculation. The calculated support working resistances are presented in Table 7.

As shown in Table 7, most of the calculated support working resistances arising from use of empirical formulae and the theoretical calculation (Equation 34) are less than the maximum support loads of the corresponding faces; moreover, because the calculated support working resistance is presented as a wide range of values due to the mining height of coal seam being large, it is difficult to determine an appropriate value for the support working resistance, however, all calculated support working resistances, according to the corresponding calculation formulae given in this paper, are greater than the maximum support loads on corresponding faces. Therefore, this indicates that using the empirical formula and theoretical calculation formula (34) to determine the support working resistance in the FMFLMH is unsafe, nevertheless, the support working resistance determined by the calculation formulae presented in this paper could ensure the safe mining of the FMFLMH. In addition, as listed in Table 7, SKS 1 of LW1611(3) in Zhangji coal mine forms a cantilever structure, but when it moves with double-side rotation, quadratic rotation, and alternate hinged movement, respectively, the corresponding maximum support loads are 12,025, 10,695, and 9,753 kN. This indicates that, even
though SKS 1 develops into the same structural form, when it undergoes different types of movement, which may impose different loads on the support of face, to determine the support working resistance in the FMFLMH, it is necessary to take into account the type of movement of SKS 1.

Reasonable selection of hydraulic support mechanism, in addition to including determination of the support working resistance, is essential. This also includes structural selection of the best hydraulic support, which is determined by characteristics of strata pressure behavior and mining conditions on the longwall face. This analysis showed that different types of movement of SKS 1 correspond to the differing characteristics of the strata pressure behavior of the mined face, therefore, the type of movement of SKS 1 will also affect the choice of support structure. For example, because the space required for the rotation associated with direct caving, double-side rotation, and quadratic rotation of SKS 1 is large, the amount of expansion of the selected hydraulic support column must also be large, to prevent hydraulic support closure during periodic loading events.

6 | CONCLUSION

In China, the FMMTLMH is widely implemented in many coal mines where coal seam thickness is less than 7 m because of its unparalleled benefits, such as lower roadway driving rates, and its high coal recovery rate in comparison with slice mining technology in thick coal seams; however, coal wall falls, roof falls, and hydraulic support failure accidents will occur in the FMFLMH, and the determination of support working resistance is key to solving these problems. Therefore, in this study we used a combination of theoretical analysis, numerical simulation, and field measurement to investigate the types of movement of SKS 1 in the FMFLMH, and on this basis, formulae allowing calculation of the support working resistance were obtained corresponding to each type of movement of SKS 1. This work was deemed to be of theoretical and practical significance in ensuring mining safety and best hydraulic support selection of the FMFLMH.

As the extraction height of the FMFLMH is large, the mining-induced overlying strata failure area must be enlarged, and so SKS 1 will present different structural forms corresponding to the different mining heights and the horizon itself. The theoretical analysis indicated that two types of structural forms of SKS 1 in FMFLMH may develop, namely, the cantilever structure and the stable hinged structure. In general, the larger the mining height and the lower the horizon of SKS 1, the more likely it is to be located in the caved zone and then form a cantilever structure. In contrast, it is more likely to be located in the fractured zone and forms a stable hinged structure otherwise.

The different structural forms of SKS 1 correspond to different types of movement in the FMFLNH, so the theoretical analysis and numerical simulation showed that the cantilever structure of SKS 1 located in the caved zone can undergo four types of movement: direct caving, double-side rotation, quadratic rotation, and alternate hinged motion. The stable hinged structure of SKS 1, when located in the fractured zone, can undergo two types of movement: that of either a voussoir or short voussoir.

On the basis of the six types of movement in SKS 1, we established calculation models corresponding to their support working resistances. Finally, the correctness of these models was verified by analysis of in situ measurement data. This also shows that the support working resistances, as calculated using the proposed models, are more reasonable, and safer, than those obtained using the traditional empirical formula as the structural characteristics of overlying strata and movement type of SKS 1 have been taken into account in these calculation formulae.

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