Study on the structural forms of the key strata in the overburden of a stope during periodic weighting and the reasonable working resistance of the support

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Abstract
Many mines often passively select supports with a higher yield load to avoid the occurrence of support crushing and roof falling during periodic weighting. This method is not conducive to improving production efficiency or reducing mining costs, but it can ensure safe mining. An effective method for overcoming these problems is to determine the reasonable working resistance of the support according to the structural forms of the key strata in the overburden of the stope during periodic weighting.

In this paper, comprehensive theoretical analysis, numerical simulation, and field observation were applied to study the discrimination of the key stratum structure (KSS) during periodic weighting and the calculation method of the support load. First, the KSS that affects the periodic weighting of the stope was classified. The “twice discrimination method” was proposed for determining the breaking form of the key strata and the articulated form of the broken blocks. On this basis, the spacing condition that determines whether adjacent key strata interact was analyzed. The discriminant conditions for synergistic breaking between the first subordinate key stratum (SKS1) and the upper key stratum were derived for the cases in which the SKS1 periodically breaks in the form of a cantilever beam, a voussoir beam, and a step beam. These conditions provide the basis for distinguishing the KSS in the overburden of the stope. In addition, mechanical models of the roof structure during periodic weighting were established, and general formulas for calculating the support loads of stopes with a single-key-stratum influence structure and a multikey-stratum influence structure were presented. Finally, five fully mechanized coal faces with various mining conditions in China were considered for engineering verification. The results of this study demonstrate that the proposed method for determining the reasonable working resistance of the support is consistent with the field practice. The research results can provide a reference for roof control and support selection of stopes.
1 INTRODUCTION

As a mining technology for increasing mining efficiency, improving the working environment, reducing labor intensity, and ensuring production safety, fully mechanized mining has been widely used in coal mines in China. The most significant difference between fully mechanized mining technology and conventionally mechanized mining technology is the application of hydraulic support. Hydraulic support can be divided into four types according to the applicable mining method: support with full-seam mining, sublevel caving support, support with a mesh laying device, and backfilling support. The primary challenge that is encountered prior to the layout of the fully mechanized face is the determination of the type and yield load of the support. Support crushing and roof falling easily occur during periodic weighting if the yield load of the selected support is low.\textsuperscript{1-6} For example, as shown in Figure 1, roof falling and rib spalling occurred in the I0130101 working face of Yannan coal mine during periodic weighting due to the low yield load of the selected sublevel caving support. Moreover, some of the supports were completely destroyed. In many mines, supports with high yield load are often passively selected to avoid this type of scenario. The weight of the support and the total investment in the fully mechanized mining equipment will increase significantly with the increase in the yield load. Therefore, although this method can guarantee the production safety, it reduces production efficiency and increases economic costs. At the same time, it will not continue to significantly affect the roof subsidence and may even damage the integrity of the roof and increase the difficulty of roof control when the yield load of the support continues to increase beyond a limit. Therefore, it is necessary to ensure that the yield load of the support is within a reasonable range, which can provide a sufficient support force for controlling the step subsidence of the roof and avoid wasting the bearing capacity of the support.\textsuperscript{7}

The methods for determining the working resistance of the support are mainly divided into the look-up table method, the empirical formula method, the analogy method, the theoretical calculation method, and the numerical simulation method. The look-up table method calculates the classification index $P_e$ of the main roof via formula (1) based on measured data of coal mines in China.\textsuperscript{8} Then, by referring to Table 1, the category of the main roof is determined. Finally, the lower limit of the support strength is determined according to the mining height. The look-up table is applicable only to a gently inclined seam face with a mining height of less than 4 m, and it is not suitable for a large mining height face or an inclined seam face. The empirical formula method estimates the support load as several times the mining height. Many coal mining countries have conducted in-depth research on the empirical formula method and have obtained applicable empirical formulas, as presented in Table 2.\textsuperscript{9} However, the empirical formula method is applicable only to stopes with small mining heights. For stopes with large mining heights, the range between the upper and lower limits of the support load is estimated as 4-8 times the mining height, which is large.\textsuperscript{10} Therefore, it is impossible to accurately determine the reasonable working resistance of the support. The analogy method determines the reasonable working resistance of the support by analyzing the appearance of rock pressure in the stope with similar mining conditions. This method cannot be applied if the geological conditions of the mine are special or if there are no mined mines nearby. The theoretical calculation method calculates the support load by establishing models of the cantilever beam and the voussoir beam and other mechanical models based on key strata theory. Although many parameters are involved and the calculation is complex, the calculation results are relatively accurate. The numerical simulation method is an efficient computing method that has emerged with the development of computer technology. The reasonable working resistance of the support is determined by simulating the roof control effects of various support strengths. The theoretical

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Roof falling and rib spalling occurred in the I0130101 working face during periodic weighting}
\end{figure}
ZHU et al. proposed three basic structures that can be formed after presented calculation methods for the support resistance; Huang et al. established a mechanical model of a roof during periodic weighting in shallow and nearly shallow seam faces according to the dynamic relationship of the support load under various structural forms of key strata in the overburden of a fully mechanized top-coal caving face, proposed a calculation method for the working resistance of a sublevel caving support, and verified it using monitoring data of rock pressure; and Li and Kuang established a mechanical model of the rotation speed of a voussoir beam structure and studied the influence of the rotation speed of the key strata block on the support load.

These research results have involved various methods for calculating the support resistance under the conditions of various key stratum structures (KSSs) in the overburden and various mining technologies. However, few studies have been conducted on the discrimination of the number of key strata that affect the periodic weighting, the discrimination methods of synergistic breaking between adjacent key strata, the influences of various breaking forms of the lower key stratum (LKS) on the synergistic breaking effect (SBE), and the development of a general support load calculation method that is applicable to stopes with various KSSs and mining technologies. Therefore, this paper classifies the KSS in the overburden of the stope, which affects the periodic weighting. Then, the “twice discrimination method” is proposed for discriminating the breaking forms of key strata and the articulated forms of broken blocks. On this basis, spacing conditions without interaction between adjacent key strata are presented. The calculation method of the breaking interval is analyzed when the LKS does not synergistically break with the upper key stratum (UKS). The discriminant conditions of synergistic breaking are studied when SKS1 breaks periodically in three structural forms. Finally, a mechanical model of the roof structure during periodic weighting is established and general calculation formulas of the support load in a stope with a single-key-stratum influence structure and of that with a multikey-stratum influence structure are presented.

### TABLE 1 Classification index of the main roof and the corresponding lower limit of the support strength

| Category of main roof | Level I | Level II | Level III | Level IV |
|-----------------------|---------|----------|-----------|----------|
|                       | $P_e < 895$ | $895 < P_e < 975$ | $975 < P_e < 1075$ | $1075 < P_e < 1145$ | $P_e > 1145$ |
| Classification index  | $L_k$ | $L_k$ | $L_k$ | $L_k$ | $L_k$ |
| Lower limit of support strength (kN/m²) | $M = 1$ m | 390 | 420 | 470 | 610 | 750 |
|                       | $M = 2$ m | 440 | 490 | 530 | 610 | 720 |
|                       | $M = 3$ m | 500 | 550 | 580 | 610 | 830 |
|                       | $M = 4$ m | 570 | 610 | 680 | 680 | 970 |

### TABLE 2 Empirical estimation formulas for the support working resistance from various countries

| Country      | Support's working resistance ($P_e$/kN) |
|--------------|---------------------------------------|
| Germany      | $P = 12 \times \gamma \times b \times L_k \times M$ |
| Japan        | $P = 5 \times \gamma \times b \times L_k \times M$ |
| America      | $P = 16 \times \gamma \times b \times L_k \times M$ |
| India        | $P = 5 \times \gamma \times b \times L_k \times M$ |
| China        | $P = (4-8) \times \gamma \times b \times L_k \times M$ |
| Hungary      | $P = 8 \times \gamma \times b \times L_k \times M$ |

Calculation method and the numerical simulation method have been widely used in scientific research and engineering practice.

$$P_e = 241.3 \ln L_0 - \frac{15.5h_0}{M} + 52.6M$$  \hspace{1cm} (1)

Here, $L_0$ is the first weighting interval of the main roof (m), $h_0$ is the thickness of the immediate roof (m), and $M$ is the mining height (m).

Here, $\gamma$ is the average volume-weight of the stratum, which is typically set as 25 kN/m³, $b$ is the width of the support (m), and $L_0$ is the roof control distance of the support (m).

Scholars at home and abroad have conducted extensive research on the influences of the fracture form and the migration law of key strata on the support load in the overburden, and they have established many theoretical calculation models for the support resistance: Huang et al. established a mechanical model of a roof during periodic weighting in shallow and nearly shallow seam faces according to the dynamic relationship between the support and the surrounding rock and presented calculation methods for the support resistance; Huang et al. proposed three basic structures that can be formed after the periodic fracture of key strata in the overburden of a shallow coal-seam group (namely “step beam–step beam,” “voussoir beam–step beam,” and “voussoir beam–voussoir beam”) and derived a calculation formula of the working resistance of the support under the coupling of dynamic and static loads; Li and Liang suggested that there are two types of structural forms and six types of movement forms of the first subordinate key stratum (SKS1) in a face with a large mining height. The formation conditions of various structural forms and movement forms were analyzed, and a calculation model of the support load was established for each movement form; Xu and Ju studied the influences of the structural forms of the key strata in the overburden of a face with a very large mining height on the rock pressure. In addition, a calculation method for the support load under various structural forms of key strata in the overburden was analyzed; Guo et al. established four structural models of key strata in the overburden of a fully mechanized top-coal caving face, proposed a calculation method for the working resistance of a sublevel caving support, and verified it using monitoring data of rock pressure; and Li and Kuang established a mechanical model of the rotation speed of a voussoir beam structure and studied the influence of the rotation speed of the key strata block on the support load.

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2 | CLASSIFICATION OF THE KSS IN TERMS OF THE EFFECT ON PERIODIC WEIGHTING

In the middle of the 1990s, “key strata theory” was proposed for strata control, providing a theoretical basis for understanding the movement of an overburden structure and its impact on strata behavior.\(^{21}\) According to the theory, the subsidence and deformation of all or part of the upper strata are consistent after the key stratum is broken. The former is named the primary key stratum (PKS), and the latter is named a subordinate key stratum (SKS). There may be several subordinate key strata in the overburden of a stope, but the PKS is unique and is located above all subordinate key strata. The SKS that is closest to the stope in the overburden is called SKS1, and the remaining subordinate key strata are called SKS2, SKS3, and so on, from the bottom up to the PKS. The strata that synchronously subside and deform with each SKS are successively named weak stratum 1 (WS1), weak stratum 2 (WS2), and so on, and the strata that are controlled by PKS are called load strata. The stable state of SKS1 directly determines whether periodic weighting occurs in the stope. However, the strength of the periodic weighting does not always depend on SKS1 alone but may also be influenced by other upper key strata. Therefore, it is unreasonable to determine the support load based only on the structural form and the movement form of SKS1. As shown in Figure 2, the buried depth, the mining height, and the number and breaking forms of the key strata in the overburden of the stopes on both sides are consistent, whereas the strengths of the periodic weighting differ significantly between the sides. The deadweight of the broken block and the upper load is mainly borne by the articulated structure after PKS breakage in the left stope; however, a partial load is still transferred to the lower stratum. The chain instability of SKS2 and SKS1 occurred under the action of the transferred load. At this time, the three key strata all affect the strength of the periodic weighting. Therefore, support crushing, roof falling, and rib spalling easily occur in the stope if the transfer load is large and the yield load of the support is low. The distance between SKS1 and UKS in the right stope is relatively large. The stability of SKS1 is not affected after the UKS has broken, and the strength of the periodic weighting depends only on SKS1.

In summary, identifying the KSS that affects the periodic weighting is the premise for determining the support load. Xu et al.\(^{22}\) classified the KSS in the overburden of a shallow seam into four types according to the number, occurrence characteristics, and fracture forms of the unbroken key strata. This classification method does not consider the corresponding relationship between the KSS and the periodic weighting. Moreover, the influence of the broken key stratum on the mining of the lower coal-seam is ignored, and the broken key stratum is regarded as only the load strata, which is unreasonable. The connection of the horizontal force is still maintained between the broken blocks; hence, the articulated structure can still be formed under the influence of mining of the lower seam.\(^{23,24}\) Therefore, this paper classifies the KSS in the overburden of the stope into two basic types, namely a single-key-stratum influence structure and a multikey-stratum influence structure, according to the number of key strata that affect the periodic weighting. In addition, the two basic types are further subdivided into four subcategories according to the category and location of the key stratum, as shown in Figure 3.

The influence of UKS breakage on SKS1 can be divided into three cases: (1) no effect on SKS1; (2) SKS1 is affected but not broken; and (3) SKS1 breaks with UKS, which indicates that SBE exists between the two key strata. In cases (1) and (2), the KSS in the overburden of the stope is a

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**FIGURE 2** Cut-away view of longwall stopes and stratum motion
3 DISCRIMINATION OF THE BREAKING FORM OF KEY STRATA AND THE ARTICULATED FORM OF BROKEN BLOCKS

The breaking forms of the key strata can be roughly divided into two types: cantilever beam and articulated beam. The difference between the two types of breaking forms is whether the absolute rotation of the broken block exceeds the maximum rotation of the articulated structure.\(^6\) The breaking form of UKS is influenced by the breaking form of LKS and the thickness and bulking factor of the weak stratum between the two key strata. Since the breaking interval of UKS is relatively large and the rotation space is more limited, it must also break in the form of an articulated beam when the LKS breaks in the form of an articulated beam. Combined with the above analysis, the “twice discrimination method” is proposed for discriminating the breaking form of the key strata and the articulated form of broken blocks. (a) First, the breaking forms of each key stratum are discriminated from SKS1. (b) It is known that there are two kinds of instability forms of voussoir beam structure, namely sliding instability and rotation instability.\(^7\) The voussoir beam structure is stable only when the S and R conditions are satisfied simultaneously. According to the “Sliding-Rotation (S-R)” stability theory of the voussoir beam structure, the structural form (voussoir beam, unstable voussoir beam, or step beam) of the key stratum, which is broken in the form of an articulated beam, continues to be distinguished, as illustrated by the roof model in Figure 4, where \(h_1\) is the thickness from SKS1 to SKSm (m), \(\sum h_1+\sum h_m\) is the thickness of the weak stratum that is controlled by each SKS (m), \(L_1\) is the breaking interval of each SKS (m), \(\theta_1\) is the rotation angle of the broken block of each SKS (°), and \(W_1\) is the absolute rotation of the broken block of each SKS (m).

First discrimination: The maximum rotation of the broken block of SKS1 that can form an articulated structure is \(\Delta_{1\text{max}}\). According to the mechanical model of the deformation and instability of the voussoir beam structure, \(\Delta_{1\text{max}}\) can be determined via formula (2)\(^28\):

\[
\Delta_{1\text{max}} = h_1 - \sqrt{\frac{2q_1L_1^2}{\sigma_{1c}}}
\]  

where \(q_1\) is the load on SKS1 (MPa), which can be calculated according to the load discrimination condition of key stratum, and \(\sigma_{1c}\) is the compressive strength of SKS1 (MPa).

The formula for calculating the absolute rotation \(W_1\) is as follows\(^29\):

\[
W_1 = M - (K_p - 1)h_0
\]

where \(K_p\) is the bulking factor of the immediate roof.

Combining formula (2) and formula (3), the criteria for SKS1 breaking in the form of a cantilever beam and an articulated beam are obtained, as presented in formula (4) and formula (5), respectively:

\[
M - (K_p - 1)h_0 > h_1 - \sqrt{\frac{2q_1L_1^2}{\sigma_{1c}}}
\]

\[
M - (K_p - 1)h_0 \leq h_1 - \sqrt{\frac{2q_1L_1^2}{\sigma_{1c}}}
\]
According to field observations, the bulking factor of WS1 is approximately equal to \( K_p \) when SKS1 is broken in the form of a cantilever beam.\(^{14}\) The bulking factor of WS1 is represented by \( K_{p0} \) when SKS1 is broken in the form of an articulated beam, and \( K_{p0} < K_p \). Therefore, the absolute rotation \( W_2 \) of the broken block of SKS2 is as follows:

\[
W_2 = M - (K_p - 1)h_0 - (K_s - 1)\Sigma h_1
\]

where \( K_s \in (K_{s0} - K_p) \), the value of which is determined by the breaking form of SKS1. According to formula (5), the criterion for the formation of an articulated beam by the broken block of SKS2 is obtained:

\[
M - (K_p - 1)h_0 - (K_s - 1)\Sigma h_1 \leq h_2 - \sqrt{\frac{2q_2L_2^2}{\sigma_{2c}}} (7)
\]

where \( q_2 \) is the load on SKS2 (MPa), which can also be calculated according to the load discrimination condition of key stratum, and \( \sigma_{2c} \) is the compressive strength of SKS2 (MPa). By analogy, the criterion for the formation of an articulated beam by the broken block of SKS\(_m\) is as follows:

\[
\begin{cases}
W_m > h_m - \sqrt{\frac{2q_mL_m^2}{\sigma_{mc}}} \text{, Cantilever beam} \\
W_m \leq h_m - \sqrt{\frac{2q_mL_m^2}{\sigma_{mc}}} \text{, Articulated beam}
\end{cases}
\]

\[
\begin{align*}
&\left\{ \begin{aligned}
&h_m + \Sigma h_m \leq \frac{\sigma_{mc}}{30\gamma} (\tan \varphi + \frac{3}{4} \sin \theta_m)^2 \\
&h_m + \Sigma h_m \leq \frac{0.15\sigma_{mc}}{\gamma} (i_m^2 - \frac{3}{2} i_m \sin \theta_m + \frac{1}{2} \sin^2 \theta_m)
\end{aligned} \right., \text{Vousssoir beam} \\
&\left\{ \begin{aligned}
&h_m + \Sigma h_m > \frac{0.15\sigma_{mc}}{\gamma} (i_m^2 - \frac{3}{2} i_m \sin \theta_m + \frac{1}{2} \sin^2 \theta_m) \\
&h_m + \Sigma h_m > \frac{\sigma_{mc}}{30\gamma} (\tan \varphi + \frac{3}{4} \sin \theta_m)^2 \\
i_m > \frac{2\cos \theta_m + 3\sin \theta_m}{4(1 - \sin \theta_m)}
\end{aligned} \right., \text{Unstable vousssoir beam}
\end{align*}
\]

where \( w_m \) is the load on SKS\(_m\) (MPa), \( \sigma_{mc} \) is the compressive strength of SKS\(_m\) (MPa), and \( L_m \) is determined via formula (9): \( L_m = h_m \sqrt{R_{mt}/3q_m} \) (9)

where \( R_{mt} \) is the ultimate tensile strength of SKS\(_m\) (MPa).

Second discrimination: The stability of the articulated beam is determined according to the "Sliding-Rotation (S-R)" stability theory of the vousssoir beam structure. Sliding instability and rotating instability will occur when the articulated beam structure cannot satisfy the requirements of formula (10) or formula (11), respectively.\(^{8,30}\) In the two formulas, \( \varphi \) is the internal friction angle of the broken block of the key stratum (°), \( i_m \) is the lumpiness of the broken block (the ratio of the height to the length), and \( \theta_m \) is calculated via Equation (12). According to the literature,\(^{5,8,11-14,31}\) the lumpiness of the broken block of the key stratum in the overburden is large during the mining of a shallow coal-seam. When formula (13) is satisfied, the broken block will slide and lose stability behind the support. At this time, the key stratum will break periodically in the form of a step beam. In summary, the discriminant conditions of the breaking form of the key strata and the articulated form of the broken blocks are obtained via formula (14).

\[
h_m + \Sigma h_m \leq \frac{\sigma_{mc}}{30\gamma} (\tan \varphi + \frac{3}{4} \sin \theta_m)^2 (10)
\]

\[
h_m + \Sigma h_m \leq \frac{0.15\sigma_{mc}}{\gamma} (i_m^2 - \frac{3}{2} i_m \sin \theta_m + \frac{1}{2} \sin^2 \theta_m) (11)
\]

\[
\theta_m = \arcsin \left( \frac{W_m}{L_m} \right) (12)
\]

\[
i_m > \frac{2\cos \theta_m + 3\sin \theta_m}{4(1 - \sin \theta_m)} (13)
\]

4 STUDY ON THE SBE BETWEEN ADJACENT KEY STRATA

4.1 Spacing condition without interaction between adjacent key strata

There is no influence on LKS after UKS breakage if the spacing between the two key strata satisfies several geometric conditions, as presented in Figure 5. In the figure, \( \beta \) is the angle between the fracture line and the vertical direction. The premise for the noninfluence on LKS after UKS breakage is that the area of LKS that is not yet broken is completely
outside the fracture line of UKS. According to the geometric conditions, \( AB = DC = L_m \), which can be evaluated in \( \triangle BDC \).

\[
h_j = L_m \cdot \cot \beta \quad (15)
\]

Therefore, the strength of the periodic weighting in the stope is affected only by SKS1 if the spacing \( h_j \) between SKS1 and UKS satisfies formula (16):

\[
h_j \geq L_1 \cdot \cot \beta \quad (16)
\]

### 4.2 Analysis of the nonsynergistic breakage of adjacent key strata

The two key strata interact if the spacing \( h_j \) between SKS1 and UKS does not satisfy formula (16). However, it is not certain that SKS1 will break synchronously after UKS breakage. Due to the influence of the transfer load, the breaking interval of SKS1 will inevitably decrease when it does not break synchronously with UKS. Figure 6 presents the mechanical models of SKS1 nonsynergistic breaking with UKS when it breaks in the forms of a cantilever beam and an articulated beam. In the figure, \( O_i \) is the intersection of fracture line and block \( A_1 \), \( q_{z1} \) is the sum of the deadweight of block \( A_1 \) and the weight of its control strata (MPa), \( Q_2 \) is the transfer load of the fracture block of UKS (MPa), \( R \) and \( T \) are the shear force and the horizontal thrust at point \( O_1 \) (MN), \( P \) is the support resistance of the support (MN), \( l_1 \) is the horizontal distance from the latest breaking position of SKS1 to the fracture line of UKS (m), \( a \) is the height of the extrusion contact surface at the end angle of the block (m), and \( L_p \) is the horizontal distance between the action point of the support resistance and point \( O \) (m). \( a \) and \( L_p \) are determined via formula (17) and formula (18), respectively.

\[
a = 0.5(h_1 - L_1 \sin \theta_1) \quad (17)
\]

\[
L_p = \frac{L_k}{2} - (h_0 + h_1) \tan \beta \quad (18)
\]

In the two cases, the bending moment \( \Sigma M_o \) at point \( O \) is as follows:

\[
\Sigma M_o = \frac{q_{z1} L_1^2}{2} + Q_2(L_1 - 0.5l_1) - P \left[ \frac{L_k}{2} - (h_0 + h_1) \tan \beta \right] \quad (19)
\]

\[
\Sigma M_o = \frac{q_{z1} L_1^2}{2} + Q_2(L_1 - 0.5l_1) + T(h_1 - 0.5a) + R \left[ L_1 - (h_1 - 0.5a) \sin \beta \right] - P \left[ \frac{L_k}{2} - (h_0 + h_1) \tan \beta \right] \quad (20)
\]

The tensile strength of rock is smaller than the compressive strength and shearing strength. According to the theory of maximum tensile stress, block \( A_1 \) with unit width satisfies the following requirements when tensile failure occurs at point \( O_3^{32-35} \):

\[
\frac{6 \Sigma M_O}{h_1^2} = R_1T \quad (21)
\]

Combining formulas (19), (20), and (21), the calculation formulas of the breaking interval \( L_1 \) in the two cases are obtained:

\[
L_1 = \sqrt{Q_2^2 + q_{z1} \left[ Q_2 l_1 + 2P \left[ \frac{L_k}{2} - (h_0 + h_1) \tan \beta \right] + \frac{R_1h_0^2}{3} \right] - Q_2} \quad (22)
\]
The calculation methods of $R$, $T$, and $Q_2$ in the two formulas are presented later.

4.3 | Analysis of the SBE between adjacent key strata

The mechanical models that are presented in Figure 7 were established for studying the SBE between adjacent key strata.\(^{32,36-39}\) The periodic failures of SKS1 in the forms of a cantilever beam, a voussoir beam, and a step beam are considered. In the figure, $\theta_{11}$ is the rotation angle of block $C_1$ ($^\circ$); $Q_{21}$ and $Q_{22}$ are the loads that are transferred from the broken block of UKS to blocks $B$ and $C$, respectively (MN); $R_1$ is the shear force at point $O_3$ (MN); $F$ is the support force of the compacted rock mass in the gob to block $C_1$ (MN); $l_{11}$ and $l_{12}$ are the lengths of blocks $B_1$ and $C_1$, respectively (m); and $s$ is the step subsidence of the block (m).

4.3.1 | SKS1 breakage in the form of a cantilever beam

As shown in Figure 7(A), the stress condition of block $A_1$ is relatively simple when SKS1 breaks in the form of a cantilever beam. At this time, $\sum M_i$, is as follows:

$$\sum M_i = \frac{q_2 l_1^2 + Q_2 l_1}{2} - P \left( \frac{L_k}{2} - (h_0 + h_1) \tan \beta \right)$$

(24)

Therefore, the tensile stress $\sigma_t$ at point $O$ must satisfy the following requirements in the case of tensile failure of block $A_1$ with unit width:

$$\sigma_t = \frac{6 \sum M_i}{h_1^2} \geq R_{1T}$$

(25)

By substituting formula (24) into formula (25), the discriminant condition of SKS1 synergistic breakage with UKS is obtained when SKS1 breaks periodically in the form of a cantilever beam:

$$\frac{3(q_2 l_1^2 + Q_2 l_1)}{h_1^2} - 6P \left( \frac{L_k}{2} - (h_0 + h_1) \tan \beta \right) \geq R_{1T}$$

(26)

According to formula (26), the value of $\sigma_t$ is affected by the thickness of the immediate roof ($h_0$), the thickness of SKS1 ($h_1$), the thickness of WS1 ($\sum h_1$), the length of block $A_1(l_1)$, the transfer load ($Q_2$), the roof control distance ($L_k$), the support resistance ($P$), the included angle $\beta$, and other parameters. The single-variable method is used to study the influences of various parameters on $\sigma_t$. Fixed-value processing is used to determine the nonresearch parameters: $M = 6.5$ m, $L_k = 5.7$ m, $\beta = 15^\circ$, and $K_p = 1.3$. The value ranges of other parameters are listed in Table 3. The fixed values in the table are the values of other parameters when a parameter is studied as a single variable. For example, when $h_0$ is studied as a single variable, $h_1 = 5$ m, $\sum h_1 = 10$ m, $Q_2 = 5$ MN, and $P = 9$ MN. The $l_1-\sigma_t$ curves of each single variable with various values are plotted in Figure 8.

According to Figure 8, (a) $\sigma_t$ and its growth rate increase synchronously with the increase in $l_1$ when all variables are fixed, and (b) $\sigma_t$ is proportional to $h_0$, $\sum h_1$, and $Q_2$ and inversely proportional to $h_1$ and $P$ when $l_1$ is fixed. Therefore, the larger the thickness of SKS1 and the support resistance of the support, the more difficult it is for SKS1 break synchronously with UKS. (c) The $l_1-\sigma_t$ curve rises overall and the slope remains unchanged with the increase in $h_0$ when $h_0$ is a single variable. Hence, $\sigma_t$ is linearly positively correlated with $h_0$. (d) The slope of the $l_1-\sigma_t$ curve decreases with the increase in $h_1$ when $h_1$ is a single variable. Hence, $\sigma_t$ is nonlinearly negatively correlated with $h_1$. (e) When $\sum h_1$ and $Q_2$ are single variables and increase gradually, the slope of the $l_1-\sigma_t$ curve increases continuously. However, $\sigma_t$ increases linearly when $l_1$ is fixed. (f) The $l_1-\sigma_t$ curve decreases overall and the slope remains unchanged with the increase in $P$ when $P$ is a single variable. Since the change in $P$ has little effect on $\sigma_t$, the support resistance is not the main factor that affects the breakage of SKS1 synchronously with UKS.

4.3.2 | SKS1 breakage in the form of a voussoir beam

The stress conditions of block $A_1$ are presented in Figure 7(B) when SKS1 breaks periodically in the form of a voussoir beam.\(^{27,40,41}\) The shear force $R$ and the horizontal thrust $T$ are calculated as follows. Since block $C_1$ is located on the compacted rock mass in the gob, the following hold:

$$L_1 = \sqrt{\frac{(Q_2 + R)^2 + q_{21}}{q_{21}}} \left\{ \frac{2R(h_1 - \frac{a}{2}) \tan \beta + Q_2 l_1 + \frac{R_{1T} h_1^2}{3}}{2P \left[ \frac{L_k}{2} - (h_0 + h_1) \tan \beta \right] - 2T(h_1 - \frac{a}{2})} \right\} - R - Q_2$$

(23)
According to the force balance condition of the articulated blocks $B_1$ and $C_1$, the following results are obtained:

$$Q_{22} + q_{21}l_{12} = F \quad \text{and} \quad \theta_{11} \approx \theta_{1}/4.8$$

Hence, there is a bed separation between block $B_1$ and block $C_1$.

**TABLE 3** Value range of each variable when SKS1 breaks in the form of a cantilever beam

| Variable | $h_0$/m | $h_1$/m | $\Sigma h_1$/m | $Q_2$/MN | $P$/MN |
|----------|---------|---------|----------------|---------|--------|
| Value range | 1 | 3 | 5 | 1 | 7 |
| | 2 | 3.5 | 10 | 3 | 9 |
| | 3 | 4 | 15 | 5 | 11 |
| | 4 | 4.5 | 20 | 7 | 13 |
| | 5 | 5 | 25 | 9 | 15 |
| | 6 | 5.5 | 30 | 11 | 17 |
| Fixed value | 3 | 5 | 10 | 5 | 9 |

**FIGURE 7** Mechanical models of SKS1 synergistic breakage with UKS. A, SKS1 breaks in the form of a cantilever beam. B, SKS1 breaks in the form of a voussoir beam. C, SKS1 breaks in the form of a step beam.
Combining formulas (27) and (32) yields:

\[
R = q_{z1} l_{11} \left[ \frac{h_1 - 0.5a}{\cos \beta} \cdot \sin (\beta + \theta_1) + 0.5l_{11} \cos \theta_1 \right] \left[ (h_1 - a - W_1) - l_{12} \sin (\theta_1/4) \right] + \tan (\theta_1/4) \left[ l_{11} \cos \theta_1 + \tan (\beta + \theta_1) (h_1 + l_{11} \sin \theta_1 - a - W_1) + l_{12} \cos (\theta_1/4) \right]
\]  

Therefore, the bending moment \( \sum M_o \) at point \( O \) is as follows:

\[
\sum M_o = 0
\]
TABLE 4  Value range of each variable when SKS1 breaks in the form of a voussoir beam

| Variable | $h_0$/m | $h_1$/m | $\Sigma h_1$/m | $Q_2$/MN | $P$/MN | $l_{11}$/m |
|--------------|--------|--------|----------------|--------|--------|----------|
| Value range  | 1   | 4     | 5         | 1      | 5      | 10       |
|              | 2   | 6     | 10        | 3      | 7      | 12.5     |
|              | 3   | 8     | 15        | 5      | 9      | 15       |
|              | 4   | 10    | 20        | 7      | 11     | 17.5     |
|              | 5   | 12    | 25        | 9      | 13     | 20       |
|              | 6   | 14    | 30        | 11     | 15     | 22.5     |
| Fixed value  | 3   | 10    | 10        | 5      | 9      | 10       |

\[
\Sigma M_0 = \frac{q_2 l_1^2 + Q_2 l_1}{2} + R \left[ l_1 - (h_1 - 0.5a) \tan \beta \right] + T(h_1 - 0.5a) - P \left[ 0.5L_k - (h_0 + h_1) \tan \beta \right] 
\]

Combining formulas (25) and (34), the criterion for SKS1 breaking synchronously with UKS is obtained when SKS1 breaks periodically in the form of a voussoir beam:

\[
\begin{aligned}
&\left\{ 3q_1 l_1^2 + 3Q_2 l_1 + R \left[ 6l_1 - (6h_1 - 3a) \tan \beta \right] + \\
&T(6h_1 - 3a) - P \left[ 3L_k - 6(h_0 + h_1) \tan \beta \right] \right\} / h_1^2 \geq R_{135}
\end{aligned}
\]

Compared with formula (26), $\sigma_t$ will be additionally affected by $l_{11}$ and $l_{12}$. The single-variable method is still used to study the influences of various parameters on $\sigma_t$. At this time, $M = 3$ m is considered, and the values of other fixed-value parameters are the same as the above. The value ranges of the variable parameters are listed in Table 4, and $l_{11} = l_{12}$ by default. The $l_{11}$ curve of each single variable with various values are plotted in Figure 9, from which the following observations are made. (a) The changes in $h_0$ and $P$ have little effect on $\sigma_t$; hence, $h_0$ and $P$ are not the key factors that affect the SBE. (b) The change rule of the $l_{11}$ curve is the same as when $h_1$, $\Sigma h_1$, and $Q_2$ are single variables. Therefore, the smaller the value of $h_1$, the larger the values of $\Sigma h_1$ and $Q_2$, and the more easily SKS breaks synchronously with UKS. (c) The slope of the $l_{11}$ curve increases with the increase in $l_{11}$ when $l_{11}$ is a single variable. Therefore, SKS1 is more likely to synchronous break with UKS as the value of $l_{11}$ increases.

FIGURE 9  $l_{11}$ curves when SKS1 breaks in the form of a voussoir beam
4.3.3 | SKS1 breakage in the form of a step beam

The mechanical model of the articulated blocks is presented in Figure 7(C) when SKS1 breaks periodically in the form of a step beam. At this time, the calculation methods of $\sum M_1$, $\sum M_2$, and $\sum M_O$ are the same as those of formulas (29), (30), and (34), respectively. Therefore, the calculation methods of $T$ and $R$ and the discrimination condition of SBE are the same as those presented above. However, $\theta_1$ is determined via formula (36):

$$\theta_1 = \arcsin \left( \frac{W_1 - s}{l_{11}} \right)$$  \hspace{1cm} (36)

4.4 | Mechanism of nonuniform periodic weighting

The nonuniform periodic weighting phenomenon is likely to occur in a stope with a multikey-stratum influence structure. In Figure 10, the following observations are made. (a) SKS2 and PKS remain stable when SKS1 first reaches the periodic breaking interval; only SKS1 affects the strength of the periodic weighting at this time. (b) SKS2 reaches the periodic breaking interval when the stope continues to advance. The rotation of the broken block of SKS2 results in the synergistic breakage of SKS1; at this time, both key strata affect the periodic weighting, and the strength of the periodic weighting changes. (c) The breaking of PKS caused the chain instability of SKS2 and SKS1. Since the three key strata all affect the periodic weighting, the strength of the periodic weighting will continue to change.

5 | DETERMINATION OF THE REASONABLE WORKING RESISTANCE OF THE SUPPORT

The determination process of the reasonable working resistance of the support is as follows. (a) First, determine the number and locations of the key strata in the overburden of the stope. (b) Identify all key strata that impact SKS1 according to the periodic weighting interval of each key stratum. (c) Determine the periodic breaking form of each key stratum and the articulated form of the broken blocks according to the “twice discrimination method.” (d) Determine all key strata that affect the periodic weighting of the stope in a bottom-up order according to the discrimination condition of SBE. (e) Continue to apply the “twice discrimination method” to determine the structural form of key strata in the overburden during periodic weighting. (f) Determine the maximum load on the support during the periodic weighting to determine the reasonable working resistance of the support.

The formula for calculating the load $P_z$ on the support during periodic weighting is as follows:\(^{42}\):

$$P_z = Q_0 + Q_1$$  \hspace{1cm} (37)

where $Q_0$ is the weight of the immediate roof above the beam (MN), and $Q_1$ is the transfer load of the broken block of SKS1 (MN). $Q_0$ is determined by formula (38):

$$Q_0 = (L_4 + 0.5h_0 \cot \alpha)h_0 b \gamma$$  \hspace{1cm} (38)

where $\alpha$ is the breaking angle of the stratum ($^\circ$).

The load transfer coefficients $k_1$, $k_2$, and $k_3$ of the cantilever beam (unstable voussoir beam), voussoir beam, and step beam, respectively, are as follows:\(^{8,10,12-14}\):

$$k_x = \begin{cases} 
1, & x = 1 \\
2 - \frac{l_m \tan (\varphi - \theta)}{2h_n + W_n}, & x = 2 \\
1 - \tan \theta \frac{h_n}{\sin (\varphi - \theta)}, & x = 3 
\end{cases}$$  \hspace{1cm} (39)

where $l_m$ is the length of the broken block of each key stratum (m). Therefore, the calculation formula of load $Q_1$ is as follows:

$$Q_1 = k_x P_1$$  \hspace{1cm} (40)

where $P_1$ is the sum of the deadweight of the broken block and the overlying load (MN). Both stopes with single-key-stratum influence structures and stopes with multikey-stratum influence structures include single-seam mining and seam-group mining.
For the mining of a coal-seam group, the compacted rock mass in the caving zone of the upper coal-seam can be regarded as a weak stratum.

5.1 | Stope with a single-key-stratum influence structure

The load $P_z$ is calculated via formula (41) in a stope with a PKS influence structure, and the load $P_z$ is calculated via formula (42) in a stope with an SKS1 influence structure.

$$P_z = (L_k + 0.5h_0 \cot \alpha)h_0b_\gamma + k_1l_1b_\gamma(h_1 + K_G H_z) \tag{41}$$

$$P_z = (L_k + 0.5h_0 \cot \alpha)h_0b_\gamma + k_1l_1b_\gamma(h_1 + \Sigma h_1) \tag{42}$$

Here, $H_z$ is the thickness of the load strata (m), and $K_G$ is the load transfer coefficient of the load strata, which is determined by formula (43)\textsuperscript{8,14}:

$$K_G = \frac{0.8L_1}{2H_z \tan \varphi_1(1 - \sin \varphi_1)} \tag{43}$$

where $\varphi_1$ is the internal friction angle of the load strata (º).

5.2 | Stope with a multikey-stratum influence structure

Considering the scenarios of single-seam mining and seam-group mining in a stope with a multikey-stratum influence structure, mechanical models of the roof structure were established, as presented in Figure 11. In the figure, $Q_i (1 \leq i \leq m)$ is the load transfer from broken block $A_i$ to the lower part (MN), $P_i$ is the sum of the deadweight of the broken block $A_i$ and the overlying load (MN), and $l_i$ is the length of the broken block $A_i$ when all key strata are broken synchronously (m). Consider the value of $l_i$ in the case of the maximum load on the unbroken area of LKS. Then, $l_i = l_{i+1} - nL_i$ and $l_i < L_i$, where $n$ is a positive integer.

Referring to formula (40), the general calculation formulas of $Q_i$ and $P_i$ are obtained:

$$Q_i = k_iP_i \tag{44}$$

$$P_i = l_ib_\gamma(h_1 + \Sigma h_1) + k_1l_{i+1}b_\gamma(h_{i+1} + \Sigma h_{i+1}) + k_x(\ldots + k_xP_m) \tag{45}$$

The load $P_m$ is calculated via formula (46) if SKS is PKS, whereas the load $P_m$ is calculated via formula (47) if SKS is not PKS.

$$P_m = l_m b_\gamma(h_m + K_G H_z) \tag{46}$$

$$P_m = l_m b_\gamma(h_m + \Sigma h_m) \tag{47}$$

Combined with formulas (37), (38), and (44), the general formula for calculating the load $P_z$ in a stope with a multikey-stratum influence structure is obtained.

$$P_z = (L_k + 0.5h_0 \cot \alpha)h_0b_\gamma + k_1l_1b_\gamma(h_1 + \Sigma h_1) + k_x(\ldots + k_xP_m) \tag{48}$$

Since the actual support efficiency of the support is 0.9, the reasonable working resistance $P_H$ of the support is determined by formula (49)\textsuperscript{12}:

$$P_H = P_z / 0.9 \tag{49}$$

FIGURE 11 Mechanical models of the roof structure during periodic weighting in a stope with a multikey-stratum influence structure. A, Mechanical model of the roof structure in single-seam mining. B, Mechanical model of the roof structure in seam-group mining.
FIGURE 12 Mining conditions and borehole columnar section of each working face. A, Geographical location of each mine and the mining conditions of each working face. B, Borehole columnar section of each working face.
ENGINEERING VERIFICATION AND DISCUSSION

Stopes with various mining conditions are selected for evaluating the rationality of the discriminant method of KSS in the overburden during periodic weighting and the calculation method of the support load. Considering factors such as buried depth, mining height, and mining technology, the 1405 working face of Fengjiata coal mine, the 22310 working face of Bulianta coal mine, the W4301 working face of Gaohe coal mine, the I0130101 working face of Yannan coal mine and the 2304s working face of Xinjulong coal mine are selected. The mining conditions and a borehole columnar section of each working face are presented in Figure 12, and the locations of the key strata in the overburden of the stope are demarcated according to the discrimination conditions of the key stratum. Due to space limitations, only the structural form of the key stratum in the overburden during the periodic weighting of the 1405 working face in Fengjiata coal mine is verified both theoretically and via numerical simulation. The structural form of the key stratum in the overburden during periodic weighting of other working faces is only theoretically verified.

6.1 Fengjiata coal mine 1405 working face

Directly above the 1405 working face is the gob of the 1204 working face. SKS2 and PKS were broken during the extraction of the 1405 working face, as shown in Figure 12(B). Therefore, SKS1 will act as the PKS. As shown in Figure 12, \( h_0 = 4.25 \text{ m} \) and \( h_1 = 11.7 \text{ m} \). According to the literature, \( K_{p0} = 1.05, K_p = 1.3, \alpha = 75^\circ, \beta = 15^\circ, \varphi = 39.5^\circ, \) and \( \varphi_1 = 33^\circ \). The results of mechanical experiments demonstrate that \( R_{1T} = 1.82 \text{ MPa}, \sigma_1c = 49.5 \text{ MPa}, \sigma_2c = 68.4 \text{ MPa}, \) and \( \sigma_3c = 83.5 \text{ MPa} \). First, calculate the load \( q_1 \) on the broken block of SKS1:

\[
q_1 = \gamma h_1 + \frac{0.8L_4}{2H_z \tan \varphi_1(1 - \sin \varphi_1)} \gamma H_z = 0.29 + 0.033L_4
\]

The algebraic expression of \( q_1 \) is substituted into formula (9), and \( L_1 = 11.2 \text{ m} \) is obtained. Substituting \( L_1 \) into formula (15) yields \( h_1 = 41.78 \text{ m} \). \( \sum h_1 \) is only 5.7 m; hence, the instability and rotation of the broken block of SKS2 will affect SKS1 during the extraction of the 1405 working face. According to formulas (2) and (3), \( \Delta_{\text{max}} = 9.48 \text{ m} \) and \( W_1 = 2.03 \text{ m} \). Formula (5) is satisfied; hence, SKS1 will break periodically in the form of an articulated beam. Therefore, the broken blocks of SKS2 and PKS can also form articulated beams after instability and rotation. The mining experience with the 1204 working face demonstrates that there is an SBE between SKS2 and PKS, and \( l_2 = 20 \text{ m} \) and \( l_3 = 40 \text{ m} \). Via the “twice discrimination method,” it is determined that SKS1 will break periodically in the form of a step beam, and a voussoir beam structure can be formed after the unstable rotation of the broken block of SKS2, while the voussoir beam structure that is formed after the unstable rotation of the broken block of PKS easily loses stability. In addition, according to the above analysis, \( l_1 = l_2 - l_1 = 9.8 \text{ m} \). According to formulas (31), (33), and (35), SKS1 will break synchronously with the rotation of the broken blocks of SKS2 and PKS. Therefore, the KSS in the overburden of the 1405 working face is a multikey-stratum influence structure. Finally, it is determined that the structural form of the key strata in the overburden during the strongest periodic weighting is a step beam-vousoir beam-unstable vousoir beam via the “twice discrimination method.”
UDEC software was used to simulate and verify the SBE and the structural forms of the key strata in the overburden during the extraction of the 1405 working face. As shown in Figure 13, the size of the model is 280 × 83.5 m. Since the top of the model is 50 m from the surface, a uniform load of 1.25 MPa is applied to simulate the load of the upper strata. According to the results of a ground stress test, the horizontal lateral pressure coefficient is determined to be 0.5. Displacement constraints are applied to the left, right, and bottom boundaries of the model. The Mohr-Coulomb constitutive model is adopted as the whole model. A 40-m-long region on both sides of the model was preserved to avoid boundary effects. Each key stratum is divided into blocks in the form of whole layers according to the breaking interval.

The #2 coal-seam, #4 coal-seam, and their roof and floor were drilled and sampled, respectively, and then processed into standard test pieces in the laboratory. The block parameters of each rock stratum are determined experimentally, and the joint parameters are determined by referring to the software manual and the literature.9,44,45 See Table 5 for details. In this model, 10,000 time steps are calculated for each meter of advance of the working face to simulate the influence of mining on the overburden.

Since the 1405 face corresponds to coal-seam-group mining, it is necessary to simulate the movement law of the key strata in the overburden of the 1204 face initially. Figure 14 presents the migration law of the key strata in the overburden during the mining of the 1204 and 1405 working faces. 
(a) The SKS2 reaches the breaking interval, and the broken block rotates to form the voussoir beam structure during the extraction of the 1204 working face. At this time, PKS remains stable and there is a bed separation between the two key strata. (b) PKS broke periodically after the 1204 working face continued to advance. SKS2 is broken synchronously, which proves that there is an SBE between two key strata. (c) SKS2 breaks periodically again. (d) SKS1 reaches the breaking interval, and the broken block rotates to form the step beam structure during the extraction of the 1405 working face. At this time, the broken blocks of SKS2 and PKS are all in a steady state, and only SKS1 affects the periodic weighting. (e) The broken block of SKS2 can still form a voussoir

![Figure 13](image-url)  Schematic diagram of the numerical model

| Lithology                  | Matrix properties | Contact properties | Tensile strength | Friction angle |
|----------------------------|-------------------|--------------------|-----------------|----------------|
|                            | $K_a$ (GPa)       | $G_a$ (GPa)        | $K_n$ (GPa/m)   | $K_s$ (GPa/m)  | Cohesion (MPa) | (MPa) | (MPa) |
| Sandy mudstone             | 2.78              | 1.35               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| Medium-grain sandstone     | 4.61              | 2.33               | 6780            | 2700           | 15.5           | 20    | 20    |
| Sandy mudstone             | 2.96              | 1.48               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| Fine mudstone              | 3.08              | 1.54               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| Coarse mudstone            | 2.73              | 1.37               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| Sandy mudstone             | 2.99              | 1.49               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| Medium-grain sandstone     | 3.43              | 1.71               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| Coarse mudstone            | 1.69              | 0.84               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| Medium Coarse sandstone    | 5.08              | 2.54               | 4650            | 1860           | 10             | 15    | 18    |
| Sandy mudstone             | 3.88              | 1.94               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| #2 coal-seam               | 1.05              | 0.55               | 2000            | 750            | 2.95           | 1.47  | 10    |
| Sandy mudstone             | 2.58              | 1.29               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| #3 coal-seam               | 1.15              | 0.63               | 2000            | 750            | 2.95           | 1.47  | 10    |
| Pelitic siltstone          | 2.79              | 1.39               | 4000            | 1520           | 12.3           | 12.5  | 18    |
| Coal-seam                  | 1.52              | 0.75               | 2000            | 750            | 2.95           | 1.47  | 10    |
| Pelitic siltstone          | 2.83              | 1.42               | 3300            | 1320           | 8.25           | 3.22  | 15    |
| #4 coal-seam               | 1.55              | 0.79               | 2000            | 750            | 2.95           | 1.47  | 10    |
beam structure after it is rotated under the influence of mining. SKS1 is broken synchronously under the influence of a transfer load, and the strength of the periodic weighting in the stope is determined by two key strata at this time. (f) The unstable voussoir beam structure is formed after instability and rotation of the broken block of PKS under the influence of mining. In the fracture block of SKS2 and SKS1, interlocking instability successively occurs under the action of an unstable load. Hence, the three key strata all affect the periodic weighting of the 1405 working face. At this time, the structural form of the key strata in the overburden is step beam-voussoir beam-unstable voussoir beam.

Combined with theoretical analysis and numerical simulation, referring to formula (48), the load on the support of the 1405 working face is determined via formula (51). The calculation result is $P_z = 9852$ kN, which is larger than the yield load of the selected support. The reasonable working resistance $P_{hy}$ of the support that is determined via formula (49) should not be <10 946 kN.

\[
P_z = (L_x + 0.5h_0 \cot \alpha)h_0b\gamma + \left[ 1 - \tan \frac{h_0}{\sin \alpha} \cdot \frac{h_0}{b} \cdot \frac{\cos (\alpha - \theta_1) + \frac{l_1}{2} \cos \theta_1}{\sin (\alpha - \theta_1) - W_1 - 0.5a} \right] \cdot \left\{ l_1\gamma(h_1 + \Sigma h_1) + \left[ 2 - \frac{l_2\tan (\varphi - \beta)}{2(h_2 - W_2)} \right] \cdot [l_3\gamma(h_2 + \Sigma h_2) + l_4\gamma(h_3 + KG H z)] \right\} \tag{51}
\]

Figure 15 plots the working resistance curve of the support in the 1405 working face. There is strong nonuniform periodic weighting in the stope. The working resistance of the support can satisfy the requirements of roof support during weak periodic weighting. However, the working resistance of the support is low during strong periodic weighting, the safety valve is continuously opened, the subsidence of the plunger is large, and some supports are damaged. The field observation is in accordance with the theoretical calculation results. However, the range of the support resistance that is determined via empirical formula method (Table 1) is 3292-6583 kN, which cannot satisfy the requirements for safe mining.

### 6.2 Bulianta coal mine 22310 working face

The 22310 working face corresponds to coal-seam-group mining, and the gob of the 12311 working face is directly above it. According to Figure 12, based on a mechanics experiment and mining experience, $h_0 = 6.23$ m and $h_1 = 14.5$ m. The values of $\alpha$, $\beta$, $\varphi$, and $\varphi_1$ are still the same as those provided above. Since $L_3 < L_2$, although the medium-grain sandstone with a thickness of 11.15 m is the only key stratum in the overburden of the 12311 working face, it serves only as the load stratum during the extraction of the 22310 working face. By using the “twice discrimination method,” it is determined that SKS1 and PKS
break periodically in the form of a voussoir beam and an unstable voussoir beam, respectively. It is known that \( l_1 = L_2 - 3l_1 = 12.4 \) m. After calculation via formula (35), it is determined that there is an SBE between SKS1 and PKS. Therefore, the KSS in the overburden of the 22310 working face is a multikey-stratum influence structure. The structural form of the key strata in the overburden during the strongest periodic weighting, as determined by the “twice discrimination method,” is step beam-unstable voussoir beam. The load on the support is calculated via formula (52). The calculation result is \( P_z = 18,049 \) kN; hence, the selected support satisfies the requirements of roof control.

\[
P_z = (L_k + 0.5h_0 \cot \alpha)h_0b\gamma
+ \left[ 1 - \tan \varphi \cdot \frac{h_1}{\sin \alpha} \cos (\alpha - \theta_1) + \frac{l_2}{2} \cos \theta_1 \right]
+ \left[ l_1 \beta (h_1 + \Delta h_1) + l_2 \beta (h_2 + K_c H_2) \right]
\] (52)

Figure 16 shows the working resistance curve of the support in the 22310 working face. It can be seen that there is also nonuniform periodic weighting in the stope. The support load is 14-15.8 MN during weak periodic weighting. The support load is 14.8-18 MN, and the average subsidence of the plunger is 500-800 mm during strong periodic weighting. This finding is basically consistent with the above calculation results. The reasonable working resistance of the support determined by the empirical formula method is 9065-18130 kN, with a large range of values. The maximum is basically consistent with the theoretical calculation results and the field-measured data.

### 6.3 W4301 working face of Gaohe coal mine

The W4301 working face of Gaohe coal mine corresponds to single-seam mining. According to the borehole columnar section that is shown in Figure 12(B) and a mechanics experiment, \( h_0 = 4.07 \) m and \( h_1 = 3.2 \) m. By using formula (9), it is obtained that \( L_1 = 10.7 \) m, \( L_2 = 19.2 \) m, and \( L_3 = 21.9 \) m. After substituting into formula (8), we obtain \( W_1 = 4.54 \) m, \( W_2 = 2.71 \) m, \( \Delta_{1\text{max}} = 2.22 \) m, and \( \Delta_{2\text{max}} = 4.15 \) m. According to the “twice discrimination method,” SKS1 breaks periodically in the form of a cantilever beam, and SKS2 and SKS3 both break periodically in the form of a voussoir beam. It is known that \( l_1 = L_2 - L_1 = 8.5 \) m, \( l_2 = L_3 - L_2 = 2.7 \) m, and \( l_1 = l_2 = 19.2 \) m. After calculation using formulas (26), (35), and (44), it is determined that there is an SBE between SKS1 and SKS2, whereas there is no SBE between SKS2 and SKS3. Hence, the periodic weighting of the W4301 working face is affected only by SKS1 and SKS2. Therefore, the KSS in the overburden of the W4301 working face is a multikey-stratum influence structure. The structural form of the key strata in the overburden during the strongest periodic weighting that is determined by the “twice discrimination method” is the cantilever beam-voussoir beam. The support load is calculated using formula (53), and the result demonstrates that \( P_z = 7098 \) kN. According to formula (49), the reasonable working resistance of the support is 7887 kN, which is smaller than the yield load of the support.

\[
P_z = [L_k + 0.5(h_0 + 2.26) \cot \alpha] (h_0 + 2.26)\gamma + l_1 \beta (h_1 + \Delta h_1)
+ \left[ 2 - \frac{l_2 \tan (\varphi - \beta)}{2(h_2 - W_2)} \right] l_2 \beta (h_2 + \Delta h_2)
\] (53)
The working resistance curve of the support in the W4301 working face is plotted in Figure 17. The nonuniform weighting phenomenon is not readily observed because, when SKS1 is broken alone, the load on the support is small, and the top coal above the support acts as a plastic cushion; hence, the cyclic compressive strength is relatively weak. The mean value of the support load is 6.42-7.47 MN when SKS1 breaks synchronously with SKS2. Thus, the theoretical calculation results are accurate. However, the value of the support load that is determined via the empirical formula method is 5.4-10.8 MN. It is unreasonable to select the maximum as the yield load of the support.

### 6.4 I0130101 working face of Yannan coal mine

The I0130101 working face of Yannan coal mine corresponds to coal-seam-group mining, and the upper 28-2# coal-seam has been mined. It is known that $h_0 = 3.6$ m and $h_1 = 5.9$ m. By using formulas (8) and (9), we calculate $L_1 = 11.5$ m, $W_1 = 5.14$ m, $W_2 = 0.7$ m, and $\Delta_{1_{\text{max}}} = 5.69$ m. Since the absolute rotation of the block is too small after the key strata above SKS2 are broken, it can be regarded as the load strata. Using the “twice discrimination method,” it is determined that SKS1 breaks periodically in the form of a voussoir beam, and the broken block of SKS2 rotates in the form of an unstable voussoir beam. After calculation using formula (35), it is determined that the rotational instability of the broken block of SKS2 will cause SKS1 synergistic breakage. Therefore, the KSS in the overburden of the I0130101 working face is multikey-stratum influence structure. At this time, $l_1 = l_2 - L_1 = 5.8$ m. We determine that the structural form is a voussoir beam-unstable voussoir beam via the “twice discrimination method” when SKS1 breaks synchronously with SKS2. The support load is calculated using formula (54), and the result demonstrates that $P_z = 10.34$ MN.

According to formula (49), the reasonable working resistance of the support is 11.5 MN; hence, the yield load of the support is too low.

$$P_z = \left[ L_2 + 0.5(h_0 + 3.22) \cot \alpha \right] (h_1 + 3.22) b \gamma + \frac{2 - l_1 \tan(\varphi - \beta)}{2(h_1 - W_1)} \cdot \left[ l_1b\gamma(h_1 + \Sigma h_1) + l_2\gamma(h_2 + K_G H_z) \right]$$

(54)

Figure 18 plots the working resistance curve of the support in the I0130101 working face. The nonuniform law of the periodic weighting interval is readily observed, essentially due to the periodic breaking of SKS1 and the rotational instability of the broken block of SKS2. Roof falling and rib spalling occurred in the stope during periodic weighting, the safety valve is opened frequently, the subsidence of the plunger is large, and the mean value of the support load is 8.48-8.85 MN. Consistent with the theoretical analysis, the yield load of the support is low. The range of the support load is 5.27-10.55 MN according to empirical formula method, and the maximum value is approximately consistent with the theoretical calculation result.

### 6.5 Xinjulong coal mine 2304S working face

Xinjulong coal mine is a deep mine. According to the borehole columnar section of the working face and a mechanics experiment, $h_0 = 2.03$ m and $h_1 = 10.3$ m. According to formulas (8) and (9), $L_1 = 16.3$ m, $L_2 = 19.5$ m, $W_1 = 7.36$ m, $W_2 = 6.98$ m, and $\Delta_{1_{\text{max}}} = 8.06$ m. By using the “twice discrimination method,” it is determined that SKS1 breaks periodically in the form of a voussoir beam, and the broken block of SKS2 rotates in the form of an unstable voussoir beam.

**FIGURE 17** Working resistance curve of the observed support in the W4301 working face

**FIGURE 18** Working resistance curve of the observed support in the I0130101 working face
beam. After calculation using formula (35), it is determined that SKS1 will not break synchronously with the rotation of the broken block of SKS2. Therefore, the periodic weighting of the 2304S working face is affected only by SKS1. The KSS in the overburden of the 2304S working face has a single-key-stratum influence structure. We calculate the support load with $L$ single-key-stratum influence structure. We calculate the support load with

$$P_z = \left[ L_k + 0.5 (h_0 + 4.17) \cot \alpha \right] (h_0 + 4.17) b \gamma \times \left[ 2 - \frac{L_1 \tan (\varphi - \beta)}{2(h_1 - W_1)} \right] \cdot [L_1 b \gamma (h_1 + \Sigma h_i)]$$

(55)

The working resistance curve of the observed support at the 2304S working face is plotted in Figure 19, and no nonuniform periodic weighting occurs. This finding is consistent with the previous analysis. The support load is 11.21-11.92 MN during the periodic weighting, which is approximately 75%-79% of the yield load. The support load is 7.95-15.9 MN according to the field observation results. The method that is proposed in this paper for determining the support load based on the structural form of the key strata in the overburden during the periodic weighting is in accordance with results based on practical experience. However, it is difficult to popularize and apply this method in coal mines in China due to its many parameters and complicated calculation process. Nevertheless, this method can be used as a verification method to supplement the empirical formula method.

7 CONCLUSIONS

1. The steady state of SKS1 directly determines whether periodic weighting occurs in the stope, but the strength of the periodic weighting may also be affected by other UKSs. The KSS in the overburden of the stope is divided into two basic types according to the number of key strata that affect the periodic weighting, and the two basic types are further subdivided into four subcategories according to the category and location of each key stratum.

2. The determination of the breaking form of SKS1 and UKS and the articulated form of the broken blocks is the premise for evaluating SBE. The “twice discrimination method” is proposed for discriminating the breaking form of key strata and the articulated form of broken blocks according to the formation conditions of cantilever-type breaking and the “S-R” stability theory of the voussoir beam structure.

3. The spacing condition for no interaction between adjacent key strata was discussed. The calculation method of the breaking interval is analyzed when the LKS does not synergistically break with the UKS. Based on the theory of maximum tensile stress, the criteria of SKS1 synergistic breakage with UKS were studied when SKS1 breaks periodically in the form of a cantilever beam, a voussoir beam, and a step beam. The single-variable method is used to study the influences of various parameters on the SBE. The mechanism of nonuniform periodic weighting in a stope with a multikey-stratum influence structure is identified.

4. Considering two types of scenarios, that is, single-coal seam mining and coal-seam-group mining, mechanical models of the roof structure during the periodic weighting of the stope were established. The general calculation formulas of the support loads in stopes with a single-key-stratum influence structure and a multiple-key-stratum influence structure are presented. The engineering verification results demonstrate that the proposed method for determining the support load based on the structural form of the key strata in the overburden during the periodic weighting is in accordance with results based on practical experience. The research results can provide a reference and experience for roof control and support selection for stopes.

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