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Study on the Working Resistance of a Support under Shallowly Buried Gobs According to the Roof Structure during Periodic Weighting

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Abstract: The phenomenon of dynamic pressure in the panel under shallowly buried gobs is obvious, resulting in limited and challenging support type selection. In this paper, theoretical analysis, numerical simulation and field measurement were combined to study the reasonable working resistance of the support in panels under shallowly buried gobs. First, the definition of the equivalent main key stratum (EMKS) was proposed. Then, a method of identifying the structure of the EMKS and broken key stratum blocks was given. The roof structure of the panel under a shallowly buried gob (PSBG) during strong periodic weighting could be divided into 12 types. Mechanical models of the roof structure were established, and the method to calculate the working resistance of the support was given. The Bulianta coal mine and Fengjiata coal mine in the Yushenfu Mining Area were taken as research objects. Based on the measured working resistance curve of the support, the structural morphology of key stratum blocks during strong periodic weighting was distinguished. On this basis, the working resistance of the support was calculated. Finally, FLAC2D numerical software was used to test the working resistance of the support. Based on the subsidence of the roof, horizontal displacement of the coal wall and the development range of the plastic zone in the surrounding rock, the working resistance of the support and adaptability of the surrounding rock control were verified and evaluated. The results show that it is reasonable to calculate the working resistance of the support based on the roof structure during strong periodic weighting. The research results can provide a reference for the scientific and rational selection of the support in a PSBG.

Keywords: shallowly buried gob; structural morphology of key stratum blocks; roof structure; strong periodic weighting; working resistance of support

1. Introduction

Coal seams with shallow mining depths, thin bedrock and thick unconsolidated strata are usually defined as shallow seams [1]. The Yushenfu Mining Area is the largest area of shallow seams in China. Many production practices show that the rock pressure in shallow seam faces is extremely high, and the roof is prone to step convergence [2–4]. In recent years, the mines in the Yushenfu Mining Area have generally been in a state of high-strength mining due to excellent geological conditions and improvements in mining equipment. At present, the upper seams near the surface have been mined out, and most of the mines have also mined the lower seams. The general interval between the lower and upper seams in this mine area is approximately 10–45 m. There is usually a key stratum between the two seams. When the spacing between two key strata is less than 41 m,
the upper key stratum will affect the structure and stability of the lower key stratum [5]. Therefore, the periodic weighting strength of the panel in the lower seam is related to not only the breaking form of the key stratum in the interval strata but also the structure of the broken key stratum (BKS). There are obvious dynamic pressures; considerable periodic weighting strength variability and support crushing are prone to occur when mining the lower seam [6].

The key to solving the above problems is to ensure that the support in the panel under the shallowly buried gob (PSBG) has a reasonable working resistance and strong adaptability. Due to the unclear load mechanism of the support in many mines, it is impossible to determine the reasonable working resistance of the support. This problem can be solved by increasing the yield load of the support only. However, increasing the yield load of the support will increase the weight of the support and the total investment of fully mechanized mining equipment. At present, research on mining under shallowly buried gobs mainly focuses on the instability mechanism and preventive measures of support crushing under residual coal pillars, as well as the rational layout and support technology of roadways in the lower seam [6,7]. There are few studies on the relationship between the roof structure of the lower seam during periodic weighting and the working resistance of the support.

In this paper, the roof structure in the PSBG is divided into 12 types based on the structural forms of key stratum blocks. The mechanical models of the roof structure are established, and calculation methods to determine the reasonable working resistance of the support are given. Taking the #22309 panel of the Bulianta coal mine and the #1404 panel of the Fengjiata coal mine as research objects, the reasonable working resistance of the support is first calculated theoretically. Based on the surrounding rock control effect obtained by numerical simulation, the theoretical calculation results are verified. The research results can provide data for consideration in the operation of other mines in the Yushenfu Mining Area.

2. Classification of Roof Structure

2.1. Breaking Forms of the Key Stratum

Only a caving zone and fracture zone exist above the longwall gob of shallow seams [8–11]. The height of the caving zone is closely related to the mining height and the type of immediate roof. The height of the caving zone can be calculated by statistical regression Formula (1) [12–16]. Generally, the height of the caving zone is considered 2.5 times the mining height in the great mining height face, which has a mining height greater than 3.5 m [17,18].

\[
H = \frac{100M}{C_1 M + C_2} \tag{1}
\]

where \(M\) is mining height; the values of \(C_1\) and \(C_2\) are selected according to the type of immediate roof, as shown in Table 1.

<table>
<thead>
<tr>
<th>Type of Immediate Roof</th>
<th>Uniaxial Compressive Strength /MPa</th>
<th>Coefficient (C_1)</th>
<th>Coefficient (C_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong and hard</td>
<td>&gt;40</td>
<td>2.1</td>
<td>16</td>
</tr>
<tr>
<td>Medium strength</td>
<td>20–40</td>
<td>4.7</td>
<td>19</td>
</tr>
<tr>
<td>Soft and weak</td>
<td>&lt;20</td>
<td>6.2</td>
<td>32</td>
</tr>
</tbody>
</table>

As shown in Figure 1a, the blocks of a key stratum can form a voussoir beam during periodic weighting when the key stratum is not in the caving zone. The blocks of the key stratum can form a step beam during periodic weighting when the partial key stratum is...
in the caving zone, as shown in Figure 1b [4,19]. The key stratum in the caving zone breaks and exhibits the form of a cantilever beam, as shown in Figure 1c.

![Figure 1. Breaking form of a key stratum: (a) voussoir beam structure; (b) step beam structure; (c) cantilever beam structure.](image)

The main key stratum in the overburden strata was broken after the upper seam was mined. The key stratum between two seams will act as the main key stratum when mining the lower seam [20]. This kind of key stratum is defined as an equivalent main key stratum (EMKS). As shown in Figure 2, the transmission of the overburden load is obstructed when the block structure of an EMKS is protected by a combined arch (coal wall-block structure of the BKS gob). At this time, the strength of periodic weighting is relatively low. The partial overlying load will be transferred to the support when the blocks of the BKS move synchronously with the blocks of the EMKS. Then, strong periodic weighting occurs in the panel. This is the main reason for the great difference in periodic weighting strength in the PSBG. Therefore, the working resistance of the support should be considered according to the roof structure during strong periodic weighting.
Figure 2. Roof structure during periodic weighting: (a) roof structure during weak periodic weighting; (b) roof structure during strong periodic weighting.

The structural form of the BKS blocks is related to the breaking form of the EMKS and the thickness and fragmentation (expansibility) of the weak strata. Some scholars have proposed that the roof of the lower seam can be divided into three structural forms: voussoir beam–voussoir beam (VV), voussoir beam–step beam (VS) and step beam–step beam (SS) [21]. However, the above study does not take into account that the EMKS may be broken and exhibit the form of a cantilever beam, nor does it take into account that the BKS has multiple key strata.

2.2. Fracturing of EMKS in the Form of a Cantilever Beam

If the BKS is a single key stratum, the roof structure during strong periodic weighting can be divided into three categories. The analysis process is shown below.

In Figure 3, $d_1$ is the thickness of weak strata1; $d_{11}$ is the thickness of the weak strata1 after caving; $W_1$ and $W_{10}$ are the absolute subsidence and step subsidence of block C, respectively; $W_2$ and $W_{20}$ are the absolute subsidence and step subsidence of block F, respectively; $L_0$ and $L_1$ are the lengths of blocks B and E, respectively; $\theta_1$ and $\theta_2$ are the rotation angles of blocks B and E, respectively; $H_1$ is the height of the caved rock mass in the gob of the upper seam after compaction; $h_1$ is the thickness of the immediate roof of the lower seam and $h_2$ and $h_3$ are the thicknesses of the EMKS and the broken main key stratum (BMKS), respectively.

The absolute subsidence of block C is calculated by Formula (2).

$$W_1 = M - (K_p - 1)h_1$$

where $K_p$ is the fragmentation expansion coefficient of the immediate roof.

The relationship between $W_{10}$ and $W_1$ is as follows.

$$W_{10} = W_1 - L_0 \cdot \sin \theta_1$$
Weak strata1 will collapse synchronously with the EMKS when the EMKS is broken in the form of a cantilever beam. The measured results show that the fragmentation expansion coefficient of the weak strata1 is basically the same as that of the immediate roof when EMKS fractures in the form of a cantilever beam, which is 1.3 [21]. According to Formulas (2) and (3), the formulas for calculating $W_2$ and $W_{20}$ are obtained.

$$W_2 = W_1 - (d_{11} - d_{1}) = M - (K_p - 1)(l_1 + d_i)$$  \hspace{1cm} (4)

$$W_{20} = W_{10} - (d_{11} - d_{1}) = M - (K_p - 1)(l_1 + d_i) - L_a \cdot \sin \theta$$  \hspace{1cm} (5)

Block E rotates with point O as the fulcrum and $r_1$ as the radius during strong period weighting. The structural morphology of the BKS blocks can be distinguished based on the step subsidence $W_{20}$. The BKS blocks can form a voussoir beam when $W_{20} \leq 0$. However, the BKS blocks can form a step beam when $0 < W_{20} \leq h_3$; the BKS blocks cannot form articulated structures when $W_{20} > h_3$.

2.3. The BKS Has Two Key Strata

The multiple key strata in the roof of the shallow seams are usually double key strata. The key stratum adjacent to the seam is the subordinate key stratum, and the key stratum farther from the seam is the main key stratum. The double key strata were broken after mining in the upper seam, and both strong and weak periodic weighting occurred in the panel [22]. The blocks of a BMKS generally form voussoir beam structures during mining of the lower seam because of the limited rotation space and large block length [23,24]. Therefore, the roof structure should be classified based on the fracture modes of the EMKS and the structural form of the broken subordinate key stratum (BSKS) blocks. If a voussoir beam is formed after the breakage of the EMKS, the BSKS blocks will also form a voussoir beam due to the limited upper rotation space. At this time, the roof structure is voussoir beam–voussoir beam–vossoir beam (VVV). If the step beam is formed after the breakage of the EMKS, the structural form of the BSKS blocks is determined based on $W_{20}$, as shown in Figure 4. In this figure, $L_2$ is the length of block H.

![Figure 4. Step beam formed after the breakage of the EMKS. $h_4$, the thicknesses of the BSKS; $d_2$, the thickness of weak strata2; $d_{21}$, the thickness of the weak strata2 after caving; $L_2$, the length of block H.](image)

The roof structure is voussoir beam–voussoir beam–step beam (VVS) when $W_{20} \leq 0$. The roof structure is voussoir beam–step beam–step beam (VSS) when $W_{20} > 0$. According to the above analysis, the roof structure should be divided into three types when the
EMKS is broken in the form of a cantilever beam: voussoir beam–voussoir beam–cantilever beam (VVC), voussoir beam–step beam–cantilever beam (VSC) and voussoir beam–instability structure–cantilever beam (VIC).

In summary, the roof structure of the PSBG during strong periodic weighting can be divided into 12 types based on the breaking form of the EMKS and the structural form of the BKS blocks, as shown in Figure 5.

3. Theoretical Analysis of the Working Resistance of the Support

Supports in the PSBG should have reasonable working resistance. To avoid roof crushing, it should be ensured that the immediate roof above the support is effectively supported and the balance of the key stratum block structure is maintained. The roof structure of the PSBG has been classified. Mechanical models of the roof structure during strong periodic weighting are established in this section.

3.1. The BKS Is a Single Key Stratum

When the BKS is a single key stratum, there are six types of roof structures during strong periodic weighting: VV, VS, SS, voussoir beam–cantilever beam (VC), SC and instability structure–cantilever beam (IC). Figure 6 shows a mechanical model of the VV roof structure during strong periodic weighting.
Figure 6. Mechanical model of VV roof structure. $R_1$, the weight of the immediate roof above the support; $R_2$, the force acting on the substructure by block B; $P_1$, the sum of the weight of block B and the overlying load; $P_2$, the sum of the weight of block E and the overlying load; $P_z$, the working resistance of the support; $q$ is the load imposed on the lower structure by the unconsolidated strata.

In Figure 6, $R_1$ is the weight of the immediate roof above the support, $R_2$ is the force acting on the substructure by block B, $P_1$ is the sum of the weight of block B and the overlying load, $P_2$ is the sum of the weight of block E and the overlying load, $q$ is the load imposed on the lower structure by the unconsolidated strata and $P_z$ is the working resistance of the support.

The formula for calculating the load on the support is as follows [25].

$$P_z = R_1 + R_2$$  \(6\)

The load transfer coefficients of the voussoir beams formed by the EMKS and BMKS are shown in Formulas (7) and (8) [6,26].

$$K_1 = \frac{4i_1(1 - \sin \theta_1) - 3 \sin \theta_1 - 2 \cos \theta_1}{4i_1 + 2i_2 \sin \theta_1 (\cos \theta_1 - 2)}$$  \(7\)

$$K_2 = \frac{4i_2(1 - \sin \theta_2) - 3 \sin \theta_2 - 2 \cos \theta_2}{4i_1 + 2i_2 \sin \theta_1 (\cos \theta_2 - 2)}$$  \(8\)

where $i_1$ and $i_2$ describe the lumpiness of blocks B and E, respectively.

By combining Formulas (6), (7) and (8), the formula for calculating the working resistance of the support when the roof structure is VV is obtained.

$$P_z = (L_k + 0.5h_1 \cot \alpha)h_2b \gamma_1 + \frac{4i_1(1 - \sin \theta_1) - 3 \sin \theta_1 - 2 \cos \theta_1}{4i_1 + 2i_2 \sin \theta_1 (\cos \theta_1 - 2)} \left[ L_qh_2b \gamma_2 + L_qd_2b \gamma_4 + L_qH_2b \gamma_4 \right. + \left. \frac{4i_2(1 - \sin \theta_2) - 3 \sin \theta_2 - 2 \cos \theta_2}{4i_1 + 2i_2 \sin \theta_1 (\cos \theta_2 - 2)} \cdot L_q(h_2 b \gamma_5 + \frac{0.8 L_2b \gamma_5}{2 \tan \phi (1 - \sin \phi)}) \right]$$  \(9\)

where $b$ is the width of the support, $\gamma_1$ is the bulk density of the immediate roof, $\alpha$ is the breaking angle of the immediate roof, $\gamma_2$ is the bulk density of the EMKS, $\gamma_3$ is the bulk density of the BMKS; $\gamma_4$ is the bulk density of the weak strata1, $\gamma_5$ is the bulk density of the unconsolidated strata; $\gamma_6$ is the bulk density of compacted rock mass in the gob and $\phi$ is the internal friction angle of the unconsolidated strata.

When a step beam is formed after the EMKS is broken, the load transfer coefficient is calculated by Formula (10).
where $\beta$ is the breaking angle of the EMKS and $\phi_1$ is the friction angle between blocks.

For the VS and SS roof structures, the working resistance of the support is calculated by Formulas (11) and (12), respectively.

\[
P_i = (L_k + 0.5h_k \cot \alpha)h_k b r_i + \left[ 1 - \frac{h_2}{\sin \beta} \cos(\beta - \theta) + \frac{L_2}{2} \cos \theta \right] \cdot \tan \varphi_1
\]

\[
\left[ L_4 h_i b y_1 + L_4 d_1 b y_4 + L_4 H_1 b y_4 + \frac{4i_1 (1 - \sin \theta_2) - 3 \sin \theta_2 - 2 \cos \theta_2}{4i_1 + 2h_1 \sin \theta_1 (\cos \theta_2 - 2)} \cdot L_4 (h_2 b y_3 + \frac{0.8L_4 b y_3}{2 \tan \varphi(1 - \sin \varphi)}) \right]
\]

\[
P_i = (L_k + 0.5h_k \cot \alpha)h_k b r_i + \left[ 1 - \frac{h_2}{\sin \beta} \cos(\beta - \theta) + \frac{L_2}{2} \cos \theta \right] \cdot \tan \varphi_1
\]

\[
\left[ L_4 h_i b y_1 + L_4 d_1 b y_4 + L_4 H_1 b y_4 + \left\{ \frac{h_3}{\sin \beta} \cos(\beta - \theta) + \frac{L_4}{2} \cos \theta \right\} \cdot L_4 (h_2 b y_3 + \frac{0.8L_4 b y_3}{2 \tan \varphi(1 - \sin \varphi)}) \right]
\]

Figure 7 is a mechanical model of the VC roof structure.

**Figure 7.** Mechanical model of the VC roof structure. $H_0$, the thickness of the immediate roof after caving.

Clearly, $R_2$ should be calculated by Formula (13).
The working resistance of the support is calculated by Formula (14).

$$P_z = (L_k + 0.5h_2 \cot \alpha)h_1 b \gamma_1 + L_0 h_2 b \gamma_2 + L_0 d_1 b \gamma_4 + L_0 H_1 b \gamma_4 +$$
$$\frac{4t_1 (1 - \sin \theta_1) - 3 \sin \theta_2 - 2 \cos \theta_2}{4t_2 + 2t_1 \sin \theta_1 (\cos \theta_1 - 2)} P_i$$  \hspace{1cm} (14)

For the SC and IC roof structures during strong periodic weighting, the working resistance of the support is calculated by Formulas (15) and (16), respectively.

$$P_z = (L_k + 0.5h_4 \cot \alpha)h_3 b \gamma_1 + L_0 h_2 b \gamma_2 + L_0 d_1 b \gamma_4 + L_0 H_1 b \gamma_4 +$$
$$\frac{h_3}{\sin \beta} \cos(\beta - \theta_1) + \frac{L_4 \cos \theta_4}{2} \tan \phi_1$$
$$\frac{h_3}{\sin \beta} \sin(\beta - \theta_2) - W_2$$
$$L_4 (h_3 b \gamma_3 + \frac{0.8L_4 b \gamma_3}{2 \tan \phi(1-\sin \phi)})$$  \hspace{1cm} (15)

$$P_z = (L_k + 0.5h_4 \cot \alpha)h_4 b \gamma_1 + L_0 h_3 b \gamma_2 + L_0 d_2 b \gamma_4 + L_0 H_2 b \gamma_4 + L_0 (h_3 b \gamma_3 + \frac{0.8L_4 b \gamma_3}{2 \tan \phi(1-\sin \phi)})$$  \hspace{1cm} (16)

3.2. The BKS Has Two Key Strata

The roof structure also can be divided into six types when the BKS has two key strata, based on the breaking form of the EMKS and the structural form of the BSKS blocks: VVV, VVS, VSS, VVC, VSC and VIC. In Figure 8, $h_1$ is the thickness of the BSKS and $d_2$ is the thickness of the weak strata between the BMKS and BSKS.

**Figure 8.** Mechanical model of the VVV roof structure.

For the VVV roof structure, the working resistance of the support is calculated by Formula (17).
\[
P_z = (L_i + 0.5L \cot \alpha)h b \gamma_1 + \frac{4i_1(1 - \sin \theta_1) - 3 \sin \theta_1 - 2 \cos \theta_1}{4i_1 + 2i_2 \sin \theta_1 (\cos \theta_1 - 2)}.
\]

\[
\begin{align*}
L_i h_2 b \gamma_1 + L_0 d_1 b \gamma_4 + L_0 H_1 b \gamma_4 + \frac{4i_2(1 - \sin \theta_1) - 3 \sin \theta_2 - 2 \cos \theta_2}{4i_2 + 2i_3 \sin \theta_1 (\cos \theta_2 - 2)}. \\
L_i h b \gamma_7 + L_0 d_2 b \gamma_8 + \frac{4i_3(1 - \sin \theta_2) - 3 \sin \theta_3 - 2 \cos \theta_3}{4i_3 + 2i_3 \sin \theta_2 (\cos \theta_3 - 2)} - L_2 (h b \gamma_3 + \frac{0.8L b \gamma_3}{2 \tan \varphi(1 - \sin \varphi)}).
\end{align*}
\]

(17)

where \(i_i\) represents the lumpiness of block I, \(\gamma_7\) is the bulk density of the BSKS and \(\gamma_8\) is the bulk density of the weak strata2.

For the VVS and VSS roof structures, the working resistance of the support is calculated by Formulas (18) and (19), respectively.

\[
P_z = (L_i + 0.5L \cot \alpha)h b \gamma_1 + 1 - \frac{h_i}{\sin \beta} \frac{\cos(\beta - \theta_1) + \frac{L_i}{2} \cos \theta_1}{\frac{\cos(\beta - \theta_1)}{\sin \beta} - W_1}.
\]

\[
\begin{align*}
L_i h_2 b \gamma_1 + L_0 d_1 b \gamma_4 + L_0 H_1 b \gamma_4 + \frac{4i_2(1 - \sin \theta_1) - 3 \sin \theta_2 - 2 \cos \theta_2}{4i_2 + 2i_3 \sin \theta_1 (\cos \theta_2 - 2)} - L_2 (h b \gamma_3 + \frac{0.8L b \gamma_3}{2 \tan \varphi(1 - \sin \varphi)}).
\end{align*}
\]

(18)

\[
P_z = (L_i + 0.5L \cot \alpha)h b \gamma_1 + 1 - \frac{h_i}{\sin \beta} \frac{\cos(\beta - \theta_2) + \frac{L_i}{2} \cos \theta_2}{\frac{\cos(\beta - \theta_2)}{\sin \beta} - W_2}.
\]

\[
\begin{align*}
L_i h_2 b \gamma_1 + L_0 d_1 b \gamma_4 + L_0 H_1 b \gamma_4 + \frac{4i_3(1 - \sin \theta_2) - 3 \sin \theta_3 - 2 \cos \theta_3}{4i_3 + 2i_3 \sin \theta_2 (\cos \theta_3 - 2)} - L_2 (h b \gamma_3 + \frac{0.8L b \gamma_3}{2 \tan \varphi(1 - \sin \varphi)}).
\end{align*}
\]

(19)

From the formulas above, including Formulas (14), (15) and (16), it is concluded that for the VVC, VSC and VIC roof structures, the working resistance of the support is calculated by Formulas (20), (21) and (22), respectively.

\[
P_z = (L_i + 0.5L \cot \alpha)h b \gamma_1 + 1 - \frac{h_i}{\sin \beta} \frac{\cos(\beta - \theta_3) + \frac{L_i}{2} \cos \theta_3}{\frac{\cos(\beta - \theta_3)}{\sin \beta} - W_3}.
\]

\[
\begin{align*}
L_i h_2 b \gamma_1 + L_0 d_1 b \gamma_4 + L_0 H_1 b \gamma_4 + \frac{4i_3(1 - \sin \theta_2) - 3 \sin \theta_3 - 2 \cos \theta_3}{4i_3 + 2i_3 \sin \theta_2 (\cos \theta_3 - 2)} - L_2 (h b \gamma_3 + \frac{0.8L b \gamma_3}{2 \tan \varphi(1 - \sin \varphi)}).
\end{align*}
\]

(20)
4. Engineering Example

4.1. The #22309 Panel in Bulianta Coal Mine

The Bulianta coal mine is located in Wulanmulun town, Ordos City, Inner Mongolia Autonomous Region. The approved production capacity of the mine is 28 Mt/a. Downward mining of the #1-2 and #2-2 seams has occurred over an average distance of 28.1 m. The occurrence characteristics and mechanical properties of the coal strata are shown in Figure 9 and Table 2. The location of the key stratum was determined based on the judgment method [27,28]. The main key stratum was broken after the #1-2 seam was first mined. Obvious strong and weak periodic weighting phenomena occurred in the panel during the mining of the #2-2 coal seam. The step subsidence occurred in the roof during strong periodic weighting, reaching a maximum subsidence of 1.3 m. The safety valves of the supports are frequently opened, and roof management is difficult.

Figure 9. Location of the Bulianta coal mine and borehole histogram of the coal strata.
### Table 2. Physical and mechanical parameters of the coal strata.

<table>
<thead>
<tr>
<th>Rock Formations</th>
<th>Bulk Modulus (GPa)</th>
<th>Shear Modulus (GPa)</th>
<th>Density (kg·m$^{-3}$)</th>
<th>Friction Angle (°)</th>
<th>Cohesion (MPa)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeolian</td>
<td>0.040</td>
<td>0.019</td>
<td>1744</td>
<td>20.0</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>Coarse sandstone</td>
<td>1.44</td>
<td>0.67</td>
<td>2040</td>
<td>23.0</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>1.40</td>
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<td>2094</td>
<td>25.0</td>
<td>0.85</td>
<td>1.30</td>
</tr>
<tr>
<td>Mudstone</td>
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<td>2399</td>
<td>30.0</td>
<td>2.45</td>
<td>1.53</td>
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<tr>
<td>Sandy mudstone</td>
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<td>17.1</td>
<td>4.88</td>
<td>2.15</td>
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<td>6.60</td>
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<td>2.80</td>
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<td>22.4</td>
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<td>3.57</td>
</tr>
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<td>2410</td>
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<td>2.70</td>
<td>3.77</td>
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<tr>
<td>Mudstone</td>
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<td>2.45</td>
<td>2486</td>
<td>36.6</td>
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<td>Sandy mudstone</td>
<td>5.84</td>
<td>2.72</td>
<td>2401</td>
<td>21.5</td>
<td>3.30</td>
<td>4.32</td>
</tr>
<tr>
<td>#1-1 coal seam</td>
<td>1.67</td>
<td>0.83</td>
<td>1522</td>
<td>28.0</td>
<td>1.20</td>
<td>2.19</td>
</tr>
<tr>
<td>Medium sandstone</td>
<td>5.95</td>
<td>2.67</td>
<td>2488</td>
<td>28.1</td>
<td>11.7</td>
<td>3.52</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>3.60</td>
<td>1.13</td>
<td>2492</td>
<td>34.0</td>
<td>3.20</td>
<td>4.66</td>
</tr>
<tr>
<td>Medium sandstone</td>
<td>7.70</td>
<td>3.83</td>
<td>2484</td>
<td>35.6</td>
<td>18.0</td>
<td>5.84</td>
</tr>
<tr>
<td>#1-2 coal seam</td>
<td>1.47</td>
<td>0.67</td>
<td>1280</td>
<td>23.6</td>
<td>1.60</td>
<td>1.69</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>1.99</td>
<td>0.89</td>
<td>2334</td>
<td>26.1</td>
<td>4.30</td>
<td>3.84</td>
</tr>
<tr>
<td>Fine sandstone</td>
<td>4.33</td>
<td>2.45</td>
<td>2330</td>
<td>34.8</td>
<td>6.40</td>
<td>3.88</td>
</tr>
<tr>
<td>Medium sandstone</td>
<td>6.85</td>
<td>3.27</td>
<td>2167</td>
<td>27.4</td>
<td>16.8</td>
<td>1.73</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>6.19</td>
<td>2.85</td>
<td>2391</td>
<td>35.2</td>
<td>4.50</td>
<td>6.49</td>
</tr>
<tr>
<td>#2-2 coal seam</td>
<td>1.68</td>
<td>0.78</td>
<td>1264</td>
<td>24.5</td>
<td>2.30</td>
<td>1.16</td>
</tr>
<tr>
<td>Mudstone</td>
<td>4.75</td>
<td>2.55</td>
<td>2401</td>
<td>33.3</td>
<td>13.1</td>
<td>6.46</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>9.03</td>
<td>4.67</td>
<td>2408</td>
<td>22.0</td>
<td>35.7</td>
<td>6.16</td>
</tr>
<tr>
<td>Fine sandstone</td>
<td>9.94</td>
<td>5.27</td>
<td>2452</td>
<td>34.5</td>
<td>30.5</td>
<td>5.50</td>
</tr>
</tbody>
</table>

Taking the #22309 panel as the research object, the reasonable working resistance of the support is studied. The panel is arranged in the #3 district of the #2-2 seam, under the gob of the #12310 panel. The mining height of the panel is 6.8 m. The panel is equipped with a ZY18000/32/70D-type support. The main technical parameters of the support are shown in Table 3. Medium sandstone with a thickness of 11.2 m acts as the EMKS after mining the #22309 panel. The working resistance curve of the support is shown in Figure 10 according to field monitoring data. The average value of the periodic weighting interval $L_0$ is approximately 14 m.

### Table 3. Main technical parameters of ZY18000/32/70D-type hydraulic support.

<table>
<thead>
<tr>
<th>Support Height (mm)</th>
<th>Width (mm)</th>
<th>Setting Load (kN)</th>
<th>Yield Load (kN)</th>
<th>Between Centers (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3200–7000</td>
<td>1950</td>
<td>12,370</td>
<td>18,000</td>
<td>2050</td>
</tr>
</tbody>
</table>
The height of the caving zone is calculated to be 17 m, which is 2.5 times the mining height. The EMKS lies in the interior of the caving zone, which indicates that the EMKS will be broken in the form of a cantilever beam. The average value of the periodic weighting interval in #12310 working face is 18 m; that is, the length $L_1$ of block E is 18 m. The rotation angle of a block in a shallow seam is generally in the range of 4° to 6°. Therefore, in this paper, it is assumed that $\theta_1$ is 6°. $W_2$ is calculated to be -0.91 m based on Formula (5), indicating a VC roof structure during strong periodic weighting. Formula (14) should be used to calculate the working resistance of the support.

The fragmentation (expansion) coefficient and bulk density of the compacted rock mass in the gob are 1.03 and 19,000 N/m$^3$, respectively [29]. $H_1$ is calculated to be 2.06 m. It is known that $L_1$ is 9.42 m, $b$ is 2.05 m, $i_2$ is 0.8, $\alpha$ is 60°, and $\beta$ is 65°. Referring to Table 2, the working resistance $P_z$ of the support is calculated to be 22440.6 kN, higher than the yield load of the support, which is the reason for the difficult roof management during strong periodic weighting.

4.2. The #1404 Panel in Fengjiata Coal Mine

The Fengjiata coal mine is located in eastern Fugu County, Yulin City, Shaanxi Province. The approved production capacity of the mine is 6 Mt/a. Downward mining of the #2 and #4 seams has occurred over an average distance of 15 m. The occurrence characteristics and mechanical properties of the coal strata are shown in Figure 11 and Table 4. There are two key strata in the roof of the #2 coal seam. There is also a key stratum between the #2 and #4 coal seams. Obvious strong and weak periodic weighting phenomena occurred in the panel when the #2 coal seam was mined. The weak periodic weighting interval is approximately 17 m, and the strong periodic weighting interval is approximately 42 m; that is, $L_1$ is 17 m, and $L_2$ is 42 m.
Figure 11. Location of the Fengjiata coal mine and borehole histogram of the coal strata.

Table 4. Physical and mechanical parameters of the coal strata.

<table>
<thead>
<tr>
<th>Rock Formations</th>
<th>Bulk Modulus (GPa)</th>
<th>Shear Modulus (GPa)</th>
<th>Density (kg·m⁻³)</th>
<th>Friction Angle (°)</th>
<th>Cohesion (MPa)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loess</td>
<td>0.040</td>
<td>0.019</td>
<td>1880</td>
<td>27.0</td>
<td>0.0018</td>
<td></td>
</tr>
<tr>
<td>Subclay</td>
<td>0.15</td>
<td>0.054</td>
<td>1840</td>
<td>23.0</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>0.28</td>
<td>0.093</td>
<td>1960</td>
<td>25.0</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>2.56</td>
<td>2.36</td>
<td>2510</td>
<td>40.0</td>
<td>2.45</td>
<td>2.01</td>
</tr>
<tr>
<td>Pelitic siltstone</td>
<td>2.20</td>
<td>1.05</td>
<td>2650</td>
<td>42.0</td>
<td>1.88</td>
<td>1.77</td>
</tr>
<tr>
<td>Coarse sandstone</td>
<td>8.29</td>
<td>5.31</td>
<td>2890</td>
<td>30.6</td>
<td>7.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>4.90</td>
<td>3.20</td>
<td>2520</td>
<td>35.0</td>
<td>1.18</td>
<td>1.80</td>
</tr>
<tr>
<td>Fine sandstone</td>
<td>4.25</td>
<td>2.57</td>
<td>2570</td>
<td>31.4</td>
<td>5.20</td>
<td>4.50</td>
</tr>
<tr>
<td>Pelitic siltstone</td>
<td>4.20</td>
<td>2.65</td>
<td>2490</td>
<td>39.0</td>
<td>3.20</td>
<td>1.29</td>
</tr>
<tr>
<td>Medium coarse sandstone</td>
<td>9.7</td>
<td>6.0</td>
<td>2550</td>
<td>37.5</td>
<td>10.5</td>
<td>6.80</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>5.50</td>
<td>3.20</td>
<td>2500</td>
<td>29.0</td>
<td>4.50</td>
<td>2.50</td>
</tr>
<tr>
<td>#2 coal seam</td>
<td>5.00</td>
<td>2.30</td>
<td>1380</td>
<td>28.0</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>4.30</td>
<td>2.80</td>
<td>2545</td>
<td>37.0</td>
<td>3.2</td>
<td>2.25</td>
</tr>
<tr>
<td>#3 coal seam</td>
<td>5.60</td>
<td>2.30</td>
<td>1390</td>
<td>28.0</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Siltstone</td>
<td>8.83</td>
<td>5.13</td>
<td>2460</td>
<td>38.0</td>
<td>7.75</td>
<td>4.84</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>4.30</td>
<td>3.36</td>
<td>2730</td>
<td>32.9</td>
<td>12.00</td>
<td>2.50</td>
</tr>
<tr>
<td>#4 coal seam</td>
<td>2.50</td>
<td>1.72</td>
<td>1420</td>
<td>29.5</td>
<td>2.11</td>
<td>2.60</td>
</tr>
<tr>
<td>Pelitic siltstone</td>
<td>6.27</td>
<td>5.19</td>
<td>2665</td>
<td>44.5</td>
<td>11.5</td>
<td>7.80</td>
</tr>
</tbody>
</table>

Support crushing accidents occurred in the panel during the mining of the #4 seam. The #1404 panel under the gob of the #1203 panel is taken as the research object. The mining height of the panel is 3.3 m. The panel is equipped with a ZY8500/20/42-type support. The main technical parameters of the support are shown in Table 5. The working resistance curve of the support is drawn in Figure 12 according to field monitoring data. The average value of the periodic weighting interval \( L \) is approximately 13 m.

Table 5. Main technical parameters of ZY8500/20/42-type hydraulic support.

<table>
<thead>
<tr>
<th>Support Height (mm)</th>
<th>Width (mm)</th>
<th>Setting Load (kN)</th>
<th>Yield Load (kN)</th>
<th>Between Centers (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000–4200</td>
<td>1660</td>
<td>6123</td>
<td>8500</td>
<td>1750</td>
</tr>
</tbody>
</table>
Figure 12. Working resistances curve of the support in the 1404 panel.

As shown in Figure 13, the uniaxial compressive strengths of the immediate roof rock samples in the #4 seam are tested by the SANS compression-testing machine. The test results show that the uniaxial compressive strength of sandy mudstone is approximately 22.2 MPa, as shown in Table 6.

Table 6. Results of uniaxial compression tests.

<table>
<thead>
<tr>
<th>Number</th>
<th>Diameter (mm)</th>
<th>Height (mm)</th>
<th>Failure Load (kN)</th>
<th>Uniaxial Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>47.24</td>
<td>101.60</td>
<td>31.72</td>
<td>16.35</td>
</tr>
<tr>
<td>F2</td>
<td>49.72</td>
<td>92.49</td>
<td>40.59</td>
<td>20.90</td>
</tr>
<tr>
<td>F3</td>
<td>49.69</td>
<td>92.63</td>
<td>42.75</td>
<td>22.04</td>
</tr>
<tr>
<td>F4</td>
<td>50.68</td>
<td>95.14</td>
<td>40.92</td>
<td>20.46</td>
</tr>
<tr>
<td>F5</td>
<td>48.80</td>
<td>100.74</td>
<td>52.42</td>
<td>28.03</td>
</tr>
<tr>
<td>F6</td>
<td>49.65</td>
<td>90.74</td>
<td>48.81</td>
<td>25.18</td>
</tr>
<tr>
<td>Average value</td>
<td></td>
<td></td>
<td></td>
<td>22.16</td>
</tr>
</tbody>
</table>

The height of the caving zone in the #1404 panel is calculated by Formula (1) to be 9.56 m, indicating that the local EMKS is in the caving zone. \( W_{10} \) is calculated to be 1.37 m by Formula (3), which indicates that a step beam is formed after EMKS breakage. \( W_{20} \) is calculated to be −0.19 m based on Formula (4). This shows that the fragmentation and expansion of weak strata can completely fill the space created by step subsidence of the EMKS blocks. Additionally, the BSKS blocks can form voussoir beams. Therefore, the VVB roof structure forms during strong periodic weighting. Formula (18) should be used to calculate the working resistance of the support.

The height \( H_i \) is calculated to be 1.95 m. It is known that \( L_s \) is 6.6 m, \( b \) is 1.75 m and \( \phi_1 \) is 22º. Referring to Table 4, the working resistance \( P_z \) of the support is calculated to be
9562.6 kN. The results show that the working resistance of the support selected in the 1404 panel is low.

5. Numerical Simulation Schemes, Results and Discussion

5.1. Simulation of the Reasonable Working Resistance of the Support in the #22309 Panel

The working resistance of the support is preliminarily determined by theoretical calculation. However, it is difficult to verify the macroscopic characteristics of the rock pressure, such as the roof subsidence and working state of support. Therefore, the deformation characteristics of the surrounding rock under different support strengths are compared by numerical simulation to comprehensively determine the reasonable working resistance of the support.

Numerical models were established with Fast Lagrangian Analysis of Continua 2D (FLAC2D) software based on the actual geological conditions of the Bulianta coal mine, as shown in Figure 14. The mechanical parameters of the rock are given in Table 2. The Mohr–Coulomb constitutive model was applied to the whole model. A uniform load was applied in the vertical direction to simulate the gravity of the overlying strata. The effect of horizontal pressure was considered. The upper boundary was a free surface, the bottom boundary was restricted to move only vertically and the side boundaries around the model restricted horizontal movement. The double yield constitutive model of the compacted rock mass in the gob was established based on the gob compaction theory [29,30]. The numerical simulation parameters of the compacted rock mass are shown in Table 7.

![Distribution of plastic zone in roof of 1-2# coal seam after mining](image)

**Figure 14.** Numerical model of mining in the #22309 panel.

<table>
<thead>
<tr>
<th>Bulk Modulus (GPa)</th>
<th>Shear Modulus (GPa)</th>
<th>Density (kg·m⁻³)</th>
<th>Friction Angle (°)</th>
<th>Cohesion (MPa)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>0.013</td>
<td>1900</td>
<td>5</td>
<td>0.001</td>
<td>0</td>
</tr>
</tbody>
</table>

The #12310 panel was mined first in the model. The open–off cut is 20 m from the left boundary of the model. Plastic failure of the main key stratum occurred after excavation.
of the #12310 panel. The main key stratum can be divided into blocks with different sizes based on the shear-tension plastic zone of penetration. The lengths of the blocks are in the range of the periodic weighting interval of the upper seam. The #22309 panel is excavated after the strata movement stabilizes. The working face advances to 140 m from the left boundary of the model. The hydraulic support is simulated by the software’s built-in support unit. The surrounding rock deformation characteristics and control effects of the support with a yield load of 18,000 kN–27,000 kN are compared. The setting load of the support is 60% of the yield load. The linear stiffness of the support is 100 kN/mm.

The statistics of roof subsidence of different simulation schemes are shown in Figure 15. The roof subsidence decreases gradually with increasing support yield load. The roof subsidence is significantly improved when the yield load of the support is 23,000 kN. The reduction in roof subsidence will be weakened when the yield load of the support exceeds 24,000 kN.

Figure 15. Roof subsidence of different yield loads of the support: (a) roof subsidence of the monitoring points; (b) average value of the roof subsidence in the panel.

The horizontal displacement of the coal wall with different simulation schemes is shown in Figure 16. The horizontal displacement of the coal wall also decreases gradually with increasing yield load of support. The difference in the horizontal displacement of the upper coal wall is larger than that of the lower coal wall. The horizontal displacement of the upper coal wall is greater than that of the lower coal wall when the yield load is less than 22,000 kN. The horizontal displacement of the lower coal wall is greater than that of the upper coal wall when the yield load is higher than 23,000 kN. The reduction in the horizontal displacement of the coal wall is weakened when the working resistance is higher than 24,000 kN.
The distribution of the plastic zone in the surrounding rock of various simulation schemes is shown in Figure 17. The development range of the plastic zone in the surrounding rock gradually decreases with increasing yield load. The development range of the plastic zone does not change significantly when the yield load exceeds 24,000 kN.

Figure 17. Distribution of plastic zone in surrounding rock with different yield loads of the support.

The reasonable working resistance of the support in the #22309 panel is determined to be 24,000 kN based on the abovementioned numerical simulation analysis and theoretical calculation results.

5.2. Simulation of the Reasonable Working Resistance of the Support in the #1404 Panel

The numerical model of the #1404 panel in the Bulianta coal mine is shown in Figure 18. The #1203 panel should be excavated first. The #1404 panel should be excavated when the movement of the rock mass in the roof of the #1203 panel tends to be stable. The theoretical calculation confirms that the reasonable working resistance of the support is 10,000 kN. Therefore, a support with a yield load of 7000 kN–14,000 kN is selected for simulation.
The statistics of the results of roof subsidence from different simulation schemes are shown in Figure 19. The roof subsidence is significantly improved when the yield load of the support is 9000 kN. The reduction in roof subsidence will be weakened when the yield load of the support is higher than 9000 kN.

Figure 19. Roof subsidence of yield loads of the support: (a) roof subsidence of the monitoring points; (b) average value of the roof subsidence in the panel.
The horizontal displacement of the coal wall with different simulation schemes is shown in Figure 20. The horizontal displacement of the coal wall is significantly improved when the yield load of the support is 9000 kN. The maximum horizontal displacement of the coal wall is approximately 26 mm when the yield load of the support is higher than 10,000 kN.

![Figure 20](Image)

**Figure 20.** Horizontal displacement of the coal wall with different yield loads of the support in the #1404 panel.

The distribution of the plastic zone in the surrounding rock is shown in Figure 21 for various simulation schemes. The development range of the plastic zone does not change significantly when the yield load exceeds 9000 kN.

![Figure 21](Image)

**Figure 21.** Distribution of the plastic zone in the surrounding rock with different yield loads of the support.

The reasonable working resistance of the support in the #1404 panel is determined to be 10,000 kN based on the abovementioned numerical simulation analysis and theoretical calculation results. The yield load of the support selected in practice is low, and support crushing can be avoided by taking appropriate measures.

5.3. Discussion

On the basis of dividing the roof structure under shallowly buried gob into 12 types, this paper gives the calculation method of the reasonable working resistance of the support. The method is in accordance with the field practice. 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.
In fact, when the yield load of the support installed is low, some measures can be taken to avoid support crushing and roof falling. For example, the Bulianta and Fengjiata coal mines have taken the following measures, respectively. (a) the support was passively retracted, and the mining height was lowered to 5.5 m during strong periodic weighting in the #22309 panel. However, the movable column has a large extent and can withstand large roof subsidence. At this time, the advancing speed of the panel is accelerated to quickly pass through the weighted influence area, effectively avoiding excessive roof subsidence. (b) The mining height was decreased from 3.3 m to 2.7 m during strong periodic weighting. Additionally, hydraulic props were installed on both sides of the hydraulic supports in the #1404 panel as reinforcement. Table 8 lists the parameters of the individual hydraulic props. Support resistance was raised to approximately 9100 kN.

<table>
<thead>
<tr>
<th>Type</th>
<th>Height (m)</th>
<th>Setting Load (kN)</th>
<th>Yield Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DZ31-30/110Q</td>
<td>2.35–3.15</td>
<td>144–188</td>
<td>300</td>
</tr>
</tbody>
</table>

6. Conclusions

Reasonable determination of the support yield load can effectively solve the problems of roof management and support selection for the PSBG. In this paper, the EMKS is defined. A method for identifying the breaking form of an EMKS and the structural form of a BKS is proposed. The roof structure in the PSBG during strong periodic weighting is classified. Additionally, the calculation methods of the reasonable working resistance of the support are given. The main conclusions are as follows.

(1) The reason for weak periodic weighting in the PSBG is that the combined arch structure obstructs the transmission of the overlying load. The synchronous motion of the EMKS and BKS blocks induces strong periodic weighting.

(2) A method for calculating step subsidence $W_{20}$ is given. The BKS blocks can form voussoir beams when $W_{20} \leq 0$. The BKS blocks can form step beams when $0 < W_{20} \leq h_3$. The BKS blocks cannot form articulated structures when $W_{20} > h_3$.

(3) Considering that the EMKS breaks in the form of a cantilever beam and the BKS is a double key strata structure, the roof structure under shallowly buried gob is divided into 12 types based on the breaking form of the EMKS and the structural form of the BKS. Mechanical models of the roof structure are established, and calculation methods of the reasonable working resistance of the support are given.

(4) Based on the actual geological conditions of the #22309 and #1404 panels, the types of roof structures during strong period weighting are distinguished, and the reasonable working resistance of the supports is calculated. The subsidence of the roof, horizontal displacement of the coal wall and plastic zone distribution in the surrounding rock of several schemes are simulated. The adaptability of the support and the deformation control of the surrounding rock are evaluated. From this evaluation, combined with the theoretical calculation results, the reasonable working resistances of the supports in the #22309 and #1404 panels are determined to be 24,000 kN and 9500 kN, respectively. Measures such as reducing mining height, accelerating the advancing speed and setting up temporary supports can effectively avoid support crushing during strong periodic weighting during actual production.

Author Contributions: All of the authors contributed extensively to the work. C.W., C.Z. and Y.Y. proposed key ideas. Y.Y. provided practice guidance in the research process. C.Z. and Z.C. contributed to field measurements. Z.C. and W.W. analyzed the data. C.W. wrote the paper. C.Z. modified the manuscript. All authors have read and agreed to the published version of the manuscript.

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**References**


