Research Article

Research on the Influence of the Key Stratum Position on the Support Working Resistance during Large Mining Height Top-Coal Caving Mining

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In recent years, in order to increase the coal recovery rate, the large mining height fully mechanized top-coal caving mining has been widely used because it has the advantages of both fully mechanized mining method and large mining height mining method. When this mining technology is used to exploit thick coal seam under upper goaf, the movement characteristics of the overlying strata and the bearing structure formed by the broken rock are complicated, which results in the abnormal pressure during mining, such as severe coal slabs and hydraulic supports being crushed. The key to solve these problems is to study the movement law and the structural evolution characteristics of the overlying strata during large mining height fully mechanized top-coal caving mining, and the movement characteristics of the overlying strata are all determined by the layer-position of the key stratum. UDEC models with different layer-position of the key stratum are established to investigate the influence of the key stratum position on the support working resistance during large mining height top-coal caving mining. Through comprehensive research, the source of support resistance comes from under different geological conditions was analyzed, and the formula for estimating the maximum support working resistance was deduced. In addition, in order to release the severe pressure during large mining height fully mechanized top-coal caving mining, it is recommended to use hydraulic fracturing method to weaken the key stratum in situ.

1. Introduction

In China, large mining height fully mechanized mining [1, 2] and fully mechanized top-coal caving mining technology [3] are widely used for thick coal seam. However, the traditional large mining height fully mechanized mining technology has some shortcomings, such as low production capacity, difficult roadway excavation and maintenance, and large coal loss [4–7]; and traditional fully mechanized top-coal caving mining technology has the disadvantages of low coal recovery rate, high gangue content, large coal dust, difficult roof management, and so forth [8–11]. In order to overcome the shortcomings of the above two coal mining methods, the large mining height fully mechanized top-coal caving mining technology has been popularized and applied in thick and extremely thick coal seams [12–15]. This mining method has the advantages of both fully mechanized top-coal caving mining and large mining height fully mechanized mining and has obvious economic advantages [12, 15].

However, the fully mechanized top-coal caving mining technology with large mining height is not yet fully mature, and there are some problems such as the severe appearance of mine pressure, the serious face wall, and the heavy load of hydraulic support [16–18]. Many scholars have studied this issue. Ning et al. analyzed the controlling effect on strata behavior of hard and thick roof [19]. The fracture failure of hard-thick sandstone roof in underground ultrathick coal extraction analysis was made based on “Key Strata” theory and numerical simulation results [4]. Yan et al. [20] analyzed the mechanism of bedding separation in roof strata overlying a roadway within a thick coal seam. China Coal Technology & Engineering Group, Datong Coal Mine
Group, and 15 other organizations in China launched a big and fundamental project to develop coal mining technologies and equipment for coal seams with thicknesses greater than 14 m. After the completion of the project, a coal extraction method was developed for top-coal caving with a large mining height, as well as a ground control theory for ultrathick coal seams [12]. Li et al. [21] analyzed the ground pressure and roof movement in fully mechanized top-coal caving with large mining height in ultrathick seam; according to the problem of mine pressure in fully mechanized caving mining of thick coal seam, a special prefracture blasting strategy just sufficient enough to form cracks in the top coal is suggested by means of comparison with the results of numerical modeling [22]. Xie et al. [23] studied the stress shell characteristics of surrounding rock in fully mechanized top-coal caving face. Based on the above research results, the key to solve the existing technical problems of high mining height fully mechanized top-coal caving mining technology is to study the law of overlying strata movement and the structural stability characteristics of large mining height fully mechanized caving mining.

To solve the problems of the physical and mechanical properties of roof strata in the process of fully mechanized caving mining with high mining height, the structure of roof strata, and the load amount of roof strata acting on the support of working face. It's essence is to study the interaction between support and surrounding rock in the transition from original rock equilibrium state to another equilibrium state [24]. In actual production, as a controllable factor in the action system of support and surrounding rock, adjusting its working state and parameters is an effective way to achieve the dynamic balance of the action system [25, 26]. Therefore, it is the key to understand the interaction between the support and surrounding rock.

This study is based on the key stratum theory proposed by Minggao et al. [27]. Using UDEC software, the failure height and collapse characteristics of overlying strata in the mining process of thick coal seam in goaf with the same propulsive length of different layers are analyzed. Through the similar simulation experiment, the structure shape of the key stratum and its influence on the rock pressure in the fully mechanized mining face under the condition of large mining height are analyzed. The model of different interlayer key stratum positions is established to analyze the influence of interlayer key stratum position on overburden movement and structure, and the maximum support strength and maximum working resistance of support are calculated. The disadvantages of the traditional methods to deal with the abnormal mine pressure are analyzed and the solution of weakening the key coal strata in situ with water in goaf and actively preventing and controlling the catastrophe is put forward.

2. Numerical Simulation

2.1. Model Description. UDEC numerical simulation software was selected, the model width × height = 240 m × 180 m, and the upper 8th coal seam left a coal pillar with a width of 20 m (as shown in Figure 1). It is assumed that the layers of the coal and rock mass are isotropic and horizontal, the horizontal and displacement constraints are established at the bottom of the model, the horizontal constraints are established at the left and right boundaries, and the upper boundary is the stress boundary. The models of interlayer rock thicknesses of 60 m, 35 m, and 15 m are established. The mechanical parameters of coal and rock and the mechanical parameters of coal-rock contact surfaces are shown in Table 1, respectively.

2.2. Results of Numerical Simulations

2.2.1. Collapse Characteristics of Overlying Strata with Working Face Advance Distance of 100 m under the Condition of Different Interlayer Rock Thickness. When the thickness of the interlayer strata is 60 m, the immediate roof and the lower main roof collapse irregularly and some of the rock masses of the immediate roof are invert, and the upper main roof gradually transited from irregular collapse to regular collapse. The upper main roof is obviously fractured in advance and forms a large arch structure (Figure 2(a)).

When the thickness of the interlayer strata is 35 m, the immediate roof and the main roof collapse irregularly and some of the rock masses of the immediate roof are invert, the main roof fractured in advance, and the distance of fracture is smaller than that of 60 m thickness. In the upper part of No. 8 coal goaf, the movement of strata gradually transited from irregular collapse to regular collapse, forming a large arch structure (Figure 2(b)).

When the thickness of the interlayer strata is 15 m, the immediate roof and the main roof collapse irregularly and some of the rock masses are invert, and the main roof that fractured in advance is not obvious. The lower main roof of No. 8 coal goaf is irregular collapse, and the upper main roof gradually transits to regular collapse (Figure 2(c)).

From the results of numerical simulation, it can be seen that when the thickness of strata is different, under the same working face advance distance, the collapse characteristics of strata and the structures formed after collapse are not the same. According to the rock pressure hypothesis of hinged rock block, the stress of hydraulic support in working face depends on the interaction between the cantilever in the regular moving zone and its adjacent rock block and also on the interaction characteristics between the suspension beam in the regular moving zone and the irregular collapse zone. The above two action characteristics are determined and controlled by the interlayer stratum.

3. Physical Experiment

It is well known that the rock pressure behavior of the working face is caused by the breaking movement of mining overburden rock, and the intensity of its manifestation is closely related to the movement characteristics of the overlying rock structure. As a key stratum that plays a major role in controlling the strata movement, its breaking movement directly controls the rock pressure behavior of the working face. Therefore, the occurrence of key stratum in the overburden and the formation of the structure after the breakage will inevitably have an impact on the rock pressure.
behavior of the working face. For a fully mechanized mining face with large mining height, the roof caving range will be greatly increased, and the structural form of the key strata of overburden rock may also change with it, resulting in the mine pressure behavior of the working face being different from that of the general working face.

In order to study the characteristics of overburden structure and its influence on mine pressure in fully mechanized top-coal caving face with large mining height, a similar material simulation experiment was carried out for the case of 15 m mining height, and a large plane strain unit with length $\times$ height $\times$ thickness $=4370 \text{ mm} \times 2600 \text{ mm} \times 200 \text{ mm}$ was adopted. The geometric similarity ratio of the model is 1:200, the stress similarity ratio is 1:300, and the density similarity ratio is 1:1.5. River sand is used as aggregate; lime, calcium carbonate, and gypsum are used as cementing materials; and borax is used as retarder. The model is layered along the horizontal direction, and mica powder is sprayed between the layers to simulate the coal and rock strata, and the top of the model is a free end, which can move with the movement of the strata.

The open-off cut is excavated at the left edge of the model, 120 mm (prototype 24 m), and the speed of advancing 2 cm at every 33.8 min interval is estimated to be moving to the right. Typical experimental results are shown in Figure 3.

From the experimental results, it can be seen that the key strata of overburden rock will not be able to form a stable “masonry beam” structure form because of the large amount of rotation under the condition of high mining height. Instead, a “cantilever beam” structure forms in the overlying strata as the working face advancing with large mining height. When the span of the cantilever is greater than the collapse step, the cantilever will fracture and collapse. The biggest difference between the “cantilever beam” structure and the “masonry beam” structure lies in the loss of the binding force of the broken block in the rear. Therefore, comparatively speaking, the “cantilever beam” structure has more space of rotation after breaking, and the roof beam of the working face support should be pushed completely beyond the breaking line of the key stratum, so that the rotating motion of the broken block will not have any effect on the support. At this time, the weighting of the working face will stop. When the key layer “masonry beam” moves under the general mining height condition, the block can touch the gangue and be restrained by the broken block of the key stratum in the rear when the block rotates at a relatively small angle, so that it can reach a stable state. That is, the working face to advance a small distance after the weighting can end. Therefore, compared with the general mining face, the weighting of the cantilever beam structure of the key layer of the oversized fully mechanized mining face will last longer than that of the general mining face.

4. Influence of Interlayer Key Stratum Position on the Movement Characteristics of Overlying Strata

According to the above theoretical analysis, the movement of overlying strata is related to the location of interlayer key stratum, and the stability of hinged arch structure formed in goaf of overburden strata is affected differently by the location of interlayer key stratum. In the following part, this paper discusses the three cases of no interlayer key stratum, the key stratum located in the middle and upper part of the interlayer, and the position close to the top coal.

(1) As shown in Figure 4, when there is no key stratum in interlayer strata, it is normal mining of coal seam under goaf. When the interbedded strata are not through, the support mainly takes on the load imposed by the interlayer strata. When the advance distance is $L$ and the overall interlayer width strata are connected, the load of the layer above the working face and the goaf caving zone is all applied on the support.

(2) As shown in Figure 5, when there is a key stratum in the interlayer strata, as the interlayer key stratum plays a certain supporting role on the overburden strata, the supports and the key stratum jointly take on the load imposed by the interlayer strata when the interlayer strata are not penetrated. When the advance distance is $L$ and the overall interlayer width strata are connected, the load of the layer above the working face and the goaf caving zone is all applied on the support.

(3) As shown in Figure 6, when the interlayer key strata are adjacent to top coal, when the advance distance
of the working face is less than L, the key strata form a stable structure above it to protect the stope; at this time, there is no obvious phenomenon of mineral pressure. When the working face continues to advance, after the overall interlayer width strata are connected, the support will bear all the weight of its upper interlayer strata, gangue in goaf, and caving zone on goaf.

5. Discussion

5.1. Calculation of Maximum Working Resistance of Support at Different Interlayer Key Stratum Positions

5.1.1. When There Is No Interlayer Key Stratum. During the advancement of the working face, the key strata will undergo bending deformation as the immediate roof collapses. In this process, key strata structures I and II can be simplified to an elastic foundation beam, and immediate roof III can be regarded as an elastic foundation. A mechanical model of the key strata was established.

The load of the interlayer strata above the working face and the caving zone above the goaf are all applied on the supports when the overall interlayer width strata are connected. Working resistance can be calculated by using the “masonry beam” structure model:

\[ P = P_{1} + P_{2} + P_{c} \]  

(1)

where \( P \) is the working resistance of the support, kN; \( P_{1} \) is the supporting intensity of the support, kPa; \( B \) is the width of the support, m; \( L_{m} \) is the face width of the support, m.

The supporting intensity \( (P_{1}) \) of the support is calculated by the following formula:

\[ P_{1} = H \gamma_{1} + M_{1} \gamma \]  

(2)

where \( H \) is the thickness of the interlayer strata, m; \( M_{1} \) is the thickness of the top coal, m; \( \gamma_{1} \) is the unit weight of the interlayer strata, kg/m³; \( \gamma \) is the unit weight of the top coal.

When the advance distance is greater than \( L \), the overall interlayer width strata are connected. At this point, the supports will take on the load of upper goaf and upper caving zone. The load of irregular caving zone in unit length is

\[ P_{c} = \sum H_{1} \gamma_{1} + N \gamma_{n} \]  

(3)

After connection, the supporting intensity of the support is

\[ P'_{1} = H \gamma_{1} + M_{1} \gamma + P_{c} \]  

(4)

According to equations (1)–(4), the maximum working resistance of the support is

\[ P' = (H \gamma_{1} + M_{1} \gamma + \sum H_{1} \gamma_{1} + N \gamma_{n} + 2 - \frac{L_{1} \tan(\theta - \phi)}{2(\sum h_{2} - \delta)} \frac{Q}{L_{m}})BL_{m} \]  

(5)

Values of this working face are as follows: \( \sum H_{1} = \sum H_{2} = 15 \text{ m}, \sum H_{3} = 20 \text{ m}, M_{1} = 10 \text{ m}, N = 5 \text{ m}, \gamma_{1} = 25 \text{ kN/m}^{3}, \gamma = 13 \text{ kN/m}^{3}, B = 1.75 \text{ m}, \text{ and } L = 6 \text{ m}. \)

From this, the following can be estimated.

When the width of the interlayer strata \( H = 60 \text{ m}, \) the supporting intensity of the support is \( P = 31552 \text{ kN/support}; \) when the width of the interlayer strata \( H = 35 \text{ m}, \) the supporting intensity of the support is \( P = 24990 \text{ kN/support}; \) when the width of the interlayer strata \( H = 15 \text{ m}, \) the supporting intensity of the support is \( P = 19740 \text{ kN/support}. \)

5.1.2. When the Interlayer Key Stratum Is Located in the Middle and Upper Part of the Strata. During the process of propelling the working face, after the first weighting of the main roof, it will sink and collapse periodically. The main roof that does not collapse is considered as a cantilever beam, and the period of the key strata is determined according to the maximum length of the cantilever without collapse.

When there is a key stratum between interlayer strata and its thickness is \( h, \) the advance distance is \( L; \) when the connection is going to be made, the supporting intensity of the support is

\[ P_{1} = (H - h) \gamma_{1} + h \gamma_{2} + M_{1} \gamma + \left[ 2 \frac{L_{1} \tan(\theta - \phi)}{2(\sum h_{2} - \delta)} \right] \frac{Q}{L_{m}} \]  

(6)

where \( \phi \) is the friction angle of the rock mass (°); \( \theta \) is the fracture angle of the rock mass (°); \( \delta \) is the rotary sinkage of the key stratum mass, m; \( L_{1} \) is the length of the key stratum mass, m; \( Q \) is the weight of the key stratum mass, kN; \( h \) is the thickness of the interlayer key stratum, m.

When the advance distance is greater than \( L, \) after the overall interlayer width strata are connected, the supporting intensity of the support can be expressed as a combination of equations (4) and (6):

\[ P'_{1} = (H - h) \gamma_{1} + h \gamma_{2} + M_{1} \gamma + \sum H_{1} \gamma_{1} + N \gamma_{n} + \left[ 2 \frac{L_{1} \tan(\theta - \phi)}{2(\sum h_{2} - \delta)} \right] \frac{Q}{L_{m}} \]  

(7)

According to equations (1)–(3) and (6), the maximum supporting intensity of the support is

\[ P' = (H \gamma_{1} + M_{1} \gamma + \sum H_{1} \gamma_{1} + N \gamma_{n} + 2 - \frac{L_{1} \tan(\theta - \phi)}{2(\sum h_{2} - \delta)} \frac{Q}{L_{m}})BL_{m} \]  

(8)
Table 1: The mechanical parameters of contact surface of coal and rock.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Normal stiffness (GPa)</th>
<th>Shear stiffness (GPa)</th>
<th>Cohesion (MPa)</th>
<th>Internal friction angle (°)</th>
<th>Strength of extension (MPa)</th>
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<td>20.2</td>
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<td>7.0</td>
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<td>19.5</td>
<td>0</td>
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<td>Argillaceous sandstone</td>
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<td>6.0</td>
<td>0</td>
<td>14.5</td>
<td>0</td>
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<td>No. 8 coal seam</td>
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<td>0</td>
<td>13.5</td>
<td>0</td>
</tr>
<tr>
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<td>8.5</td>
<td>1.5</td>
<td>19.5</td>
<td>0</td>
</tr>
<tr>
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<td>7.5</td>
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<td>13.5</td>
<td>0</td>
</tr>
<tr>
<td>Sandstone</td>
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<td>8.5</td>
<td>1.5</td>
<td>20.2</td>
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</tr>
</tbody>
</table>

Figure 2: The characteristics of rock collapse with different interlayer thickness when the working face advances 100 m. (a) Thickness of interlayer strata is 60 m. (b) Thickness of interlayer strata is 35 m. (c) Thickness of interlayer strata is 15 m.

Figure 3: Typical map of roof caving with a thickness of 15 m.
Values of this working face are as follows: 
\[ \sum H_1 = \sum H_2 = 15 \text{ m}, \quad \sum H_3 = 20 \text{ m}, \quad M_1 = 10 \text{ m}, \quad N = 5 \text{ m}, \quad \gamma_1 = 25 \text{kN/m}^3, \quad \gamma = 13 \text{kN/m}^3, \quad B = 1.75 \text{ m}, \text{ and } L = 6 \text{ m}.

From this, the following can be estimated.

When the width of the interlayer strata \( H = 60 \text{ m} \), the supporting intensity of the support is \( P = 28982 \text{kN/support} \);
when the width of the interlayer strata \( H = 15 \text{ m} \), the supporting intensity of the support is \( P = 16785 \text{kN/support} \).

5.1.3. When the Interlayer Key Stratum Is Located in the Lower Part of the Strata. When the interlayer key strata are adjacent to top coal, when the advance distance of the working face is less than \( L \), the key strata form a stable
structure above it to protect the stope; at this time, there is no obvious phenomenon of mineral pressure. When the advance distance is greater than $L$, after the overall interlayer width strata are connected, the support will bear all the weight of its upper interlayer strata, gangue in goaf, and caving zone on goaf; at this point, the maximum working resistance of the support can be obtained by equation (10).

$h_2$ is the distance between the interlayer key stratum and the top of the main layer, which can be obtained from the following formula:

$$h_2 = H + N + \sum H_1 + \sum H_2 + \sum H_3. \quad (9)$$

$\beta$ is the fracture angle; the maximum working resistance of the support can be obtained from the following formula:

$$P = \frac{hL_1^2}{2L_m} + h_2L_1\gamma_1\left(\frac{L_1 + h_2 \cot \beta}{2L_m}\right) + \gamma M_1L_m + \frac{\gamma M_2 \cot \beta}{2}. \quad (10)$$

Values of this working face are as follows: $\sum H_1 = \sum H_2 = 15 \text{ m}$, $\sum H_3 = 20 \text{ m}$, $M_1 = 10 \text{ m}$, $N = 5 \text{ m}$, $h = 5 \text{ m}$, $L_1 = 15 \text{ m}$, $\gamma_1 = 25 \text{ kN/m}^3$, $\gamma = 13 \text{ kN/m}^3$, $B = 1.75 \text{ m}$, $L = 6 \text{ m}$, and $\beta = 75^\circ$.

From this, the following can be estimated.

When the width of the interlayer strata $H = 60 \text{ m}$, the supporting intensity of the support is $P = 167943 \text{ kN/support}$; when the width of the interlayer strata $H = 35 \text{ m}$, the supporting intensity of the support is $P = 113310 \text{ kN/support}$; when the width of the interlayer strata $H = 15 \text{ m}$, the supporting intensity of the support is $P = 77140 \text{ kN/support}$.

6. Conclusions

Through theoretical analysis, numerical and physical simulation experiments, and the establishment of a mechanical model, this paper analyzes the influence of the interlayer key strata of the goaf on the overburden structure, the caving characteristics of the stope coal and rock, and the influence on the working resistance of the support. The main conclusions are as follows:

1. When the thickness of strata is different, under the same working face advance distance, the collapse characteristics of strata and the structures formed after collapse are not the same. The above two are determined and controlled by the interlayer stratum.

2. In the case of high mining height, the overburden key layer will cause the “cantilever beam” structure to collapse directly because of the large amount of rotation; the weighting of the cantilever beam structure of the key layer will last longer than that of the general mining face.

3. When there is no key stratum in interlayer strata, it is normal mining of coal seam under goaf. When the interlayer strata are not through, the support mainly takes on the load imposed by the interlayer strata. The load of the interlayer strata above the working face and the caving zone above the goaf are all applied on the supports when the overall interlayer width strata are connected.
(4) When there is a key stratum in the interlayer strata, as the interlayer key stratum plays a certain supporting role on the overburden strata, the supports and the key stratum jointly take on the load imposed by the interlayer strata when the interlayer strata are not penetrated. The load of the strata and the upper goaf caving zone are borne by the stope support and the interlayer key stratum, when the overall interlayer width strata are connected.

(5) When the interlayer key strata are adjacent to top coal, when the advance distance of the working face is less than a certain distance, the key strata form a stable structure above it to protect the stope; at this time, there is no obvious phenomenon of mineral pressure. When the working face continues to advance, after the overall interlayer width strata are connected, the support will bear all the weight of its upper interlayer strata, gangue in goaf, and caving zone on goaf.

(6) In order to deal with the abnormal pressure phenomenon, the method of weakening the main coal strata in situ with water in goaf can be used, and, compared with the traditional method, the method of weakening the main control strata with water in the goaf has obvious advantages.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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