Research Article

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Mechanical analysis of basic roof fracture mechanism and feature in coal mining with partial gangue backfilling

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Abstract: Coal mining with partial gangue backfilling (CMPGB) method has the advantages of both high filling efficiency and excellent workface capacity, which breaks through the technical bottleneck of full-section backfilling mining. In order to reveal the fracture mechanism and characteristics in CMPGB workface, this paper presents a comparative analysis of the filling ratio of different filling patterns in CMPGB. A local composite elastic foundation mechanical model of basic roof in CMPGB was established using thin elastic plate theory. Then, Galerkin’s semi-analytic solution process was designed according to local composite elastic foundation characteristics. A deflection equation of the basic roof was derived, and a critical condition of the basic roof breakage was given. Based on engineering calculation example of Ji15-31010 workface of Pingdingshan No. 12 Coal Mine, the following conclusions are drawn. (1) At the basic roof of caving section, tensile-shear failure occurred in workface, cutoff position, and transition section, while compressive-shear failure occurred in the central part of the goaf. The basic roof showed a typical local “C-X” failure characteristic. (2) The value of first caving span decreased from 32.7 to 31.4 m as the elastic foundation coefficient of backfilling body increased from $70 \times 10^6$ to $120 \times 10^6$ N/m$^3$, with a decreasing amplitude of only 4.1%. The increase of density of backfilling body only changed the support structure of backfilling section and had an insignificant effect on the first caving span. (3) The value of the first caving span decreased from 59.1 to 21.68 m as the length of caving section increased from 40 to 140 m, indicating that the first caving span was mainly influenced by the length of caving section. The measured value of the first caving span of Ji15-31010 CMPGB workface was 29.8 m, which was close to the theoretical value of mechanical model.

Keywords: solid backfill mining, partial filling, caving mining, mechanical model, fracture mechanism, first caving span

1 Introduction

The traditional caving mining method leads to the deterioration of the environment and seriously restricts the ecological civilization construction of coal mining areas [1,2]. As a key green coal mining technology [3], solid backfilling mining method has been increasingly used because of its technical advantages in roof disaster prevention [4], surface subsidence control [5], waste disposal of gangue [6], and ecological environment protection [7,8]. Due to the disadvantages of low filling speed, mutual interfere between filling and mining procedures, shortage of filling material full-section backfilling coal mining normally has low efficiency and productivity [9,10]. How to improve filling efficiency has become a challenging issue in large-scale application of solid backfilling mining. Aiming at the disadvantages of full section backfilling coal mining, Professor Xu Jialin put forward “partial backfilling coal mining” technical concept [11,12], which basically refers to filling the partial region of gob instead of all area of gob. In recent years, some partial backfilling methods such as long-wall column
backfilling [13], inclined long-wall gap filling [14], short-wall strip gap mining [15] and “mining–backfilling–retaining” coordinated mining technology [16] have been developed, and some significant research results have been made in theory and practice.

A series of problems are encountered during the transition period of coal mining of Pingdingshan No. 12 Coal Mine: large volumes of gangue are taken from near full-rock protective coal seam, no accumulation space on the earth surface and failure of meeting the production capacity requirement by using conventional solid backfilling mining. Aimed at these actual difficulties and based on “partial filling” concept, Professor Zhang Jixiong put forward a new partial filling method, namely coal mining with partial gangue backfilling (hereinafter referred to as CMPGB) [17–20]. By integrating with conventional solid backfilling mining and traditional caving mining methods, CMPGB method proposed has both high filling efficiency and large production capacity and can reduce filling cost, which expands the application prospect of solid backfilling mining method.

The basic roof load is the main source of hydraulic support load [21]. Establishing the basic roof mechanical model and studying its fracture mechanism are the key of pressure control in CMPGB. Regarding the CMPGB in China, the majority of existing researches focused on mining craft and equipment coordination [22], and only a few scholars analyzed the mining pressure in CMPGB workface by numerical simulation or physical similarity simulation method [23,24]. In particular, the mechanical model analysis of breaking mechanism of the basic roof has never been reported. Studies have shown that in traditional caving mining, the periodic fracture of the basic roof occurs and results in roof weighting in workface, which presents a typical “O–X” failure characteristic [25,26]. However, in dense solid backfilling mining, dense filling material can effectively control the overlying strata movement, only local break of immediate roof occurred, without obvious periodic weighting phenomenon [27].

The CMPGB is not a simple composition of traditional caving mining and solid backfilling mining, and its strata behaviors and strata movement are neither as same as solid backfilling mining nor as traditional caving mining. Numerical simulation results showed that strata behavior of CMPGB workface presented significant non-symmetrical feature, the value of abutment stress in the backfilling section was less than caving section, and there existed a rapid transition area with strong mine pressure between backfilling section and caving section [28]. In this paper, the technical principle and filling pattern of CMPGB are introduced, and the mechanical model of the basic roof in CMPGB is established. The fracture mechanism of the basic roof is analyzed. The first caving span is calculated. Finally, the rationality and feasibility of mechanical model are verified through an engineering case study. The purpose of this paper is to provide a reference for engineering design and mine pressure control of CMPGB.

2 Technical principle and filling pattern of CMPGB

2.1 Technical principle of CMPGB

In order to satisfy the requirement of filling efficiency and production capacity, CMPGB method integrates the traditional caving mining with solid backfilling mining. By adding a caving section to the conventional solid backfilling workface, the length of both backfilling section and caving section can reach 100 m each, and the entire CMPGB workface length can be more than 200 m. Through strict equipment matching, backfilling section and caving section can share a set of equipment to complete the coal mining process in front of the CMPGB workface. In the back of backfilling section, the waste gangue is filled into goaf of backfilling section by using a series of filling equipment such as filling hydraulic support, bottom-dump scraper conveyor, and punning apparatus. The CMPGB workface not only reserves the advantage of high filling capacity but also has improved productivity and efficiency, so that the multiple technical objectives of filling efficiency, productivity, and waste gangue disposal can be realized. The technical principle and layout of BCCFM workface are illustrated in Figure 1.

The advantages and disadvantages of the CMPGB:

1. The length of conventional backfilling workface is usually no more than 120 m considering the limited length of bottom-dump scraper conveyor and filling efficiency. However, the total designed length of CMPGB workface can exceed 200 m, which can meet the single-face capacity requirement. Moreover, CMPGB work face has a decreased number of workface layouts, lower frequency of workface removing, and decreased tunnel drivage ratio compared with conventional backfilling workface.

2. Continuous mechanized filling is realized in the backfilling section, and the designed length of the backfilling section is more than 100 m, which can meet the large waste gangue consumption.
(3) In CMPGB workface, filling process and mining process are carried out simultaneously, without interfering with each other, so that improved filling efficiency can be achieved while satisfying the requirement of filling efficiency and production capacity at the meantime.

However, compared with traditional caving method and conventional backfilling mining, CMPGB requires larger quantity of hydraulic supports and operating personnel, which limits its application to a certain extent. The initial investment of CMPGB workface will be large if the coal mines have no idle hydraulic supports.

### 2.2 The classification of filling pattern and filling ratio

According to the requirement of solid waste treatment capacity and ground control, different filling patterns can be selected for CMPGB workface, as shown in Figure 2, where the filling ratio varies from one filling pattern to another. The difference in filling ratio was mainly due to whether the punning apparatus was installed at filling hydraulic support as well as due to its punning process. Taking Pingdingshan No. 12 Coal Mine as an example, filling ratio of three filling patterns of each workface is analyzed, as shown in Figure 2.

Pattern (a): In this pattern, filling body falls by self-weight. The solid waste treatment capacity is small under such pattern. Punning apparatus is not installed at filling hydraulic support. The goaf filling material piles up to the bottom of bottom-dump scraper conveyor by self-weight, and the filling material cannot attach the immediate roof. Such filling pattern is characterized by small filling capacity, low filling ratio, short filling time, and high filling efficiency.

Pattern (b): Pattern (b) is also known as roof-contacted filling pattern. Aided by punning apparatus, the gangue filling materials can attach the immediate roof. Such filling pattern has improved solid waste treatment capacity but in longer filling time. However, repeated punning of the filling material is not required under such filling pattern, because filling ratio is not the top priority of this filling pattern. Compared with pattern (a), pattern (b) has a better balance between filling capacity and filling efficiency although there is a decline in filling efficiency.

Pattern (c): Pattern (c) is also called dense filling. In order to control the subsidence of overlying strata, the repeated punning of gangue filling materials is conducted to make the filling materials attach the immediate roof, thus achieving a dense state [29]. In general, the filling efficiency of pattern (c) is low, but the filling ratio is high.

The filling efficiency can be measured by using filling efficiency coefficient \( \varepsilon \). The efficiency coefficient \( \varepsilon \) can be calculated as follows:
where \( t_c (h) \) represents the filling time of each working cycle of workface and \( t_m (h) \) represents the coal cutting time of each working cycle of workface.

3 Local composite elastic foundation mechanical model of CMPGB basic roof

Establishing an appropriate mechanical model, figuring out the failure mechanism of the basic roof, and calculating the first caving span of the basic roof are important for prevention and control of strata behaviors in CMPGB mining. The control effect of overlying strata subsidence in solid backfilling mining is determined by dense state of gangue materials, and the dense state of gangue materials can be expressed using filling ratio [30]. The premise of establishing mechanical model is to distinguish the filling state in CMPGB workface.

Research has shown that loose gangue materials cannot contact the immediate roof, and the unbroken roof is not well supported when gangue materials are in a low filling ratio (as shown in Figure 2(a)) [31]. The mechanical calculation of roof failure characteristic can be conducted by referring to the traditional caving mining method. The mechanical model of the basic roof established in this paper is mainly suitable for the filling states as shown in Figure 2(b and c).

3.1 Hypothesis of mechanical model

(1) Elastic thin plate hypothesis. If the conditions of equation (2) are satisfied, a plate can be regarded as an elastic thin plate [32].

\[
\left( \frac{1}{100} \sim \frac{1}{80} \right) \leq \frac{t}{L} \leq \left( \frac{1}{8} \sim \frac{1}{5} \right)
\]  

(2) Composite elastic foundation hypothesis.

As shown in Figure 3, the immediate roof blocks were in close contact with gangue filling body in goaf of backfilling section. As the CMPGB workface advanced, the immediate roof blocks and gangue filling body were continuously compacted, so the immediate roof blocks...
\[ \sigma_i = k_i \frac{\Delta h_i}{h_i} \Rightarrow \Delta h_i = \frac{\sigma_i h_i}{k_i} \]  
\[ k_d = \frac{k_1 k_2}{h_1 k_3 + h_2 k_4} \]  

**3.2 Local composite elastic foundation mechanical model**

The composite elastic foundation mechanical model of the basic roof was established, as shown in Figure 4. The intersection point of backfilling section and caving section in cutoff is defined as coordinate origin. The x-axis represents tendency direction of workface and y-axis represents advance direction. The boundary condition around the workface can be regarded as simply supported boundary where \( a \) is the length of backfilling section, \( b \) is the length of caving section, and \( C \) is the advance distance. The composite elastic foundation counterforce \( P \) can be expressed as follows:

\[ P = k_d w \]  

**3.3 Design of Galerkin’s semi-analytical solution process**

The numerical simulation results showed that strata movement of caving section was much greater than backfilling section in CMPGB workface. The deformation of overburden strata showed a typical “spoon” shaped asymmetrical pattern [23]. According to the normal plate-type solution method, it is hard to find a analytical trial function satisfying the condition of asymmetrical feature, boundary conditions, and precision requirements simultaneously.
Based on the area rectangular feature of the basic roof in CMPGB workface, Galerkin's semi-analytical solution process was designed in this paper, as shown in Figure 5.

3.4 Calculation of basic roof deflection

3.4.1 Governing differential equation

Firstly, the basic roof plate is divided into two sections, backfilling section and caving section, and both sections share a common boundary. The governing differential equation of each section is shown as follows:

\[
\begin{align*}
D \cdot \nabla^4 w_1(x, y) + k_d w_1(x, y) &= q(x, y) \\
D \cdot \nabla^4 w_2(x, y) &= q(x, y)
\end{align*}
\]  

where \( w_1(x,y) \) (m) is the deflection of basic roof in backfilling section, \( w_2(x,y) \) (m) is the deflection of basic roof in caving section, \( q(x,y) \) (MPa) is the equivalent load of basic roof, \( D \) (N/m) is the bending stiffness of basic roof, \( h \) (m) is the thickness of basic roof, \( E \) is the elasticity modulus of basic roof, and \( \mu \) is Poisson’s ratio of basic roof.

\[ D = \frac{Eh^3}{12(1 - \mu^2)} \]  

The constructed deflection function \( Z_1 \) of backfilling section contains an unknown parameter \( A_i \), which can be expressed as follows:

\[ Z_i(x, y; A_i) = \sin(A_i(x + a)) \sin(\pi y/c) \]  

It can be seen from the test that the function \( Z_1 \) satisfies the boundary conditions of equation (12).

The boundary of caving section is \( 0 \leq x \leq b \), \( 0 \leq y \leq c \). The upside, downside, and right-side
boundary conditions of caving section are simply supported. The deflection function of caving section conforms to equation (14). The boundary conditions of caving section satisfy equation (15).

\[
w_2(x, y) = S_2z_2(x, y; A_2), \quad 0 \leq x \leq b, \quad 0 \leq y \leq c \quad (14)
\]

\[
\begin{align*}
&w_{2x} = 0 \\
&w_{2y} = 0, c = 0 \\
&\frac{\partial w_2}{\partial x} = 0 \quad x = b \\
&\frac{\partial w_2}{\partial y} = 0 \quad y = 0, c
\end{align*} \quad (15)
\]

The constructed deflection function \( Z_2 \) of backfilling contains an unknown parameter \( A_2 \), which can be expressed as follows:

\[
z_2(x, y; A_2) = \sin(A_2(b-x)) \sin(\pi y/c) \quad (16)
\]

It can be seen from the test that the function \( Z_2 \) satisfies the conditions of equation (15).

### 3.4.3 The solution of deflection function of each section

Galerkin’s method was used to solve the deflection function of backfilling section and caving section. Galerkin’s method assumes that the value of virtual displacement work is zero [33]. The expression is shown as follows:

\[
\iint \left[ \sum \int S_i z_i(x, y; A_i) + k_d S \int z_i(x, y; A_i) - q \right] \cdot z_i(x, y; A_i) \, dx \, dy = 0
\]

\[
(17)
\]
For the area of backfilling section, there is a following expression:

$$[M_i] \times S_i = [N_i]$$  \hspace{1cm} (18)

where $M_i$ and $N_i$ satisfy equation (19)

$$[M_i] = \int_0^c \int_0^a \left( D \nabla^4 z(x, y; A_i) \right) dx \, dy \\
+ k_d \int_0^c \int_0^a z(x, y; A_i) d_x \, d_y$$

$$[N_i] = \int_0^c \int_0^a q z(x, y; A_i) d_x \, d_y$$  \hspace{1cm} (19)

where $\nabla^4 z(x, y; A_i)$ is calculated by referring to equation (20) [34]:

$$\nabla^4 w(x, y) = \left( \frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right)$$  \hspace{1cm} (20)

By combing equations (18)–(20), equation (21) is obtained:

$$S_i = \left\{ \begin{array}{c}
\int_0^c \int_0^a \left( D \nabla^4 \left( \sin(A(x + a)) \sin \left( \frac{ny}{c} \right) \right) \right. \\
\left. + k_d \left( \sin(A(x + a)) \sin \left( \frac{ny}{c} \right) \right) \right) dx \, dy \\
\left. \times \left( \frac{\partial (\sin(A(x + a)) \sin \left( \frac{ny}{c} \right))}{\partial x} \right) \right) \right. \\
\left. \times \left( \frac{\partial (\sin(A(x + a)) \sin \left( \frac{ny}{c} \right))}{\partial y} \right) \right) \right. \\
\left. \times \int_0^c \int_0^a q \left( \sin(A(x + a)) \sin \left( \frac{ny}{c} \right) \right) dx \, dy \right\}$$  \hspace{1cm} (21)

By substituting equation (21) into equation (11), the expression of $w(x, y)$ can be obtained as follows:

$$w(x, y) = \left( \frac{\partial^2 w}{\partial x^2} \right) + \left( \frac{\partial^2 w}{\partial y^2} \right) \left. \right|_{x=0}^{x=a}$$

4.3.4 The solution of unknown parameters $A_1$ and $A_2$

For the expression of $w_1(x, y)$ and $w_2(x, y)$ containing unknown parameters $A_1$ and $A_2$, the unknown parameters $A_1$ and $A_2$ need to be solved. By analyzing the boundary conditions of mechanical model, it can be found that the backfilling section and the caving section share a common boundary and satisfy the continuity condition of equation (25) as follows:

$$\frac{\partial^3 w_1}{\partial x^3} + (2 - \mu) \frac{\partial^2 w_1}{\partial x^2 \partial y} \left|_{x=0}^{x=a} \right. = \frac{\partial^2 w_2}{\partial y^2} \left|_{x=0}^{x=a} \right. = \frac{\partial^2 w_2}{\partial x \partial y} \left|_{x=0}^{x=a} \right. \hspace{1cm} (25)$$

The values of unknown parameters $A_1$ and $A_2$ can be calculated by using equation (25), based on which the expression of $w_1(x, y)$ and $w_2(x, y)$ without unknown parameters can be determined. The solution of specific equation expression was extremely complex, but after the engineering parameters were given, the numerical solution will be more easy with the help of Maple software.
4 Fracturing mechanism and characteristic of basic roof

4.1 Critical conditions for instability of basic roof

The normal stress and the shear stress of thin plate model satisfy equation (26)

\[
\begin{align*}
\sigma_x &= -\frac{E}{1-\mu^2} \left( \frac{\partial^2 W}{\partial x^2} + \mu \frac{\partial^2 W}{\partial y^2} \right) \\
\sigma_y &= -\frac{E}{1-\mu^2} \left( \frac{\partial^2 W}{\partial y^2} + \mu \frac{\partial^2 W}{\partial x^2} \right) \\
\tau_{xy} &= -\frac{E}{1+\mu^2} \frac{\partial^2 W}{\partial y \partial x}
\end{align*}
\]

where \( E \) is the elasticity modulus of basic roof, GPa.

The relationship between principal stress, maximum shear stress, and normal stress satisfies equation (27).

\[
\begin{align*}
\frac{\sigma_{\max}}{\sigma_{\min}} &= \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left( \frac{\sigma_x - \sigma_y}{2} \right)^2 + \tau_{xy}^2} \\
\tau_{\max} &= \frac{\sigma_{\max} - \sigma_{\min}}{2}
\end{align*}
\]

Since the rocks are brittle material, the tensile strength is much less than compressive strength. According to the first strength theory [35], the basic roof was fractured when the maximum principal stress \( (\sigma_{\max}) \) was greater than the ultimate tensile strength \((\sigma)\). The breakpoint of the basic roof appeared in the position with maximum principal stress. The criterion for instability of the basic roof is as follows:

\[
\sigma_{\max} \geq [\sigma]
\]

4.2 Engineering case analysis and fracture mechanism of basic roof

Taking Ji15-31010 CMPGB workface of Pingdingshan No. 12 Coal Mine as an example, all the parameters were determined except the value of \( C \). The engineering parameters are summarized in Table 1. According to equations (22) and (23), once the value of \( C \) is determined, the value of principal stress can be calculated.

In order to analyze the distribution principal stress and fracturing characteristic of the basic roof, the value of \( C \) can be defined as 30 m and the value of principal stress can also be calculated. The principal stress distribution of Ji15-31010 CMPGB workface is shown in Figure 6.

Figure 6 shows the principal stress distribution of the basic roof at Ji15-31010 CMPGB workface, which presents as a typical symmetrical pattern. The roof stress of backfilling section was obviously higher than that of caving sections, and the peak value of stress was occurred from transition section to caving section. There was tensile stress in workface and cutoff position, of which the peak value was about 8 MPa. The central part of the goaf bore the compressive stress, of which the peak value was about 26 MPa. The maximum principal stress increased gradually as the CMPGB workface advanced. The basic roof would fracture when the maximum principal stress was greater than the ultimate tensile strength or compressive strength. In general, tensile failure occurs in position of workface and cutoff, or compression failure in the central part of the goaf.

The researches have shown that the basic roof is usually in three-dimensional pressure state, and the fracture of overlying strata is the result of joint action of tensile failure and shear-compression failure [36]. In order to comprehensively analyze the fracture mechanism of the basic roof, the shear stress distribution of the basic roof was determined, as shown in Figure 7.

Along the advance direction of workface, the peak value of shear stress occurred in the workface, cutoff area, and central part of the goaf position, while along the tendency direction of workface, the peak value of shear stress occurred from transition section to caving section, which was about 9.0 MPa. The maximum shear stress increased gradually as the CMPGB workface advanced. The peak area of shear stress in the basic roof exhibited shear failure when the maximum shear stress was greater than the ultimate shear strength.

Considering the combined action of stretch, compress, and shear effect in the basic roof, it can be concluded that the tensile-shear compound failure of the basic roof occurred in workface, cutoff, and transition section, while compressive-shear compound failure occurred in the central part of the goaf. To sum up, the fracturing of the basic roof showed a typical local “C–X” fracturing feature, as shown in Figure 8.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( a )</th>
<th>( b )</th>
<th>( h )</th>
<th>( H )</th>
<th>( q )</th>
<th>( \mu )</th>
<th>( E )</th>
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<td>MPa</td>
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<td>GPa</td>
</tr>
</tbody>
</table>
4.3 First caving span of basic roof

The principal stress distribution of the basic roof was determined primarily by using the value of $C$ when the specific engineering parameters were determined. For each given value of $C$, the maximum value of principal stress ($\sigma_{\text{max}}$) can be calculated. Then, the fracturing state of the basic roof was judged by comparing the values of $\sigma_{\text{max}}$ and $[\sigma]$. Lastly, the value of the first caving span $L_f$ could be obtained by iterating the value of $C$. The calculation step of the first caving span of the basic roof is shown in Figure 9.

The analysis reveals that the main affecting factors on $L_f$ are $S_d$ (coefficient of composite elastic foundation), $a$ (length of backfilling section), and $b$ (length of caving section).

The value of $S_d$ depends on $k_1$ and $k_2$, and the value of $k_1$ can be obtained by compaction experiment. The value of $b$ is equal to the difference between $L$ and $a$, and the value of $L$ can be determined by mine production capacity. Therefore, it can be concluded that the main affecting factors on $L_f$ are $k_2$ and $b$.

The density state of backfilling body is normally characterized by elastic foundation coefficient. The relationship between the $k_c$ and $k_2$ satisfied equation (29). The relationship between $L_f$ and $k_c$, $L_f$ and $b$ were shown in Figures 10 and 11.

$$k_c = K_2/h_2$$  (29)
From Figures 9 and 10, the following conclusions can be drawn.

As shown in Figure 10, as the value of $k_c$ increased from $70 \times 10^6$ N/m$^3$ to $120 \times 10^6$ N/m$^3$, the value of $L_t$ decreased from 32.7 m to 31.4 m, with a decreasing amplitude of only 4.1%. This is mainly due to the breakpoint of the basic roof appeared in the position of caving section, and increasing the density of backfilling body (i.e., increasing the value of $k_c$) only changed the support structure of backfilling section but did not change the caving section. Therefore, it can be concluded that the elastic foundation coefficient of backfilling body has little effect on the first caving span.

As shown in Figure 11, as the value of $b$ increased from 40 to 140 m, the value of $L_t$ decreased from 59.1 to 21.68 m, with a decreasing amplitude of up to 63.3%, indicating that the value of $b$ has a significant effect on the first caving span. It can predict the first caving span and control the strata behaviors according to the relationship between $L_t$ and $b$ in CMPGB mining.

5 Engineering practice

5.1 Project profile of the Ji15-31010 workface

The industrial test workface was Ji15-31010 workface of Pingdingshan No. 12 Coal Mine. The average thickness of Ji15 coal seam was 3.2 m and the bury depth was 1,005–1,166 m. The average dip angle of the coal seam was 5°. The Ji15 coal seams suffered the potential risk of coal and gas outbursts. According to the concerned rules prescribed in “Safety Regulations of Coal Mine,” the Ji15 coal seams must adopt protective layer mining. Considering the engineering situation of the Ji15-31010 workface, the near full-rock protective coal seam (Ji14-31010 workface) shall be mined first. The Ji14-31010 workface was consisted of 1.4 m siltstone and 0.5 m coal seam, and its excavation height was 1.9 m.

The main filling target of Ji15-31010 workface was the waste gangue consumption of Ji14-31010 workface. To
realize the balance between filling efficiency and filling capacity, the roof-contacted filling pattern was selected for Ji15-31010 workface. The advancing length of the workface was 929 m and the length of the workface was 218 m. The length of the backfilling section was 120 m and the length of caving section was 98 m. The gradation of gangue material is shown in Table 2. The value of $k_c$ can be calculated to be approximately $69 \times 10^6$ N/m³. The system layout of the Ji15-31010 workface is shown in Figure 12.

5.2 Field measurement of first caving span

In order to monitor the first caving span of CMPGB workface, the hydraulic support working resistance monitors were arranged with hydraulic support No. 1, 14, 27, 40, 53, 65, 66, 67, 68, 69, 70, 81, 94, 107, 120, 133, and 145, respectively. Among them, there were seven 1-channel working resistance monitors (caving section) and ten 2-channel working resistance monitors (backfilling section). These monitors were responsible for dynamically monitoring the working resistance of hydraulic supports. In addition, underground data collectors were used to save and collect the monitoring data. The layout of monitor equipment in Ji15-31010 workface is as shown in Figure 13.

Monitoring data were collected continuously from the resistance monitor (4# and 14#) when the workface advanced from the cutoff to 87 m. In order to compare and analyze the first caving span in the advance process, a graph is plotted (Figure 14).

From Figure 13, the following conclusions can be drawn.

1. The maximum working resistance of filling hydraulic support (14# resistance monitor) was 31.81 MPa, the minimum working resistance was 19.50 MPa, and the average working resistance was 27.12 MPa. As Ji15-31010 workface advanced to 87 m, the working resistance of filling hydraulic support did not exceed the rated resistance (32.5 MPa) and the safety valves of hydraulic support remained closed. These results show that gangue filling body reduced the mining pressure and the basic roof in backfilling section was broken. The strata pressure behavior and strata movement in backfilling section were moderate.

2. The maximum working resistance of traditional hydraulic support (4# resistance monitor) was 43.56 MPa, the minimum working resistance was 26.96 MPa, and the average working resistance was 38.12 MPa. The safety valves of hydraulic support were opened as the workface advanced to 29.8 m. This indicates that the basic roof in caving section was fractured and the first caving span of Ji15-31010 workface was 29.8 m. The field measurement value of the first caving span was close to theoretical value of mechanical model, which verifies the reliability of mechanical model.
6 Conclusions

(1) This paper briefly introduced the technical principle, investigated the layout of CMPGB workface, and analyzed the filling ratio of three different filling patterns in CMPGB workface.

(2) In this study, the local composite elastic foundation mechanical model of the basic roof in CMPGB was established, and Galerkin's semi-analytic solution process was designed. The deflection equation of the basic roof was derived and the critical condition for the basic roof breakage was given.

(3) Based on an engineering example of Ji15-31010 CMPGB workface of Pingdingshan No. 12 Coal Mine, the mechanical model analysis showed that the tensile-shear compound failure of the basic roof of caving section occurred in workface, cutoff region, and transition section. In contrast, the compressive-shear compound failure occurred in the central part of the goaf. The fracturing of the basic roof of CMPGB
workface showed a typical local “C–X” shaped pattern.

(4) The influence factors of the first caving span in CMPGB workface were analyzed. The results illustrate that the first caving span was mainly influenced by the length of the caving section, and the elastic foundation coefficient of backfilling body had little influence on the first caving span.

(5) The measured value of the first caving span of Ji15-31010 CMPGB workface was 29.8 m and the theoretical value of the mechanical model was 32.7 m. The measured value was close to the theoretical value, which verifies the reliability of mechanical models.

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