Research Article

Analysis of Influencing Factors of Roadway Stability and Adaptability Criterion for Gob-Side Pre-Backfill Driving

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To reduce the loss of coal pillars between two adjacent longwall working faces, gob-side pre-back/fill driving (GPD) procedure is suggested. This paper introduces in detail the principles and characteristics of the GPD procedure. Based on the arc triangle block (ATB) formed by the fractures of the main roof, the Winkel Elastic Foundation Beam model of the relevant rock strata structure is established and analyzed. The influence of the different breaking positions of the ATB of the main roof, the different geological conditions of the surrounding rock, and the parameters of the back/fill body on the stability of the back/fill body are analyzed. Also, the adaptability of the GPD procedure under any geological conditions is analyzed. The results show that the sensitivity of the aforementioned factors on the stability of the back/fill from high to low is as follows: the thickness of the immediate roof, the elastic modulus of the main roof, the elastic modulus of the immediate roof, the thickness of the main roof, the thickness of the coal seam, the elastic modulus of the coal seam, the width of the back/fill body, the buried depth, and the elastic modulus of the back/fill body. According to the geological conditions of the Changcun Mine, it can be determined that if the fracture location of ATB of the main roof from the back/fill is less than 5 m, the GPD procedure cannot be adopted. For this situation, the required strength of the back/fill is high; the back/fill is difficult to maintain, and it is prone to fracture failure. The GPD procedure cannot be used for all geological conditions. Before the GPD procedure is implemented, a pre-judgment must be made not to cause unnecessary losses.

1. Introduction

Coal accounts for more than 58% of China’s primary energy consumption category for a long time. Realizing efficient and intensive coal production, improving the coal recovery rate, and the research on the law of ground pressure behavior and rock strata movement and the feature extraction technology of coal gangue image are the hot issues in the development of the world’s coal industry [1–4].

The longwall mining method has the characteristics of high efficiency and high recovery rate and has been widely used in coal mining [5, 6]. However, this coal mining method requires a large number of supporting coal pillars and then abandoning the coal pillars [7]. Therefore, for thick coal seams, the use of the longwall mining method results in a significant waste of resources [8]. With the rapid development of coal pillarless roadway technology, the gob-side entry retaining (GER) and gob-side entry driving (GED) procedures have gradually become new technology and effective ways to improve the resource recovery rate and extend the service lives of the mines.

As shown in Figure 1(a), in the GER procedure a back/fill wall is constructed along the edge of the goaf behind the work face while the work face is advanced. In this way, the gob-side entry is maintained as the tailgate of the next adjacent work face, thereby achieving pillarless mining technology [9]. In the GED procedure (Figure 1(b)) a narrow coal pillar (5–7 m) is left at the edge of the abandoned entry and the stable goaf, and a gob-side entry is driven, as the roadway of the next adjacent work face. In the process of the GED roadway excavation, the narrow coal pillar becomes a rib with the same function as the back/fill wall in the GER procedure [10]. This method greatly reduces the width of the supporting coal pillar between the work faces.

The development of the GER procedure can be summarized in three parts. Firstly, for the stability analysis of the
surrounding rock of the roadway during the procedures of the GER, many scholars have understood the rock mass movement mechanism of the GER technology. The roof movement is divided into three periods, namely the early activities, transitional activities, and late activities [12, 13]. Due to the overburden movement of the stope, the transfer mechanism of the roof in the wedge-shaped area of the goaf is illustrated, which further strengthens the structural control principle of the roadway retention along the goaf [14]. The floor heave is also an inevitable problem in the mining process of the roadway. The floor heave is mainly caused by the bearing capacity failure and the instability of expansion [15]. Yi et al. [16, 17] studied the evolution process of coal mine engineering geological hazards and risks, and proposed effective countermeasures. Gong et al. [18] studied the mechanical characteristics of the rock mass floor and proposed a theoretical mechanical model for the backfill of the goaf, and gave a comprehensive treatment plan to effectively control the floor heave [19]. New quick-setting high-water backfill materials and high-strength and low-cost paste backfill materials have been developed for the backfill wall of the GER procedure [20–23]. Compared with the traditional gangue bags and concrete blocks, these new materials have greater resistance, higher backfill efficiency, and better sealing effect [24–26]. It is difficult to maintain the stability of the roadway due to traditional wood supports and I-beams. Therefore, many scholars have proposed new support systems. For example, Kang et al. [27] and Kang et al. [28], and other scholars proposed the theory of high pre-stress and strong bolt support. By the strengthened bolts and cables, the deformation of the surrounding rock of the roadway has been effectively controlled [29–31].

Compared with the GER procedure, the rapid development of the GED procedure is based on the surrounding rock and the narrow coal pillar control technology [32, 33]. Determination of a reasonable coal pillar size is particularly important for the GED procedure. Bai [34, 35] explained the control principle of surrounding rock along the gob in the fully mechanized caving face by investigating the mining stress. Via theoretical analysis and numerical calculations, it was concluded that the use of high-strength bolts can increase the bearing capacity of the surrounding rock of the narrow coal pillar roadway, and effectively maintain the stability of the roadway. By investigating the reasonable location and time of construction of narrow coal pillars, the stability control technology of coal pillars under special geological conditions has been studied, and the failure mechanism of narrow coal pillars has been determined through field measurements and numerical calculations [33, 36, 37]. In addition, 6 types of failure and two stages of deformation have been suggested for narrow coal pillars [33, 36, 37]. Xi et al. [38] used field measurements and numerical simulations to determine the coal pillar width to be 5.0–7.2 m.
Although the GER and GED procedures have significantly solved the problem of waste of coal resources, still some shortcomings exist. The application of the GER procedure leads to two mining impacts. The maintenance of the roadway is relatively difficult, and the cost of roadway maintenance increases accordingly, especially in the presence of thick coal seams. While the GED procedure experiences the impact of mining only once, and the roadway is easier to maintain; however, it is still necessary to leave a narrow coal pillar of 5–7 m to maintain the stability of the roadway. In the case of thick coal seams, the GED procedure leads to a permanent loss of 2% to 3% of coal resources.

Due to the above shortcomings, in China, scholars have proposed the pre-backfill and pillar-free roadway driving technology for the construction and operation of the roadway (referred to as the “gob-side pre-backfill driving (GPD) procedure”) [39–42]. In this technique, the backfill wall replaces the coal pillars that should be retained in the GED procedure.

This paper first introduces in detail the principles and characteristics of the GPD procedure. After that, it explains the formation of the so-called Arc Triangle Block (ATB) [43] resulting from the fractures that occur in the main roof due to the open space created below the roof from mining activities. Based on the ATB [43], the Winkel Elastic Foundation Beam model for the relevant rock strata structure is introduced and analyzed. The influence of the different breaking positions of the ATB of the main roof, the different geological conditions of the surrounding rock, and the parameters of the backfill body on the stability of the backfill body are analyzed, and the adaptability of the GPD under any geological condition is discussed.

2. The Principles and Characteristics of the GPD Procedure

2.1. Steps of the GPD Procedure. As shown in Figure 2, the technical steps of the GPD procedure are as follows:

(i) Large section entry driving; that is, the expanded width entry of the current panel includes the width needed for the backfill body (Figure 2(a)).

(ii) The backfill wall is constructed in the entry as shown in Figure 2(b). Its height is consistent with the mining height, and the width and strength should meet the stability of the current panel mining stage, the gob-side entry driving stage of the next adjacent panel, and the mining stage of the next adjacent panel.

(iii) The current panel retreating (Figure 2(c)).

(iv) Upon reaching stable overburden condition, the entry of the adjacent panel is excavated along the backfill (Figure 2(d)).

2.2. Technical Characteristics of the GPD Procedure

(1) Compared to the GER procedure, the roadways of GED and GPD procedures are only affected by one-time mining and have a shorter service life, which reduces the difficulty and cost of roadway maintenance. However, compared to the GER procedure, GED and GPD procedures need excavation of one additional roadway, which increases the tunneling work.

(2) Compared to the GER procedure, the backfill of the GPD procedure requires a smaller width, resulting in width to height ratio of less than 0.5 or even smaller, which effectively reduces the backfill cost.

(3) The backfill body of the GPD procedure is constructed before the current panel is mined. Compared with the GER procedure, the initial strength requirement of the material of the GPD procedure is low; that is, the high strength is not required in the initial stage of construction, and only the final strength needs to meet the design requirement. In addition, the construction and mining work of the GPD procedure is not carried out at the same time, but are independent of each other, and do not affect mine production.

(4) For the GPD procedure, the strength and width of the backfill body can be designed to achieve the needed stability. While for the GED procedure, the narrow coal pillar can only be strengthened by rock bolts, cables, or grouting to maintain its stability.

3. Formation of the ATB Model of the Main Roof

Figure 3 shows a typical 3-D model of the GPD procedure of the longwall mining during the mining of the current panel. In the mining process of the current panel, the overlying strata of the goaf cave in, and the tensile bending stresses of the main roof that exceeds the tensile strength result in forming a fracture system perpendicular to each other to form "O" fractures (shown in blue in Figure 4(a)) and then another fracture system non-perpendicular to the "O" fractures to form the “X” fractures (shown in red in Figure 4(a)) in the main roof. The combination of these two fracture systems creates the so-called “O-X” fracture system (see Figure 4(a)). With the advance of the work face, the voussoir beam structure is formed perpendicular to the mining direction after the periodic failure of the main roof parallel and perpendicular to the work face to form the arc triangle block (ATB), as shown in Figure 4. The locations of the fractures, movement state, and stability of the ATB directly affect the stress and deformation of the pre-constructed backfill and the coal mass below.

According to the breaking and moving characteristics of the main roof, illustrated through the plan view and the sectional views of the ATB in Figure 4, the ATB structure of the main roof is simplified as follows:

(1) After the current panel is mined, the main roof generally fractures on the left side of the backfill body, and after the fracture, the ATB is formed (Figures 4(a) and 4(b)), and the fracture line is used as the axis for downward rotation (Figure 4(b)).
(2) Because the work face’s periodic weighting (The roof pressure phenomena caused by the periodic caving of the main roof in the fractured zone is called periodic weighting.) interval is the same, and the fracture characteristics of the main roof are the same, the ATB is simplified as an isosceles arc triangle (Figure 4(a)).

(3) The ATB acts on the underlying immediate roof, solid coal, and backfill body with a given deformation (i.e. the amount of deformation of ATB after it reaches the stable state.).

(4) During the mining of the next adjacent panel, the immediate roof and the coal seam under block A are under stress to sink, and block B (ATB) is expected to rotate to sink [44]. The structural parameters of the ATB in the main roof mainly include: $b$, the fracture length of the main roof along the mining direction (i.e., the work face’s periodic weighting interval) (Figures 4(a) and 4(c)); $l$, the fracture span length in the direction perpendicular to the mining direction (Figures 4(a) and 4(b)), and $X_0$, the distance to the fracture position of the ATB from the backfill wall (Figure 4(a)).
3.1. Determination of $b$. The value of $b$ can be obtained by field observations or theoretical calculations. The following formula can be used to calculate $b$ [45]:

$$b = h \sqrt{\frac{R_t}{2q}}$$

where $h$ is the thickness of the main roof, $R_t$ is the uniaxial tensile strength of the main roof in MPa and $q$ is the load per unit area on the main roof in MPa.

For the top coal caving mining method, $b$ is generally about 10 m ~ 20 m.

3.2. Determination of $l$. According to the yield line analysis method of a plate, it is considered that $l$ is related to the work face length $s$ and the work face's periodic weighting interval $b$. The length of $l$ can be calculated by the following formula [43]:

$$l = \frac{2b}{17} \left[ \sqrt{\frac{b^2}{s^2} + 102} - \frac{b}{s} \right].$$

When $s/b > 6$, $l$ is equal to $b$. For the longwall work face, $l$ is generally about 10~20 m, and $s$ is between 150 m and 300 m. Therefore, the $s/l$ is about 7~30. That means $l$ is approximately equal to $b$.

3.3. The Distance to the Fracture Position of the Main Roof from the Backfill Wall ($X_0$). The fracture position of the main roof above the solid coal plays a key role in the GPD procedure and the stability of the backfill body in the fully mechanized top coal caving technology. The fracture position of the main roof affects the stress distribution on the backfill body and the coal and rock mass next to the goaf, the required strength and width of the backfill body in the roadway, and the integrity of the surrounding rock of the pillarless roadway. It even determines whether a certain mining geological condition can adopt the method of the GPD procedure.

Many factors that affect the fracture location of the main roof, including the buried depth, the in-situ stress state of the original rock, the width and elastic modulus of the backfill body, the thickness and elastic modulus of the coal seam, the thickness and elastic modulus of the immediate roof, the thickness and elastic modulus of the main roof, etc., are studied in detail below.

4. Analysis of the ATB Model of the Main Roof

4.1. Mechanical Model of ATB. According to the characteristics of the ATB structure, it is simplified into a model combining two elastic beams with foundations, and one section of a cantilever beam. As shown in Figures 5 and 6, section $a$ is an elastic beam with the immediate roof and coal seam as the foundation. Section $c$ is an elastic beam with the backfill body, top coal, and immediate roof as the foundation (i.e. $X_0 = a + c$). Section $d$ is a cantilever beam with goaf below that. The calculation of the two sections of the elastic beams with foundations is solved by the Winkler elastic foundation beam model [43]. According to the previous simplification, the ATB acts on the underlying immediate roof, solid coal, and the backfill below that with a certain deformation (i.e. the amount of deformation of ATB after it reaches the stable state.). The displacement at the right end of the cantilever beam is equal to the given deformation, that is when the ATB just touches the gangue. The model is assumed to be in equilibrium under that situation.

Under the action of the overburden load, the beam exerts certain stress on the foundation, as follows:
Immediate roof
Coal seam
Arc triangle
Block (ATB)

Figure 5: Sectional view of the ATB structure of the main roof (before the ATB rotation).

σ = ky,  \hspace{1cm} (3)

where σ is the stress on the foundation in MPa; k is the elastic coefficient of the foundation in N/m^3; y is the vertical displacement of the beam in m.

At the same time, under the action of the beam, the foundation surface is subjected to a certain pressure. The foundation generates an upward reaction force on the beam, which is equal to p, as follows:

\[ p = ab, \hspace{1cm} (4) \]

where b is the fracture length of the main roof in the direction of mining.

Under the action of the overburden load and the reaction force of the foundation, the right side of the beam rotates, and the beam bends in the horizontal plane. Under the external force, the elastic beam needs to satisfy the equilibrium differential equation given as follows:

\[ EI \frac{d^4y}{dx^4} = q(x) - p(x), \hspace{1cm} (5) \]

where \( q(x) \) is the linear load of the overlying strata in the direction perpendicular to the mining direction on the ATB in N/m, \( p(x) \) is the reaction force per unit length in the direction perpendicular to the mining direction on the ATB from the foundation in N/m, \( E \) is the elastic modulus of the ATB in GPa, and \( I \) is the moment of inertia of the ATB in m^4.

The vertical displacement of the right end of the two sections of the elastic foundation beam and the cantilever beam can be obtained by solving this differential equation using the boundary conditions.

4.1.1. Vertical Displacement of Elastic Foundation in Section a. The elastic foundation of section a is the immediate roof and the coal seam. Because the ATB is a variable section beam with gradually decreasing width, its bending interface coefficient \( I(x) \) is a linear function of \( x \) as given in:

\[ I(x) = \frac{b_0 h^3}{12} \left( 1 - \frac{x}{l} \right), \hspace{1cm} (6) \]

where \( b_0 \) is the fracture length of the ATB at \( x = 0 \) in the direction of mining in m; \( h \) is the thickness of the ATB in m; \( l \) is the fracture span length of the ATB in the direction perpendicular to the mining direction in m.

Substituting (3) and (4) in (5), the (7) and (8) are obtained:

\[ EI \frac{d^4y}{dx^4} + k_0 b(x)y = q(x), \hspace{1cm} (7) \]

where, \( k_0 \) is the elastic foundation coefficient of section a in N/m^3.

\[ EI_0 \frac{d^4y}{dx^4} + k_0 b_0 y = q_0, \hspace{1cm} (8) \]

where \( q_0 \) is the linear load of the overlying strata in the direction perpendicular to the mining direction on ATB at \( x = 0 \) in N/m; \( I_0 \) is the moment of inertia of ATB at \( x = 0 \) in m^4.

Let \( k_0 b_0 = k_a \) and \( \beta_1 = \sqrt{(k_a/4EI_0)} \); then (8) get simplified to the equilibrium differential equation given in:

\[ \frac{d^4y}{dx^4} + 4\beta_1 y = \frac{q_0}{EI_0}, \hspace{1cm} (9) \]

where, \( k_a \) is the linear elastic foundation coefficient of section a in N/m^3; \( \beta_1 \) is the characteristic coefficient in m^-1, which has an important influence on the stress and deformation characteristics of the ATB.

Solving (9) using the boundary conditions provides the vertical displacement as follows:

\[ y = e^{\beta_1 x} (a_{11} \cos \beta_1 x + a_{12} \sin \beta_1 x) + e^{-\beta_1 x} (a_{13} \cos \beta_1 x + a_{14} \sin \beta_1 x) + \frac{q_0}{k_a} \hspace{1cm} (10) \]
4.1.2. Vertical Displacement of Elastic Foundation in Section c. For section c, the solution for the vertical displacement can be obtained similar to the section a as follows:

\[ y_1 = e^{h_1(x-a)}\left[\alpha_{21} \cos \beta_2 (x-a) + \alpha_{22} \sin \beta_2 (x-a)\right] + e^{-h_1(x-a)}\left[\alpha_{33} \cos \beta_3 (x-a) + \alpha_{34} \sin \beta_3 (x-a)\right] + \frac{q_0 (l-a)}{k_c} \]

\[ \beta_2 = \sqrt{\frac{k_c}{4EI_c}} \]

(11)

where, \( k_c \) is the combined equivalent elastic foundation coefficient of the immediate roof and the top coal; \( k_3 \) is the elastic foundation coefficient of the backfill; \( k_3 \) is the combined equivalent elastic foundation coefficient of \( k_3 \) and \( k_2 \); \( b_c \) is the length of the ATB at \( x = c \) in \( m \); \( k_c \) is the linear elastic foundation coefficient of section c in N/m²; \( I_c \) is the moment of inertia of the ATB at \( x = c \) in \( m^4 \); \( \beta_2 \) is the characteristic coefficient in \( m^{-1} \), which has an important influence on the stress and deformation characteristics of the ATB.

4.1.3. Vertical Displacement of the Cantilever Beam of Section d. In section d, the hulking coefficients of the coal seam and the immediate roof are 1.4 and 1.35 respectively, and the recovery rate of the work face is 80%; then the displacement \( (w_0) \) of ATB when it touches gangue can be obtained as (i.e. \( M' + D = w_0 + 1.4M' (1 - 80\%) - 1.35 D \)):

\[ w_0 = 0.72M' - 0.35 D \]

(12)

where, \( M' \) is the thickness of the coal seam in \( m \); \( D \) is the thickness of the immediate roof in \( m \).

The cantilever beam theory is adopted to derive the vertical displacement solution of section d as:

\[ y_2 = y_{arc} + \theta_{arc}(x-a-c) \]

\[ + \frac{1}{E} \left( \frac{3d}{bh^3}(x-a-c)^2 - \frac{ld_0}{bh^3}(x-a-c)^3 \right) \]

(13)

where \( \theta_{arc} \) is the rotation angle of the ATB at \( x = a + c \) in rad; \( y_{arc} \) is the vertical displacement of the ATB at \( x = a + c \) in \( m \).

4.1.4. Boundary Conditions of the ATB Model. The left end of the ATB is simplified to a freely supported structure; thus the bending moment and displacement are 0, that is:

\[ y = 0 \ M = 0 \]

(14)

At the joint of the two sections of a and c of the foundation beams (i.e., \( x = a \)), through the joint surface section, a exerts a force on section c; thus the displacement, bending moment, and shearing force at the joint surface are equal, that is:

\[ y|_{x=a} = y_1|_{x=a}, \]

\[ \frac{d^2 y}{dx^2}|_{x=a} = \frac{d^2 y_1}{dx^2}|_{x=a}, \]

\[ \frac{d^3 y}{dx^3}|_{x=a} = \frac{d^3 y_1}{dx^3}|_{x=a}. \]

(15)

Similarly, at the interface of sections c and d, the cantilever d exerts a force through the joint surface on section c; that leads to the following equations:

\[ M = \frac{d^2 y_1}{dx^2} = \frac{q_0 d^3}{6l}, \]

\[ F = \frac{d^3 y_1}{dx^3} = \frac{q_0 d^2}{2l}. \]

At the right end of the ATB (i.e., the right end of the cantilever beam d), a displacement \( (w_0) \) is given, and it is a constant as given in:

\[ y_2|_{x=d} = w_0. \]

(17)

4.1.5. Solution of the Normal Stress at the Cross-Section of the Backfill Body. The unknown parameters in the equation of the ATB model are complicated; therefore, the variable iteration method is used to solve the problem. By obtaining the parameters \( \alpha_{11}, \alpha_{12}, \alpha_{13}, \alpha_{14}, \alpha_{21}, \alpha_{22}, \alpha_{23}, \) and \( \alpha_{24}, \) the displacements of the ATB can be obtained, and the normal stress in the backfill body can be derived to determine whether the backfill body meets the requirements of strength.

The sum of the displacements of the immediate roof, top coal, and backfill body is the displacement at section c of the ATB; that is:

\[ \epsilon_0 h_0 + \epsilon_1 h_1 + \epsilon_2 h_2 = y_1, \]

(18)

where \( \epsilon_0 \) is the strain of the top coal; \( h_0 \) is the thickness of the top coal in \( m \); \( \epsilon_1 \) is the strain of the immediate roof; \( h_1 \) is the thickness of the immediate roof in \( m \); \( \epsilon_2 \) is the strain of the backfill body; \( h_2 \) is the thickness of the backfill body in \( m \).

When the ATB reaches the equilibrium, that is when the ATB first touches the gangue, the vertical normal stress of the immediate roof, top coal, and backfill is equal as given in:

\[ E_0 \epsilon_0 = E_1 \epsilon_1 = E_2 \epsilon_2 = \sigma, \]

(19)

where \( E_0 \) is the elastic modulus of the top coal in GPa; \( E_1 \) is the elastic modulus of the immediate roof in GPa; \( E_2 \) is the elastic modulus of the backfill body in GPa; \( \sigma \) is the normal stress at the cross-section of the backfill body in MPa.

The normal stress at the cross section of the backfill body can be obtained from as follows:
\[
\sigma = \frac{E_2}{(E_2/E_1)h_1 + (E_2/E_0)h_0 + h_2} \\
\frac{\beta_2^x}{2} \left[ \alpha_{21} \cos \beta_2^x (x - a) + \alpha_{22} \sin \beta_2^x (x - a) \right] \\
+ e^{-\beta_2^x (a-x)} \left[ \alpha_{23} \cos \beta_2^x (x - a) + \alpha_{24} \sin \beta_2^x (x - a) \right] \\
+ \frac{q_0}{k_1} (l-a) \right].
\]

(20)

4.2. Stress Analysis of the Backfill Body. In the analysis of the normal stress of the backfill body, the fixed variable method is used to study the influence of a certain variable on the backfill body. Linear regression fitting is conducted on discrete data to obtain the fitting equation, and the relationship between the data is analyzed to determine whether the backfill meets the requirements of stability.

Specific conditions and parameters of Changcun mine in China’s Lu’an Group are analyzed. The average buried depth of the S511 fully mechanized caving work face is 450 m. The vertical stress \(q_0\) at the work face is 11.25 MPa. The periodic weighting interval of the main roof of the adjacent work face is about 20 m. The length of the ATB \(b\) is taken here as 20 m. The thickness of the main roof \(h\) is 7.5 m, and the elastic modulus of the main roof \(E\) is 11 GPa. The thickness of the immediate roof \(D\) is 3.4 m, and the elastic modulus of the immediate roof \(E_1\) is 4.5 GPa. The thickness of the coal seam \(M'\) is 6.1 m (the mining height is 3.2 m, and the top coal caving height is 2.9 m), and the elastic modulus of the coal seam \(E_0\) is 1.6 GPa. The width of the backfill body \(c\) is 1.6 m, and the height of the backfill body is equal to the mining height. The strength grade of the backfill body is C30. The fracture position of ATB on the solid coal \(X_n\) is assumed to be 7 m away from the right end of the backfill.

The influences of the buried depth, the thickness and elastic modulus of the main roof, the thickness and elastic modulus of the immediate roof, the thickness and elastic modulus of the coal seam, and the width and elastic modulus of the backfill body on the normal stress of the backfill body are analyzed respectively.

1) Influence of the buried depth on the normal stress at the cross section of the backfill body.

The buried depth is set to 250 m, 450 m, 650 m, and 850 m. These correspond to overlying surrounding rock stresses of 6.25 MPa, 11.25 MPa, 16.25 MPa, and 21.25 MPa, respectively. The loads are substituted into equation (20) to calculate the normal stress at the cross section of the backfill body, as shown in Table 1.

Figure 7 shows the variation relation of the normal stress at the cross section of the backfill with the buried depth, where \(R^2\) is the regression coefficient. When the value of \(R^2\) is approximately 1, it indicates that the trend line is the most reliable. It can be seen from Figure 7 that the normal stress at the cross section of the backfill body is linear with the depth of the roadway. With the increase of the buried depth, the normal stress of the backfill body increases linearly. Therefore, the deeper the roadway is, the higher the strength of the backfill required to be constructed.

2) Influence of thickness of the main roof on the normal stress at the cross section of the backfill body

Table 2 shows the calculated normal stresses on the backfill body by setting the thickness of the main roof at different values between 5 and 20 m.

Figure 8 shows the variation relation of the normal stress at the cross section of the backfill with the thickness of the main roof. It can be seen from the figure that the normal stress is approximately a negative power functional relation with the thickness of the main roof. As the thickness of the main roof increases, the normal stress gradually decreases, and the decreasing rate gradually slows down. Under the condition of constant external constraints, the larger the thickness of the main roof is, the smaller the deformation of the ATB on the upper part of the backfill, and the smaller the stress of the backfill. Therefore, the greater the thickness of the main roof, the lesser the required strength of the backfill to be constructed.

3) Influence of the elastic modulus of the main roof on the normal stress at the cross section of the backfill body

Table 3 shows the calculated results for the normal stresses on the backfill body by setting the elastic modulus of the main roof as 3.4 m, and the elastic modulus of the immediate roof is 7.5 m, and the thickness of the main roof is about 20 m. The length of the ATB is taken here as 20 m. The thickness of the main roof \(h\) is 7.5 m, and the elastic modulus of the main roof \(E\) is 11 GPa. The thickness of the immediate roof \(D\) is 3.4 m, and the elastic modulus of the immediate roof \(E_1\) is 4.5 GPa. The thickness of the coal seam \(M'\) is 6.1 m (the mining height is 3.2 m, and the top coal caving height is 2.9 m), and the elastic modulus of the coal seam \(E_0\) is 1.6 GPa. The width of the backfill body \(c\) is 1.6 m, and the height of the backfill body is equal to the mining height. The strength grade of the backfill body is C30. The fracture position of ATB on the solid coal \(X_n\) is assumed to be 7 m away from the right end of the backfill.
modulus of the main roof to different values spanning between 5 and 30 GPa.

Figure 9 shows the variation relation of the normal stress at the cross section of the backfill with the elastic modulus of the main roof. It can be seen from the figure that the normal stress shows an approximately negative power functional relation with the elastic modulus of the main roof. With the increase of the elastic modulus of the main roof, the normal stress gradually decreases, and the decreasing rate gradually slows down. When the elastic modulus of the main roof reaches 20 GPa, the normal stress changes little and tends to an asymptotic value. Under the condition of constant external constraints, the larger the elastic modulus of the main roof is, the more difficult it is for the ATB to deform and the smaller the stress transferred to the backfill body. Therefore, the greater the elastic modulus of the main roof, the lesser the required strength of the backfill to be constructed.

(4) Influence of the thickness of the immediate roof on the normal stress at the cross section of the backfill body

Table 4 shows the calculated normal stresses on the backfill body by setting the thickness of the immediate roof at different values spanning between 0 and 10 m.

Figure 10 shows the variation relation of the normal stress at the cross section of the backfill with the thickness of the immediate roof. It can be seen from the figure that the normal stress is in a negative power functional relation with the thickness of the immediate roof. As the thickness of the immediate roof increases, the normal stress gradually decreases, and the decreasing rate gradually slows down. As the thickness of the immediate roof increases, the height of the caving of the coal and rock mass in the goaf increases after the coal seam is mined, so that the gangue can be in contact with the main roof by a smaller angle of rotation. The subsidence of the main roof decreases, and the stress of the backfill body reduces relatively, which is beneficial to the stability of the backfill body.

(5) Influence of the elastic modulus of the immediate roof on the normal stress at the cross section of the backfill body

Table 5 shows the calculation results of the normal stress on the backfill due to different values of the elastic modulus of the immediate roof spanning between 0 and 8 GPa.

Figure 11 shows the variation relation of the normal stress at the cross section of the backfill with the elastic modulus of the immediate roof. It can be seen from the figure that the normal stress varies linearly with the elastic modulus of the immediate roof. When the elastic modulus of the immediate roof is small, the deformation above the backfill body caused by the main roof rotation is absorbed more by the deformation of the immediate roof, so that the stress of the backfill is smaller. Therefore, the greater the elastic modulus of the immediate roof, the greater the required strength of the backfill to be constructed.

| Table 2: The normal stress at the cross section of the backfill for different thicknesses of the main roof. |
|---------------|-----|-----|-----|-----|-----|
| $h$ (m) | 5 | 7.5 | 10 | 15 | 20 |
| $\sigma$ (MPa) | 41.3 | 30.74 | 21.1 | 17.1 | 16.6 |

$y = -0.0116x^3 + 0.6305x^2 - 11.32x + 83.944$  
$R^2 = 0.994$

| Table 3: The normal stress at the cross section of the backfill in different elastic modulus of the main roof. |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $E$ (GPa) | 5 | 10 | 15 | 20 | 25 | 30 |
| $\sigma$ (MPa) | 66.2 | 45.5 | 16.17 | 12 | 10 | 9.4 |

$y = 525.72x - 1.217$  
$R^2 = 0.9402$

| Table 4: The normal stress at the cross section of the backfill for different thicknesses of the immediate roof. |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $D$ (m) | 0 | 2 | 4 | 6 | 8 | 10 |
| $\sigma$ (MPa) | 258.4 | 54.4 | 25.23 | 14.07 | 8.17 | 4.53 |

| Table 5: The normal stress at the cross section of the backfill in different elastic modulus of the immediate roof. |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $E'$ (GPa) | 5 | 10 | 15 | 20 | 25 | 30 |
| $\sigma'$ (MPa) | 66.2 | 45.5 | 16.17 | 12 | 10 | 9.4 |

$y = 525.72x - 1.217$  
$R^2 = 0.9402$
Influence of the thickness of the coal seam on the normal stress at the cross section of the backfill body

Table 6 shows the calculated normal stresses on the backfill resulting from the thickness of the coal seam varying between 3.2 and 10 m.

Figure 12 shows the variation relation of the normal stress at the cross section of the backfill with the thickness of the coal seam. It can be seen from the figure that the normal stress is approximately logarithmically related to the thickness of the coal seam. As the thickness of the coal seam increases, the normal stress gradually increases. The relation of thickness of the coal seam is opposite to the relation of thickness of the immediate roof. With the increase of the thickness of the coal seam, the goaf formed by mining is larger, and the height of caving of the coal and rock mass is relatively smaller, which requires the main roof to get rotated with a larger angle to touch the gangue. The displacement of the roof above the backfill body increases, and the stress of the backfill body increases.

(7) Influence of the elastic modulus of the coal seam on the normal stress at the cross section of the backfill body

Table 7 shows the calculated normal stresses resulting from varying the elastic modulus of the coal seam ($E_0$) between 0 and 5 GPa.

Figure 13 shows the variation relation of the normal stress at the cross section of the backfill with the elastic modulus of the coal seam. It can be seen from the figure that the normal stress approximately has a negative power functional relation with the elastic modulus of the coal seam. With the increase of the elastic modulus of the coal seam, the normal stress gradually reduces, and the decreasing rate slows down. After the current panel is mined, the fractured main roof rotation transfers the pressure to the coal seam and the backfill body through the immediate roof. With the increase of the elastic modulus of the coal seam, the coal seam has a stronger ability to resist deformation and shares more pressure from the overlying strata; thus the stress of the backfill body gets smaller.

(8) Influence of the width of the backfill body on the normal stress at the cross section of the backfill body

Table 8 shows the calculated normal stresses on the backfill for the width values varying between 0.8 and 2.0 m.

Figure 14 shows the variation relation of the normal stress at the cross section of the backfill with the width of the backfill body. It can be seen from the figure that the normal stress shows an approximately negative logarithm relation with the width of the backfill body. With the increase of the width of the backfill body, the normal stress decreases.
The normal stress at the cross section of the backfill for different elastic moduli of the coal seam.

| $E_0$ (GPa) | 0.1 | 1 | 1.6 | 2 | 3 | 4 | 5 |
|-------------|-----|---|-----|---|---|---|---|
| $\sigma$ (MPa) | 145.5 | 38.6 | 30.74 | 28.65 | 27.1 | 26.21 | 25.8 |

The normal stress at the cross section of the backfill for different width values of the backfill body.

| $c$ (m) | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |
|--------|-----|-----|-----|-----|-----|-----|-----|
| $\sigma$ (MPa) | 47.6 | 41.47 | 37.51 | 33.6 | 30.74 | 27.62 | 23.49 |

The normal stress at the cross section of the backfill for different strength grades of the backfill body.

| Strength grades of the backfill body | C15 | C20 | C30 | C40 |
|-----------------------------------|-----|-----|-----|-----|
| $E_2$ (GPa) | 22 | 25.5 | 30 | 32.5 |
| $\sigma$ (MPa) | 27.1 | 29.9 | 30.74 | 31.62 |

The normal stress at the cross section of the backfill with the elastic modulus of the coal seam.

$$y = -0.919x^5 + 13.877x^4 - 79.77x^3 + 217.69x^2 - 283.69x + 171.74$$

$$R^2 = 0.9998$$

The normal stress at the cross section of the backfill with the width of the backfill body.

$$y = -25.23\ln(x) + 41.955$$

$$R^2 = 0.9955$$

The normal stress at the cross section of the backfill with the elastic modulus of the backfill body.

$$y = 0.0096x^3 - 0.8169x^2 + 23.41x - 194.25$$

$$R^2 = 1$$

The normal stress at the cross section of the backfill with the elastic modulus of the backfill body.

$$y = 0.0096x^3 - 0.8169x^2 + 23.41x - 194.25$$

$$R^2 = 1$$

Influence of the elastic modulus of the backfill body on the normal stress at the cross section of the backfill body

Table 7 shows the calculated normal stresses according to the different strength grades of the backfill body as C15, C20, C30, C40.

Figure 15 shows the variation relation of the normal stress at the cross section of the backfill with the elastic modulus of the backfill body. It can be seen from the figure that the normal stress is a logarithmic function of the elastic modulus of the backfill body. As the elastic modulus of the backfill body increases, the normal stress gradually increases. Under the condition that the backfill body is subjected to the same external force, the larger the elastic modulus is, the more difficult it is to deform. Therefore, under the effect of “hardening”, the stress on the backfill body is larger.

Based on the above analysis results and the mining and geological conditions of the Changcun mine, the sensitivity of the considered factors on the stability of the backfill from high to low is as follows: the thickness of the immediate roof, the elastic modulus of the main roof, the elastic modulus of the immediate roof, the thickness of the main roof, the thickness of the coal seam, the elastic modulus of the coal seam, the width of the backfill body, the buried depth, and the elastic modulus of the backfill body.

5. Criterion for Adaptability of the GPD Procedure

Generally, due to the narrow width of the pre-constructed backfill in the roadway, the ATB fractures at the solid coal side, as shown in Figures 16(a) and 16(b). When the parameters of the work face, periodic weighting interval, coal seam, and roof and floor reach certain values, the main roof can break just at the goaf side of the backfill wall, as shown in Figure 16(c). For the latter case, the pressure from the main roof and the overburden of the current panel is difficult to transfer to the backfill wall. The strength and width
requirements of the backfill body are naturally low. Therefore, different fracture positions of the main roof greatly affect the stability of the backfill body.

Based on the calculation method of the normal stress at the cross section of the backfill body (i.e., equation (20)), the mining and geological conditions of the S511 fully mechanized caving work face in Changcun Mine are substituted, and the fracture position of the main roof is changed to obtain the stress on the backfill body, as shown in Table 10.

Figure 17 is the normal stress at the cross section of the backfill for different fracture positions of the main roof. The fracture positions are specified by the distance between the main roof fracture position at the solid coal and the right-side end of the backfill body by the goaf. It can be seen from the figure that the normal stress shows an approximately negative exponential relation with the fracture position distance of the main roof. As the fracture position of the main roof is closer to the backfill body, the normal stress of the backfill body increases. When the fracture position of the main roof is 6 m from the backfill body, the backfill stress reaches around 46 MPa; when the fracture position of the main roof is 5 m from the backfill body, the backfill stress reaches around 63 MPa. Although the stress can be reduced by widening the backfill body, the previous analysis showed that the increase in width and decrease in the stress of the backfill body is linear, and the stress reduction is not obvious. Besides, the increase in the width of the backfill body increases the cost of construction.

When the fracture position of the main roof is 5 m from the backfill body, the backfill wall of usual strength gets destroyed, failing the GPD engineering. Moreover, as the distance between the fracture position and the backfill decreases, the stress of the backfill wall increases sharply. For such a case, the fracture location of the ATB in the solid coal is in a position of stress concentration; so the closer the backfill is to the fracture, the more difficult it is to maintain the stability of the backfill and the roadway.
According to the above analysis, it can be determined that under the geological conditions of the Changcun Mine, if the fracture location of ATB of the main roof from the backfill is less than 5m, the GPD procedure cannot be adopted. For this situation, the required strength of the backfill is large; the backfill is difficult to maintain, and it is prone to fracture failure. Therefore, not all geological conditions are suitable for the GPD procedure. By analyzing the fracture position of the ATB, the adaptability of this mining method can be obtained. Before the GPD is implemented, a pre-judgment must be made not to cause unnecessary losses.

6. Conclusions

(1) To reduce the loss of coal pillars in the thick coal seams, the GPD procedure is suggested. That is, using the time of installation of the hydraulic supports and other equipment on the current panel, a backfill wall is constructed at the non-cutting side of the entry. Upon reaching a stable overburden, the entry of the next adjacent panel is excavated along the backfill wall and no coal pillar is left. Finally, the non-pillar mining in a fully mechanized caving panel of the thick coal seam is realized.

(2) Based on the ATB formed by the fractures of the main roof, the Winkler elastic foundation beam model with the main roof, immediate roof, coal seam, and backfill was established. The different fracture positions of the ATBs, the different surrounding rock geological conditions (including the buried depth, the thickness and elastic modulus of the main roof, the immediate roof, and the coal seam, etc.), and different backfill parameters on the stability of the backfill body were analyzed. Using the analysis results, the adaptability of the GPD procedure under the corresponding geological conditions was analyzed.

(3) Based on the mining and geological conditions of the Changcun mine, the sensitivity of the aforementioned factors on the stability of backfill from high to low is as follows: the thickness of the immediate roof, the elastic modulus of the main roof, the elastic modulus of the immediate roof, the thickness of the main roof, the thickness of the coal seam, the elastic modulus of the coal seam, the width of the backfill body, the buried depth, and the elastic modulus of the backfill body.

(4) According to the geological conditions of the Changcun Mine, it was determined that if the fracture location of the ATB of the main roof from the backfill is less than 5m, the GPD procedure cannot be adopted. For this situation, the required strength of the backfill is high; the backfill is difficult to maintain, and it is prone to fracture failure. The GPD procedure cannot be applied for all geological conditions. By analyzing the fracture position of the ATB, the adaptability of this mining method can be obtained. Before the GPD procedure is implemented, a pre-judgment must be made not to cause unnecessary losses.
Data Availability

The data appearing in the manuscript can be made available by contacting the first author of the manuscript after publishing the paper.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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