Roof fracture and front abutment stress evolution of large mining height coal face with weak overburden under goaf

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Abstract. The mining pressure evolution of large mining height coal face with weak overburden under goaf is complicated, significantly influencing mining safety. This study uses the actual geological conditions of the I3 coal seam in Lingdong Coal Mine as research background. First, we combine the key layer theory and roof and floor lithology, the middle sandstone strata are determined as key strata. The fracture thin plate model for weak overburden with large mining height is established, considering elastic-plastic theory. We then obtain the calculation formula of key strata initial fracture span $l_0$, periodic fracture span $l_1$, and front abutment stress. Second, the roof fracture and front abutment stress evolution during lower coal mining are obtained using the FLAC3D numerical simulation method. As the coal face advances, the immediate roof continues to collapse, and periodic fracture subsidence occurs. The coal face periodically appears, causing the phenomenon of roof subsidence acceleration, serious coal wall spalling, increasing pillar stress, and roof-stepped subsidence. The numerical simulation results show that the initial fracture span is approximately 25 m, and the stress of the key strata is approximately 12.5 MPa. The roof weighting span of the first cycle is approximately 2.39 m, the front abutment stress peak is approximately 14.33 MPa, and the influence range of the front abutment stress is approximately 17.50 m. Finally, comparing the numerical simulation results with the theoretical results shows that the evolution is similar, verifying the correctness of the mechanical model. The research results can predict the periodic weighting of overburden and provide a reference for the design of roof mining pressure control for large mining height coal face with weak overburden of lower coal seam.

1. Introduction
The mining of coal resources in the western region is a critical energy strategic task in China. Coal strata in the western region are characterized by low strength, weakly cementation, and easier mudding when meeting water. Therefore, mining is challenging in this area. Because of the large thickness of the coal seams in the western coal mine, the mining height has gradually increased. With the emergence of coal seam group mining and other problems, face pressure has become more serious, and the overburden rock failure is also more complicated. Therefore, the evolution and ensuring safe mining of coal faces are one of the problems to be solved urgently in the mining of coal resources in the west coal mine of China.

Currently, many domestic and foreign scholars have conducted relevant research on the coal seam group, weak overburden, and large mining height fully-mechanized mining. In the large mining height fully-mechanized mining field, Gong Peilin and other scholars have proposed to accord to different
strata structures of the immediate roof of the large mining height, which was divided into three types. A mechanical model of roof control for coal face with large mining height was designed to analyze the roof movement,[3] which has engineering significance. Some scholars have analyzed the relationship between the ground pressure strength and supporting force through the actual measurement method,[4] providing a theoretical basis for roof support technology in large mining height face. Regarding the large mining height fully-mechanized mining face under weak overburden conditions, many scholars have analyzed the strata-pressure behavior and adaptability of support under the large mining height coal face on the weak broken roof. Through rock mechanics experiments and FLAC3D numerical simulation, the roof movement law was obtained, and corresponding safety measures were proposed,[5-6] providing practical engineering application technology for large mining height fully-mechanized mining technology under weak overburden conditions. Foreign scholars who analyzed weak overburden mostly studied its ultimate load through triaxial shear experiments, and analyzed the mechanical properties of weak overburden.[7-9] They provided a critical reference basis for the solution of weak overburden engineering. For coal seam group mining and changes in stope stress, Zhu Tao et al. established the loosen-blocky roof structure model based on the roof structure characteristics of the lower seam mining in ultra-close multiple seams.[10] This method revealed the roof-collapsing mechanism in the lower seam mining. The mechanism provided theoretical support for the roof control design under the condition of lower coal. Zhang Fengda used numerical simulation software to analyze the influence range of the front abutment pressure of the coal face and vertical stress distribution in the inclined direction of the coal face.[11] It is instructive to calculate the range of advanced support under such conditions.

Note that most existing studies consider the influence of unilateral factors. However, they fail to consider the law of the spatiotemporal evolution of stope stress under the three conditions. As a special type of rock mass, weak overburden has numerous natural joints and fissures distributed in it. When mining a coal seam in weak overburden, the stress of the stope changes drastically,[12-15] and the influence of mining is obvious. Under this condition, after the upper coal seam has been mined, the upper coal seam on the surrounding rock mass affects mining of the lower coal seam.[16-19] The evolution of stope stress is more complicated, and the impact of mining is more obvious. Therefore, it is significant to study roof fracture and front abutment stress evolution of large mining height coal face with weak overburden under goaf.

In this study, by studying the overburden failure and mining stress change during mining the II3 coal seam in Lingdong Coal Mine of Zhaluo’er Coal Co., roof fracture and front abutment stress evolution of large mining height coal face with weak overburden under goaf are analyzed. First, based on the elastic-plastic thin plate theory, the fracture thin plate model for weak overburden with large mining height is established. The key strata fracture span and front abutment stress of coal face calculation formula are derived. Then, the roof fracture and front abutment stress evolution during lower coal mining are obtained using the FLAC3D numerical simulation method. Finally, the simulation results are compared with the derivation process and results. This study provides a theoretical basis for the roof control of large mining height coal face with weak overburden under goaf.

2. Overview of the study area
The II2-1 and II3 coal seams are the principal coal seams of the Lingdong Coal Mine of Zhaluo’er Coal Co. The coal seam thickness is 15–20 m, and the structure is simple. The coal face length is 240 m, the coal seam dip angle is 1°–3°. The coal seam roof lithology is mostly siltstone, fine sandstone, and medium sandstone of 0 m–32 m thick. The interlayer rock is mostly sandy mudstone and siltstone, which are strongly affected by mining. The II 2-1 coal seam adopts the top coal caving and filling methods to treat goaf. The II3 coal seam is 100 m below the mined area of the II 2-1 coal seam. The II3 coal seam adopts the fully-mechanized caving method with pre-mining top-slicing. The top strata are mined using large mining height fully-mechanized mining technology. The mining height is 5 m. Mining of the II 2-1 coal seam affects the overburden rock, so the upper roof strata of the II 3 coal
seam leads to more obvious spatiality and anisotropy and more complicated stress change. Figures 1 and 2 show the columnar section of the rock strata and the mine location map, respectively.

| Columnar lithology      | Thickness (m) | Lithology description                                      |
|-------------------------|---------------|------------------------------------------------------------|
| Sandy mudstone          | 40            | Muddy structure massive structure                          |
| Coarse-grained sandstone| 12            | Sand-like structure horizontal bedding structure            |
| Sandy mudstone          | 24            | Muddy structure massive structure                          |
| Siltstone               | 12            | Dark gray, vertical bedding development uneven cracks       |
| 2-1 coal                | 15            | Black, strip, layered structure                            |
| Siltstone               | 30            | Dark gray, vertical bedding development uneven cracks       |
| Sandy mudstone          | 8             | Muddy structure massive structure                          |
| 2-2 coal                | 3             | Black, strip, layered structure                            |
| Siltstone               | 13            | Dark gray, vertical bedding development uneven cracks       |
| Sandy mudstone          | 18            | Muddy structure massive structure                          |
| Medium sandstone        | 18            | Uniform bedding, mud filled cracks, moderate hardness       |
| Sandy mudstone          | 10            | Muddy structure massive structure                          |
| 3 coal                  | 20            | Dark gray, vertical bedding development uneven cracks       |
| Sandy mudstone          | 10            | Muddy structure massive structure                          |
| Mudstone                | 110           | Gray-green, muddy, layered structure, wave-shaped bedding cracks |

**Figure 1** Rock strata columnar section
3. Fracture thin plate model for large mining height coal face

3.1. Establishment of mechanical model

After mining the II2-1 coal seam, the surrounding rock is damaged. When mining the II3 coal seam, fissure blocks in the lower coal seam roof exist. The upper mining area and the remaining coal pillar affect these blocks. This type of fissure block will affect the breaking of the overlying coal, resulting in the spatiality and anisotropy is more obvious. Under weak overburden conditions, it is affected by factors such as cracks in the roof rock, fracture, and low compressive strength, leading to greater front abutment stress. Recently, in China’s research on roof problems of mining, the traditional method is to calculate the roof as a beam model. Although this method simplifies the analysis process, it cannot reflect the spatiality and anisotropy of roofs. Therefore, using the beam model to solve this type of roof breakage is inconsistent with the actual situation, and it is impossible to obtain more accurate results. This study regards the top rock strata as an elastic thin plate. From the literature, this method is feasible. The thin plate is subjected to the gravity of the overlying rock strata, and the fracture thin plate model for weak overburden with large mining height is established (Figure 3). By using the plastic limit analysis theory to study the ultimate load of the key strata, the fracture span of the key strata is obtained. This method does not need to study the elastic and elastic-plastic state of the key strata, simplifying the calculation relatively and is more convenient to apply.
First, the position of the key layer is calculated, and the mechanical model is established. The key strata refer to the rock strata significantly influencing the activity of the overlying rock strata in the stope. It is thicker and harder than other similar rock strata. When it sinks and deforms, the subsidence of the overlying strata is synchronized with it. Therefore, by monitoring the movement of the key strata, strata-pressure behavior of the mining face can be judged. According to the columnar section of rock strata, the load of the upper rock strata on the lower rock strata is calculated using formula (3-1).\(^2\)

\[
q_{m/n} = E_i h_i \sum_{i=1}^{n} \gamma_i h_i (\sum_{m=1}^{n} E_m h_m)^{-1}
\]

In the formula, \(q_{m/n}\) is the load from the strata \(n\) on the strata \(m\), \(n > m\), the unit is kN/m\(^2\). \(E_i\) and \(E_m\) are the elastic modulus of strata \(i\) and strata \(m\), respectively, the unit is MPa, and \(h_i\) and \(h_m\) are the thickness of strata \(i\) and strata \(m\), respectively, the unit is m. \(\gamma_i\) is the bulk density of the strata \(i\), the unit is kN/m\(^3\). The necessary conditions for determining certain strata as key strata are

\[
q_{\min +1} < q_{\min}
\]

The calculation shows that the middle sandstone and the II2-2 coal seam above the II3 coal seam meet the above formula, which is hard rock strata. However, whether the hard strata are key strata must be determined by comparing the fracture spans of each hard rock stratum.

3.2. Fracture span of key strata

3.2.1. The first fracture of key strata

After the above and the following crossheading is transfixed to form the open-off cut, the coal face roof is assumed to be a rectangular plate. The four sides of the plate are fixedly supported along the advancing direction of the coal face. We assume that \(a\) is the advancement length of the coal face, and \(b\) is the length of the coal face. As the working face advances, the plate size in the \(a\)-direction increases. When the limit fracture span is reached, the yield will be produced under the action of the uniformly distributed load, mainly caused by the weight of the rock itself and the overburden weight. The \(c\) is the lateral span, and A, B, C, and D are the four points of the rectangle. The yield line should be as in Figure 4\(^{27}\).

\[
\begin{align*}
& q_{\min +1} < q_{\min} \\
& W_i
\end{align*}
\]

Figure 3 Fracture thin plate model for weak overburden with large mining height

Figure 4 Limit state of rectangular plate with four sides fixed

If the small displacement in the center of the plate because of the uniformly distributed load is 1, the plastic limit bending moment of the plate is \(M_i\). Then, the internal force work required for the formation of all strands is \(W_i\).
\[
W_r = 12M_s [a(3c)^{-1} + 2b(3a)^{-1}] 
\]

The work done by the external force is \( W_e \). So
\[
W_e = 6^{-1} qa(3b-2c) \quad (3-4)
\]

Known by the principle of virtual work, \( W'_r = W_e \), and eliminate \( c \) to get
\[
q_s = 48M_s a^2 \left[ \left( ab^{-1} \right)^2 + 3 \right]^{-1} M_{pl} \quad (3-5)
\]

In the formula, \( M_s \) is the plastic limit bending moment
\[
M_s = 4^{-1} h^2 \sigma_s \quad (3-6)
\]

where \( h \) is the thickness of the key strata and \( \sigma_s \) is the tensile strength of the strata.

Substitute equation (3-6) into equation (3-5), and solve for \( a \), which is the initial fracture span of the key strata.
\[
l_i = 2h \sigma_s \left[ b(3q \sigma_s)^{1/2} - 2h \sigma_s \right] - b^2 \left[ 16 \sigma_s h^3 (3 \sigma_s)^{1/2} - 9b \sigma_s^3 + 36q \sigma_s h^2 \sigma_s \right] (3b^2 q - 16h \sigma_s^2)^{-1} q \sigma_s (3b^2 q - 4h \sigma_s) \quad (3-7)
\]

3.2.2. The periodic fracture of the key strata

From the end of the first movement of the rock strata, the roof rock strata follow a regular fracture movement in a certain cycle. The immediate roof follows the mining and collapses. In addition to the influence of the weight of the overlying rock strata, the collapsed rock strata also influence the periodic motion of the key strata. The stress of the collapsed rock strata on the key strata can be simplified as the load \( q_i \), and act on the boundary AB. Therefore, the periodicity moving of rock strata is a rectangular plate with three sides fixedly supported, and one side of the plate is applied on a uniform load. The mechanical model is simplified in Figure 5.

![Figure 5 Limit state of rectangular plate with uniform load on three sides](image_url)

It is assumed that the small displacement of the plate center is 1. All strands form the required internal force work \( W'_r \) and external force work \( W_e \) is
\[
W_r = 12M_s \left[ 2a(3b)^{-1} + b(6a-c) \right]^{-1} \quad (3-8)
\]
\[
W_e = 6^{-1} b[q(2a+c)+3q_i] \quad (3-9)
\]

From the principle of virtual work,
\[
q_i = 3(16aM_s - b^2 q_i)^3 T [b^2 (2bM_s + T) \left[ 4M_s (12a^2 + b^2)^{-1} + 2bT - 3ab^2 q_i \right]^{-1} \quad (3-10)
\]

Among them, \( T = 2abM_s \left( \left( 2a^2 + b^2 \right) (a^2 b^{-1})^{-1} - 3q_i (4aM_s)^{-1} \right) \).

The load of the collapsed roof rock strata is approximately \( q_i = 2^{-1} qa_i \).

In the formula, \( a_i \) is the previous fracture span of the key strata, \( m \).

The simultaneous equations (3-6), (3-10), and (3-11) obtained the fracture span \( l \) during the cycle fracture of the key strata.
\[
l = \left[ 4h(3q \sigma_s)^{1/2} - 3qa \right] (16 \sigma_s [q + 4h b^{-1}])^{-1} \quad (3-12)
\]

The above calculations show that the key strata of the II3 coal seam are the upper-middle sandstone strata, with a thickness of 18 m, the initial fracture span is 23.28 m, and the ultimate load of the key strata is 13.57 MPa. The roof weighting span of the first cycle was calculated as 2.39 m, and the roof
weighting span of the second cycle is 12.94 m.

3.3. Front abutment stress calculation of coal face
As mentioned above, the key strata are the elastic thin plate. According to the differential equation of elastic curved surface of the thin plate, the stress in the vertical direction is

\[ Q = 2a(2^1 - zh^1)^{1/2} (1 + zh^{-1}). \]  

(3-13)

In the formula, \( h \) is the thickness of the key strata, and the value range of \( z \) is \([0, h]\).

From this, we can obtain the pressure of the key strata on the lower rock mass, according to the literature.[30] The vertical stress in the wedge body is

\[ \sigma_v = Q + 2(2\tan(\beta) - 2\beta)^{-1}\{2\tan(\beta)\cdot x_1^2 + y_1^2 + 2\sin[y(x_1^2 + y_1^2)^{1/2} - 2xy(x_1^2 + y_1^2)^{1/2}] + 2\beta \cdot x_1^2 + y_1^2 \} \]

\[ + 2(2\tan(\beta) - 2\beta)^{-1}\{2\tan(\beta)\cdot x_1^2 + y_1^2 + 2\sin[y(x_1^2 + y_1^2)^{1/2} - 2xy(x_1^2 + y_1^2)^{1/2} + 2\beta \cdot x_1^2 + y_1^2 \} \]

\[ - 2\cdot 2(x_1^2 + y_1^2)^{-1}\{2\tan(\beta)\cdot x_1^2 + y_1^2 + 2\sin[y(x_1^2 + y_1^2)^{1/2} - 2xy(x_1^2 + y_1^2)^{1/2} + 2\beta \cdot x_1^2 + y_1^2 \} \]

\[ - 2\cdot 2(x_1^2 + y_1^2)^{-1}\{2\tan(\beta)\cdot x_1^2 + y_1^2 + 2\sin[y(x_1^2 + y_1^2)^{1/2} - 2xy(x_1^2 + y_1^2)^{1/2} + 2\beta \cdot x_1^2 + y_1^2 \} \]

\[ + 2Qy(x_1^2 + y_1^2)\{2(2\tan(\beta) - 2\beta)^{-1}(2 - 2(x_1^2 + y_1^2)^{-1} - 2xy(x_1^2 + y_1^2)^{-1}) \]

In the formula, \( x > \sum h \tan^{-1} \beta \), \( \beta \) is the breaking angle of the rock strata, taking \( \tan \beta = 2 \), \( y(\sum h) \) is the distance from the key strata to the coal strata. Substituting the pressure of the key strata on the lower rock mass into the above formula, the front abutment stress peak can be obtained. After calculation, the front abutment stress peak is approximately 13.56 MPa, and the influence range of the front abutment stress is approximately 16.72 m.

4. Numerical simulation calculation

4.1. Model establishment and simulation scheme
The impact of overburden mining can be quantitatively analyzed by calculating the numerical simulation model of coal mining. The model range is set to 900 m \( \times \) 240 m \( \times \) 500 m (length \( \times \) width \( \times \) height), and the coal face length is 240 m. The section coal pillar is taken at 70 m, and the mining height is 5 m. By using the strata-by-strata and group modeling method, the numerical simulation model is constructed from the bottom up. The left and right, front and rear, and lower boundaries of the model are fixed. The top is used to apply stress to simulate the weight of the overlying rock strata.

The study uses three to five rock specimens for different strata. The diameter of the specimen is not less than 50 mm and the length not less than 100 mm. The retrieved specimens were evaluated on the micro-control electro-hydraulic servo-universal testing machine for rock characteristics. After calculation, the tensile strength, cohesion, internal friction angle, bulk modulus, and shear modulus of each stratum are obtained. Table 1 shows the mechanical parameters of the coal and rock mass in the model.

The Mohr-Coulomb plastic model is adopted, and the shear yield complies with the Mohr-Coulomb criterion. It is calculated by formula (3-15). When \( \sigma_i > 0 \), shear failure occurs. Tensile yield is evaluated by tensile strength. When \( \sigma_s \geq \sigma_t \), tensile failure occurs.

\[ f_\sigma = \sigma_1 - \sigma_3(1 + \sin\phi)(1 - \sin\phi)^{-1} - 2c[(1 + \sin\phi)(1 - \sin\phi)^{-1}]^{1/2}, \]  

(3-15)

where \( \sigma_s - \sigma_3 \) are the maximum, minimum principal stress, MPa, \( \phi \) is internal friction angle, (°), and \( c \) is the cohesion, MPa.

First, after the II 2-1 coal seam is excavated, the goaf is treated by the filling method, the mining of the II 3 coal seam after calculating the balance starts. To study the ultimate load and fracture span of the key strata, the advancement steps of the II 3 coal seam are set to 15 m and 25 m, respectively. The overburden failure and change of stress state are observed. Finally, the calculated key strata ultimate load, fracture span, and front abutment stress are compared with the theoretical calculation values.
### Table 1. Mechanical parameters of the coal and rock mass

| Lithology          | Strata thickness/m | Tensile strength/MPa | Cohesion/MPa | Internal friction angle/° | Bulk modulus/MPa | Shear modulus/MPa |
|-------------------|--------------------|-----------------------|--------------|---------------------------|------------------|------------------|
| Sandy mudstone    | 40                 | 0.17                  | 1.10         | 30.60                     | 2.27             | 1.36             |
| Coarse sandstone  | 12                 | 0.11                  | 0.67         | 32.50                     | 1.47             | 1.29             |
| Sandy mudstone    | 24                 | 0.17                  | 1.10         | 30.60                     | 2.27             | 1.36             |
| Siltstone         | 12                 | 0.20                  | 1.22         | 28.00                     | 2.47             | 1.63             |
| 2-1-coal          | 15                 | 3.00                  | 1.34         | 30.20                     | 3.15             | 2.17             |
| Siltstone         | 30                 | 0.20                  | 1.22         | 28.00                     | 2.47             | 1.63             |
| Sandy mudstone    | 8                  | 0.17                  | 1.10         | 30.60                     | 2.27             | 1.36             |
| 2-2-coal          | 3                  | 3.00                  | 1.34         | 30.20                     | 3.15             | 2.17             |
| Siltstone         | 13                 | 0.20                  | 1.22         | 28.00                     | 2.47             | 1.63             |
| Sandy mudstone    | 18                 | 0.17                  | 1.10         | 30.60                     | 2.27             | 1.36             |
| Medium sandstone  | 18                 | 0.24                  | 1.47         | 28.96                     | 1.84             | 1.32             |
| Sandy mudstone    | 10                 | 0.17                  | 1.10         | 30.60                     | 2.27             | 1.36             |
| 3-coal            | 20                 | 3.00                  | 1.34         | 30.20                     | 3.15             | 2.17             |
| Sandy mudstone    | 10                 | 0.17                  | 1.10         | 30.60                     | 2.27             | 1.36             |
| Mudstone          | 110                | 0.13                  | 1.21         | 21.70                     | 2.69             | 1.69             |

#### 4.2. Analysis of simulation results

Figure 6 shows that after excavating the coal seam II2-1, the stress in the stope is redistributed, and stress-increasing areas appear at both ends of the stope. Mining affects roof rock strata above the goaf, and the stress decreasing area appears. Simultaneously, stress concentration occurs in the coal pillar area. The stress concentration sheared and damaged the surrounding rock of the roadway. Because of the advancement of the coal face and influence of the stress concentration, plastic failure occurs in a certain area above the coal face. However, because of the influence of the filling body, the scope and degree of the plastic failure areas are relatively smaller.

![Figure 6 II2-1 stress nephogram after coal seam excavation](image-url)
With the continuous advancement of the coal face, the immediate roof continues to collapse. The original equilibrium state of the overlying rock strata is broken, and the distribution area of the plastic zone gradually increases during the progress of the coal face. Figure 7 shows that under the influence of II2-1 coal mining, the overlying roof of the II3 coal seam has been damaged. The complete body is no longer. Therefore, the surrounding rock stress around the roadway is small, and only the stress in front of the coal face is large. The cracks in the overburden strata above the II3 coal seam gradually expand. The large area of cracks intersected, leading to a large area of pressure. Figure 8 shows that when the coal face advances to 25 m, the key strata of the II3 coal seam produce fractures for the first time. The stress of the key strata is approximately 12.5 MPa, the front abutment stress peak is approximately 14.33 MPa, and the influence range of the front abutment stress is approximately 17.50 m.

### 4.3. Comparison with the theoretical calculation

Table 2 shows the comparison between the simulation results of the key strata ultimate load, initial fracture span, and front abutment stress and the theoretical calculation values.

| Category               | Calculated value | Simulated result | Error  |
|------------------------|------------------|------------------|--------|
| Key strata ultimate load | 13.57            | 12.5             | 8.56%  |
| Initial fracture span   | 23.28            | 25               | 6.88%  |
| Front abutment stress   | 13.56            | 14.33            | 5.37%  |

Table 2 shows that by comparing with the theoretical calculation values, the simulation results of the key strata ultimate load, initial fracture span, and front abutment stress peak have an error of less than 10%. The theoretical values are a little different from the simulation result. This can verify the
correctness of the fracture thin plate model for weak overburden with large mining height and the formula. This provides a basis for the design of roof control under similar conditions.

5. Conclusions
(1) The strata characteristics of the large mining height coal face with weak overburden under goaf show that the fracture thin plate model for weak overburden with large mining height is established considering the elastic-plastic thin plate theory. By comparing it to the beam model, this model can better reflect the spatiality and anisotropy of such roof. The key strata ultimate load, fracture span, and front abutment stress calculation formula are derived, assisting with the analysis of such problems.
(2) The fracture span and front abutment stress of the large mining height coal face with weak overburden under goaf are analyzed using the numerical simulation method. The initial fracture span is approximately 25 m, and the front abutment stress peak is approximately 14.33 MPa, approximately 8.2 m ahead of the coal wall. The influence range of the front abutment stress is approximately 17.50 m.
(3) The comparison of the numerical simulation results with the theoretical results shows that the key strata ultimate load, initial fracture span, front abutment stress peak, and influence range have an error of less than 10%. The result verifies the correctness of the mechanical model. This research provides a theoretical basis for roof control of large mining height coal face with weak overburden under goaf.

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