

The Mechanism of Roof Cutting and Pressure Relief under Different Overburden Structures in the Working Face after Mining Cessation

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Abstract

A protective coal pillar with a width of 200 m was retained in the working face of Guqiao Coal Mine after mining cessation, while the roadway in the corresponding section was severely deformed, affecting the normal use of the roadway. To improve the stress environment of the roadway in the working face after mining cessation, the overburden roof cutting was used to reduce the mining-induced disturbance on the working face and eliminate the manifestation of large deformation in the roadway. Based on theoretical analysis methods, the overburden structure of the working face after mining cessation was analyzed, the overburden structure before and after the roof cutting was uniformly modeled, and the mechanism of roof cutting and pressure relief in the working face after mining cessation was revealed. Research results have shown that as the roof fracture height increases in the stop-mining working face, the structural characteristics of the overburden change significantly from those under normal mining conditions; The abutment pressure of the overburden suspended plate and the balanced arch are the main causes of high-stress load of the roadway in the working face after mining cessation. The implementation of roof cutting in the advanced working face can reduce the length of the overburden suspended plate, lower the additional load on the suspended plate, and block the transmission path of mining stress from the working face in advance. When the roof cutting was carried out at an advanced distance of 60 m from the stop-mining working face, and the maximum roadway deformation did not exceed 140 mm, it resulted in a significant pressure relief effect. Additionally, an equivalent stress index was used to describe the stress transfer law of coal and rock, which effectively reflects the bimodal distribution characteristics of the supporting pressure curve. To accurately determine the position of the roof cutting line for the working face, the collaborative bearing law between the roof cutting with the interval pillar and the working face support was explored based on the discontinuous roof structure model. It is recommended to limit the size of the interval pillar for roof cutting to below 20 m, or even eliminate the retention of the interval pillar for roof cutting, to enhance the recovery rate of coal resources.

Keywords

Overburden structure, Roof cutting pressure relief, Coal pillar retention, Roof cutting roadway protection, Deep hole blasting



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Introduction

During the coal mining process, the roof of the goaf naturally collapses as the working face advances. Different fracture sizes and caving patterns of the roof result in different characteristics of overburden structures, leading to different mining pressures in the mining area (Pan et al., 2022; Kuang et al., 2019; Yu et al., 2022; Yu et al., 2019). In general, effective control of mining pressure can be achieved through reasonable selection of hydraulic supports on the working face (Wen et al., 2019; Wang et al., 2022; Cheng et al., 2020; Sun et al., 2021). During mining operations under a hard roof, the overburden suspended plates can be induced into the goaf. The sudden fracture and migration of a larger suspended plate in the overburden can easily lead to strong mining pressure in the mining area (Liu et al., 2020; Shi et al., 2020; Xue et al., 2020; Yue et al., 2022). To ensure the safe mining of the working face, the advanced and reliable support equipment should be used, and the evolution characteristics of the overburden structure in the mining area should be clarified. Consequently, the action mechanism of mining pressure in the mining area can be correctly revealed, and the target layer of overburden can be accurately located and controlled to implement efficient roof control technology (Zhang et al., 2019; Lu et al., 2019; He et al., 2020; Lu et al., 2019). During the normal mining of the working face, the roof collapses directly after the support is removed, and the roof structure of the key high-level roof is relatively stable, the coefficient of fragmentation and swelling of the caving gangue in the goaf is relatively large, and the disturbance height of the working face mining is limited (Tian et al., 2020; Zhang et al., 2009; Li et al., 2019; Li et al., 2006). The overburden of the stop-mining working face has experienced long-term stable equilibrium, the gangue in the goaf has gradually compacted, and the fracture height of the roof has increased. However, the fracture blocks of the high-level rock layer are mutually clamped, and the fracture size of the roof is increased, and the fracture of the high-level rock layer significantly affects the mining pressure of the mining site. After the cessation of mining on the working face, the stability time of the overburden structure in the goaf is long, the fallen gangue is fully compacted, and the height of the roof fracture increases. In addition, the boundary effect of the retreat channel after the cessation of mining affects the overburden structure, which is different from the normal mining condition. Besides, the mechanism of mining pressure in the stop-mining working face was explored to guide the design of roadway protection for the working face after mining cessation.

From the perspective of controlling mining pressure in the mining site, the longer the length of the overburden suspended plate, the stronger the corresponding additional bending moment of the suspended plate, and the more obvious the leverage effect (Yang et al., 2024). The solid coal rock of the working face serves as the fulcrum of the suspended plate, bearing high additional stress (Liu et al., 2019; Ji et al., 2020; Jiao et al., 2021; Wang et al., 2019), which is the main reason for the high stress and large deformation of the roadway surrounding rock in the working face. On the contrary, timely cutting off the overburden suspended plate (Tai et al., 2020; Wang et al., 2020; Ma et al., 2018; Tu et al., 2022) and eliminating the leverage effect of the overburden suspended plate will be beneficial for improving the stress environment of the surrounding rock in the mining site. However, the selection of the roof-cutting position in the working face after mining cessation necessitates careful consideration (Wang et al., 2019; Fan et al., 2019; Wang et al., 2022; I G Sakhno et al., 2022). When roof cutting is conducted at the stop-mining position of the working face, the bending moment of the overburden suspended plate can be eliminated in a timely manner, reducing the range of stress transmission caused by the bending moment. When the roof cutting is performed at a certain distance from the stop-mining line of the advanced working face, an interval pillar is left between the stop-mining line and the cutting line of the working face, which carries the mining stress of the working face and the effect of the overburden suspended plate. As a result, the high-stress transmission path from the working face direction can be effectively blocked, and the stress environment of the roadway surrounding rock can be improved. Based on the characteristics of the overburden structure in the working face after mining cessation, a mechanical model of the overburden structure was established in this study to reveal the mechanism of mining pressure before and after the overburden roof cutting. Additionally, the influence of the roof-cutting position on the stress of the interval pillar in the stop-mining working face was explored, and reasonable technical parameters for overburden roof cutting and pressure relief were determined. This study provides a theoretical basis for the roof-cutting design and roadway protection of the working face after mining cessation.

The evolution of the overburden structure in the stop-mining working face

Production and geological overview of the working face

Based on the geological conditions in the working face 1311 (1) in the Guqiao Coal Mine of the Huainan Mining Group, the characteristics of the overburden structure and the mechanism of roof cutting and pressure relief in the stop-mining working face were explored in this study. The elevation of the working face was -549.1 to -741.6 m. During the mining process, the width of the working face was locally shortened, with an initial width of 280 m and a corresponding strike length of 1240 m; The ending width was 135 m and the corresponding strike length was 550 m. The northern side of the working face 1311 (1) was adjacent to the mined working face 1312 (1), while the other three sides were solid coal. The coal seam 11-2 was mined on the working face, with stable

occurrence, an average thickness of 2.8 m, an average dip angle of 5°, and a solidity coefficient of 0.54 to 0.90. It belonged to the Class II failure type. Geological information of XLZM1 was used to represent the occurrence of coal and rock at the position of the stop-mining line. The working face layout and geological column of the working face are shown in Figure 1.

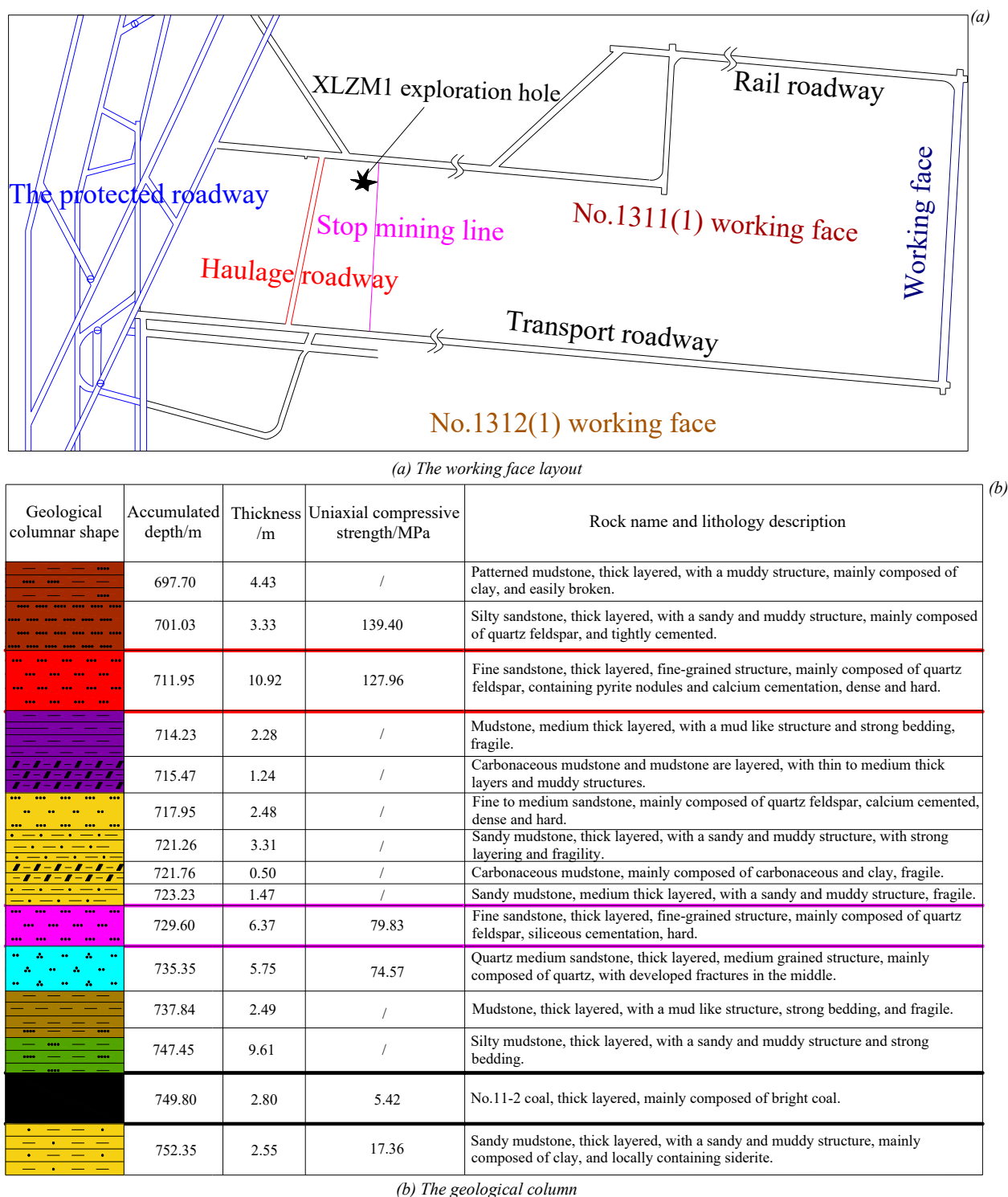


Fig.1. The working face layout and geological column.

The rock layer of the immediate roof in the working face 1131 (1) was mainly composed of mudstone and sandy mudstone, with low strength. The fragmentation and swelling coefficient of the caving gangue in the goaf was 1.2 to 1.3, corresponding to a normal collapse height of 9 to 14 m in the goaf. According to the columnar distribution of rock layers in Figure 1, the overlying fine sandstone layer, with a thickness of 6.37 m, is identified

as the key layer of the roof. Its fracture migration has a direct impact on the stress of the solid coal and rock in the working face.

After a period of mining cessation, the falling gangue in the goaf undergoes gradual compaction due to residual fragmentation and swelling effects. Therefore, the residual fragmentation and swelling coefficient range from 1.05 to 1.10. Based on this, the height of the roof disturbance is 28 to 56 m. In addition, due to the boundary effect of the retreat channel of the working face, the disturbance height of the overburden in the working face increases, affecting a thick sandstone layer about 35m away from the coal seam. The roof fracture in this layer will form a larger high-stress affected zone.

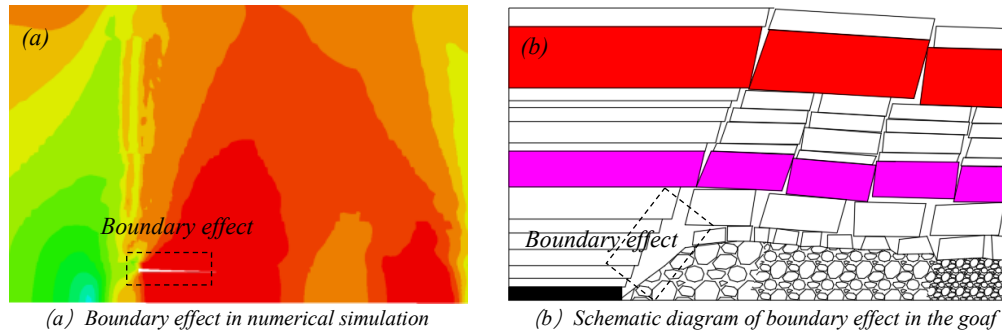


Fig.2. Boundary effect of the goaf in the working face after mining cessation

Evolution of overburden structure in the working face after mining cessation

During the mining process of working face 1311 (1), the fragmentation and swelling coefficient of caving gangue in the goaf adjacent to the mining site was high, and the caving height in the goaf was about 9 to 14 m. A fine sandstone with a thickness of 6.37m, located about 17.8 m above the coal seam, formed the key layer of the low-level roof of the working face. With the advancement of the working face, the gangue in the goaf gradually bears the load, which has a time delay effect on the support of the roof key layer, leading to the delayed fracture of the roof key layer. Based on this, the overburden structure during the normal mining process of the working face was obtained, as shown in Figure 3a. After the cessation of mining on the working face, the mining disturbance no longer exists. The overburden in the goaf tends to stabilize, and the caving gangue is fully compacted, showing residual fragmentation and swelling characteristics. The fracture height of the roof increases, and even affects the extra-thick sandstone 35 m away from the coal seam with a thickness of 11 m. The roof fracture of this layer is sandwiched by adjacent layers, and the fractured blocks are squeezed and interlocked with each other, forming a key layer of the high-level roof. The overburden structure after the cessation of mining on the working face is obtained, as shown in Figure 3b.

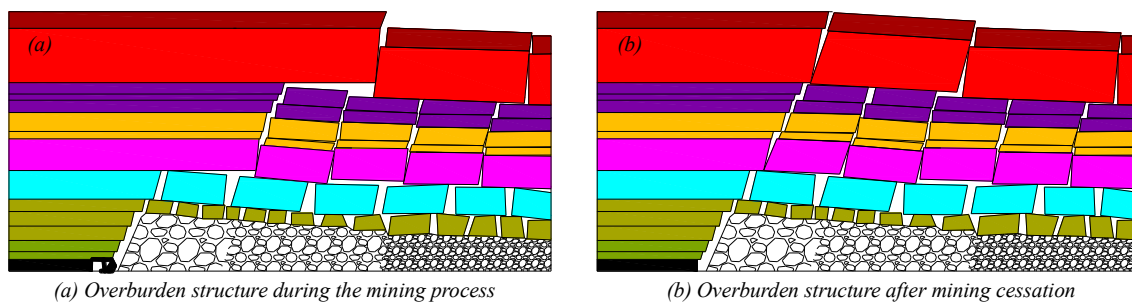


Fig.3. Evolution of overburden structure after the mining cessation.

The overburden structure in the working face after the mining cessation has unique characteristics. Firstly, the overburden structure is free from the mining disturbance of the working face, and the roof movement gradually tends to stabilize. Secondly, there are key layers of high-level and low-level roof in the overburden structure. The roof fractures and blocks are squeezed and interlocked, forming a masonry beam structure. After long-term stability in the goaf, the squeezing effect between blocks tends to weaken. Finally, with the migration of the key layers on the roof, the weak rock layers between the key layers of the high-level and low-level roof and their overlying layers exhibit dynamic characteristics, and there is a weak contact force between the fractured block and the equilibrium arch boundary.

Based on the geological occurrence and mining technology conditions of the working face, it is believed that the main sources of stress on the roadway after the cessation of mining are from three aspects: ① self-weight of the overburden (including geostress); ② balance arch abutment pressure; ③ the effect of overburden suspended plate. Among them, the self-weight of the overburden on the working face always exists. Before the cessation of

mining in the working face, there is no significant deformation of the surrounding rock in the roadway, indicating that the self-weight of the overburden is not the main factor affecting roadway deformation. After the mining of the working face, the roof naturally collapses, forming a balanced arch structure. Due to the bearing capacity of the gangue in the goaf, the compaction degree of the gangue near the working face is not high. The solid coal rock at the boundary of the balanced arch carries the weight of the overburden in the goaf, generating the supporting pressure of the balanced arch. The mining conditions of the working face remain unchanged, and the balanced arch structure of the overburden is similar. The distribution form of the supporting pressure of the balanced arch remains consistent. After the mining cessation of the working face, the side roof of the goaf remains in a suspended state, inevitably generating additional bending moment loads and exhibiting a leverage effect. The solid coal rock of the working face serves as a fulcrum, bearing the high stress induced by the suspended plate effect of the overburden.

To sum up, the self-weight of coal and rock is a secondary factor affecting the stress of solid coal and rock at the stop-mining position of the working face; The balance arch abutment pressure in the goaf and the bending moment of the overburden suspended plate are the main causes of high-stress bearing in the solid coal rock at the stop-mining position of the working face. The supporting pressure of the balanced arch is mainly distributed on the layered suspended plate of the overburden, and the composite stress is formed by the bending moment of the comprehensive suspended plate, as shown in Figure 4.

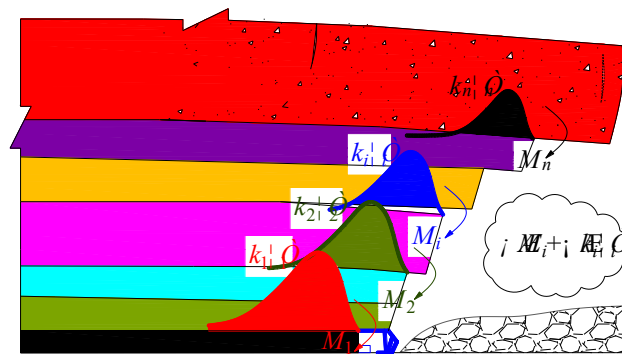


Fig. 4. Formation of composite stress.

To reduce the impact of composite stress on the roadway, two aspects should be taken from the perspective of roof control: ① Adopting roof cutting technology to reduce the bending moment of the overburden suspended plate; ② The balance arch abutment pressure in the goaf is difficult to eliminate, but the roof cutting can also be used to block the high-stress transmission path. The principle of roof cutting for pressure relief at the advanced working face is to block the transmission path of composite stress in the overburden. If coal pillars are left between the roof cutting line and the stop-mining line, the interval pillars bear the mining-induced stress from the working face direction; In the absence of coal pillars between the roof cutting line and the stop-mining line, roof cutting of the advanced working face can actively relieve the bending moment effect of the overburden suspended plate, and also have a positive effect on reducing the pressure of the balance arch support.

Principle of roof cutting and pressure relief for the working face

Stress analysis of overburden without roof cutting in advance

Equivalent stress of overburden

Along the vertical direction of the working face, the roof layer is divided into four load-bearing plates: from bottom to top, the roof layer between the coal seam and the low-level key layer constitutes the first plate; The low-level key layer forms the second plate on its own; The roof layer between the low-level and high-level key layers forms the third plate; The high-level key layer acts independently as the fourth plate, as shown in Figure 5.

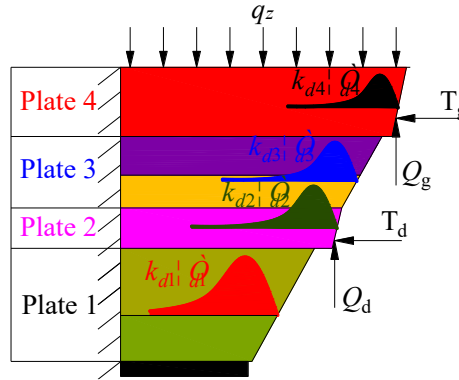


Fig. 5. Equivalent stress of overburden on the working face.

In this figure, q_z is the given load for the overburden, T_d and T_g are the horizontal squeezing force of the gangue at the boundary of the low-level and high-level key layers; Q_d and Q_g are the rock support forces at the boundary of the low-level and high-level key layers; k_{di} is the equivalent stress concentration factor of the abutment pressure of the i -th plate; i is the sequence number of the overburden plate, ranging from 1 - 4; σ_{di} is the equivalent original rock stress of the i -th plate. The structure of the overburden plates is similar, and their stress conditions are the same. The equivalent method is adopted to describe the stress of the plates uniformly. According to the average burial depth of the layered roof within the plate, the peak abutment pressure of the i -th plate is calculated as follows:

$$\sigma_{Fi} = k_{di} \sigma_{di} = k_{di} \gamma_i H_i \quad (1)$$

Where σ_{Fi} is the peak stress of the i -th plate; γ_i is the average bulk density of the i -th plate; H_i is the average burial depth of the i -th plate.

The isolation analysis along the coal wall direction of the working face is performed. The left isolation body is mainly subjected to uniformly distributed loads (including self-weight) and equivalent loads at its right boundary. The equivalent load is distributed on the left boundary of the right suspended plate isolation body, and the right boundary is subjected to the action of the goaf gangue. After a certain period of mining cessation in the working face, the overburden movement gradually stabilizes, and the broken blocks of the roof undergo horizontal rotation. The squeezing and interlocking effect between the blocks weakens. In order to reduce the complex analysis of the stress on the edge blocks of the goaf, the influence of the gangue effect on the equilibrium arch boundary is discarded. According to the force balance relationship between the composite blocks, the equivalent concentrated force and equivalent bending moment under the combined action of the self-weight of the overburden and the supporting pressure of the balanced arch are obtained as (Yang et al., 2024):

$$F = \frac{1}{2} \gamma l_d h_z (n - \lambda k) + \lambda k \gamma l_d (n - 1) \left(\frac{h_z}{2} + H \right) \quad (2)$$

$$M = \frac{\lambda k \gamma l_d^2 (n^2 - 1) (h_z + 3H) + \gamma l_d^2 h_z (n^2 - 2\lambda k)}{6} \quad (3)$$

where F and M represent the equivalent concentrated force and equivalent bending moment in the direction of the coal wall on the working face; h_z is the fracture height of the roof in the goaf; γ is the average bulk density of the overburden; l_d is the suspended plate length of the low-level roof; N is the ratio of the suspended plate length of the high-level and low-level roof; k is the average stress concentration factor; λ is the average coefficient of supporting pressure load; H is the average burial depth of the overburden.

The fracture height of the roof in the goaf of the working face 1311 (1) of the Guqiao Coal Mine is about 46 m, and the fracture angle of the roof is calculated at 70 to 75°, corresponding to a length of 10.8 to 14.4m for the overburden suspended plate. Under the condition of a hard roof, the influence range of bearing pressure is about 10 to 20m. The bearing pressure on the suspended plate is considered as a uniform load, and the value $\lambda_{di} k_{di} \sigma_{di}$ is taken, where λ_{di} is the average coefficient of load. The average density of the sandy rock layer on the roof of the working face is 2500 kg/m³, and the fracture size of the lower-level roof is about 12m. When the ratio of the fracture size of the lower-level and high-level roof is 2 to 7, the corresponding fracture size of the high-level roof is about 24 to 84m. The average stress concentration factor is set at 1.4 to 5.0, and the average coefficient of the supporting pressure load is set at 0.5 to 0.8, depending on the overburden layer and the degree of compaction of the gangue in the goaf. The average burial depth of the coal seam at the stop-mining position of the working face

is -750m. By substituting the relevant data into equations (2) and (3), the influence of the fracture height of the goaf roof on the equivalent concentrated force and equivalent bending moment of the overburden under different suspended plate lengths is obtained, as shown in Figure 6.

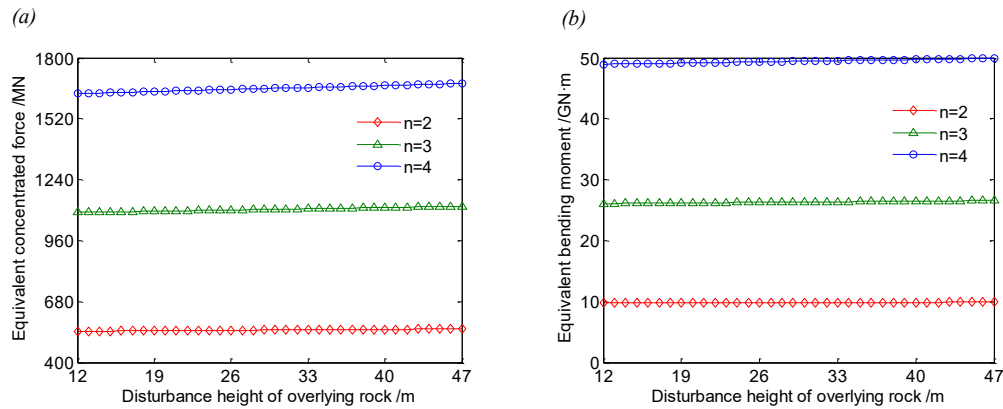


Fig. 6. Relationship between the equivalent load of overburden and fracture height of the roof.

As shown in Figure 6, the fracture height of the roof in the working face. ① The length of the suspended plate is the main reason for the high-strength bearing capacity of the overburden. Under the same suspended plate length, the equivalent concentrated force and equivalent bending moment of the overburden are not sensitive to changes in the roof fracture height of the working face. ② Under the same fracture height of the roof and the same length of suspended plate, the absolute value of the equivalent bending moment of overburden is relatively high. Based on this, it can be concluded that the mining of the working face will result in a certain height of roof fracture, and the overhang length of the roof within the range of overburden disturbance is the main factor affecting the manifestation of mining pressure. From the perspective of managing mining pressure in the mining area, the cutting height is the height of the roof fracture evolution. The relationship between the equivalent load of the overburden and the ratio of the fracture size of the high-level and low-level roof is obtained, as shown in Figure 7.

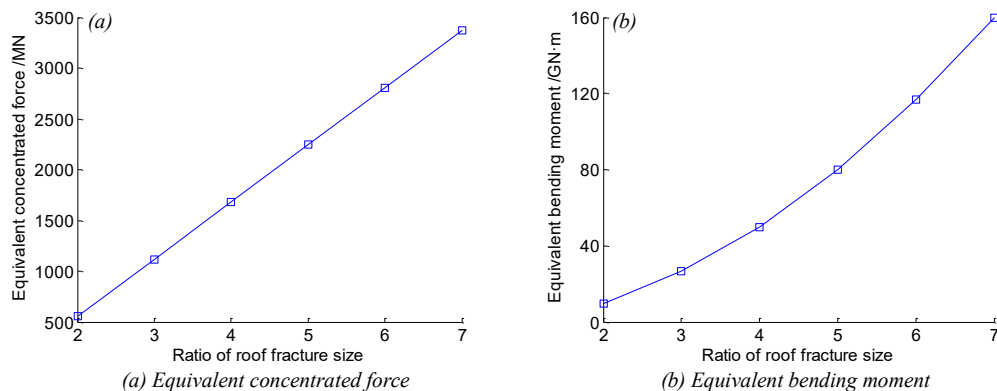


Fig. 7. Relationship between the equivalent load of overburden and the ratio of roof fracture size.

As shown in Figure 7, there is a linear increasing relationship between the equivalent concentration force of the overburden and the ratio of the fracture size of the roof. The larger the ratio of the fracture size of the roof, the higher the equivalent concentration force of the overburden. There is a curvilinear growth relationship between the equivalent bending moment of the overburden and the ratio of the fracture size of the roof. The larger the ratio of the fracture size of the roof, the more significant the increase in equivalent bending moment. When the ratio of the fracture size of the high-level and low-level roof is 3, the equivalent load of the overburden under different fracture size conditions of the low-level roof is obtained, as shown in Figure 8.

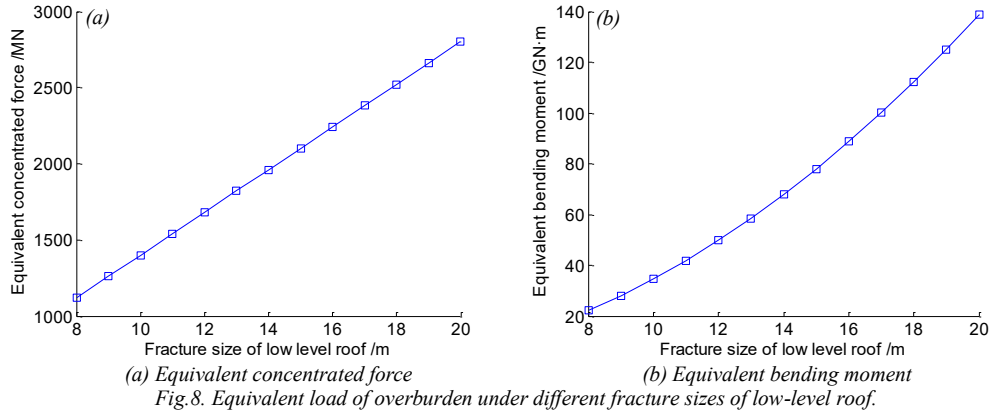


Fig.8. Equivalent load of overburden under different fracture sizes of low-level roof.

When the fracture size of the low-level roof is 8 to 20m and the ratio of the fracture sizes of the high-level and low-level roof is 3, the equivalent concentrated force of the overburden obtained is 1100 to 2800 MN; The equivalent bending moment is 21 to 136GN·m.

Overburden stress transmission

Based on the equivalent load of the overburden obtained from the previous analysis, the elastic semi-infinite body theory is used to mechanically solve the stress distribution of the overburden under the action of the equivalent load, as shown in Figure 9. It should be noted that the mechanical model shown in Figure 9 is not suitable for direct application of the semi-infinite body theory due to the adjacent space on the right boundary. Therefore, the coordinate system is rotated with the y-axis facing the semi-infinite body direction.

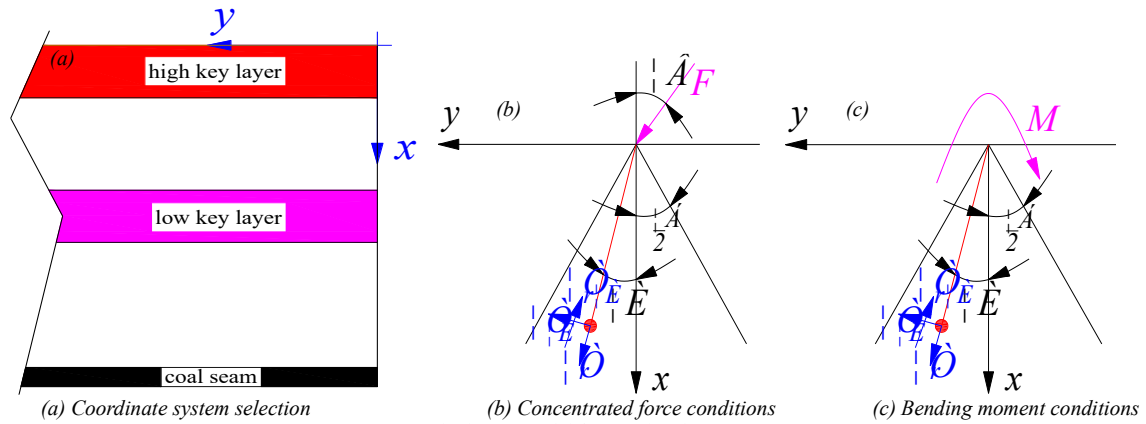


Fig.9. Calculation model for overburden stress.

According to the force calculation method for wedge-shaped bodies, the expression for the stress distribution of overburden under the combined action of equivalent concentrated force and equivalent bending moment load is obtained through coordinate transformation:

$$\begin{cases} \sigma_{xx} = \frac{2F}{\pi} \frac{x^2 y}{(x^2 + y^2)^2} - \frac{8M}{\pi(x^2 + y^2)^3} x^3 y \\ \sigma_{xy} = \frac{2F}{\pi} \frac{xy^2}{(x^2 + y^2)^2} - \frac{2M}{\pi(x^2 + y^2)^3} (3y^2 - x^2) x^2 \\ \sigma_{yy} = \frac{2F}{\pi} \frac{y^3}{(x^2 + y^2)^2} - \frac{4M}{\pi(x^2 + y^2)^3} (y^2 - x^2) xy \end{cases} \quad (4)$$

where σ_{xx} is the horizontal stress of the overburden; σ_{xy} is the shear stress of the overburden; σ_{yy} is the vertical stress of the overburden; x and y are position coordinates of the stress point.

Equation (4) is used to analyze the stress distribution characteristics of the coal seam strike when the suspended plate length of the high-level roof is 36 m, as shown in Figure 10. The red line in the figure represents

the stress component under the action of equivalent concentrated force; The blue line represents the stress component under equivalent bending moment; The black line represents the stress component under the comprehensive action of equivalent load.

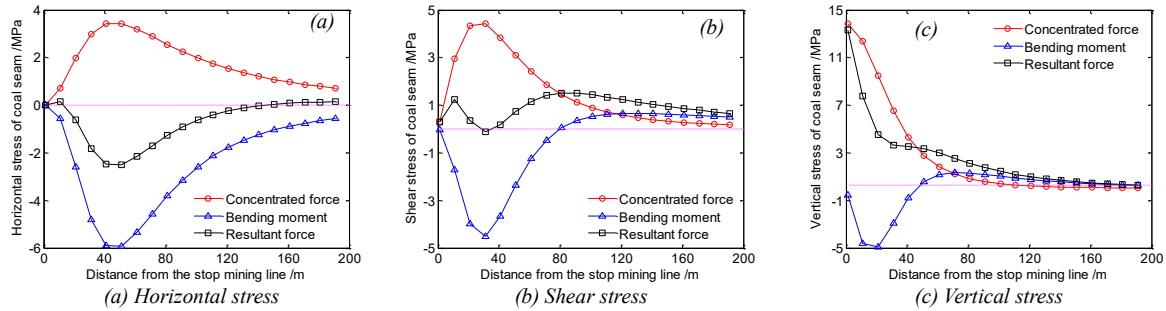


Fig.10. Stress distribution characteristics of coal seam strike.

As shown in Figure 10, the stress components of the coal seam under the equivalent concentrated force and equivalent bending moment of the overburden remain consistent, which is different from the characteristic that the equivalent bending moment value is significantly higher than the equivalent concentrated force. According to the distribution characteristics of horizontal stress and shear stress in coal seams, the stress component generated by the equivalent bending moment is significantly larger, and the influence of the equivalent bending moment is more significant. An equivalent concentrated force mainly affects the vertical stress distribution of coal seams.

To reflect the comprehensive effect of stress components and the overall macroscopic stress characteristic of coal and rock, according to the fourth strength criterion of the material, the equivalent stress index is used to analyze the stress of the overburden under the comprehensive effect of equivalent load:

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (5)$$

and

$$\sigma_1 = \frac{\sigma_{xx} + \sigma_{yy}}{2} + \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \sigma_{xy}^2}, \quad \sigma_3 = \frac{\sigma_{xx} + \sigma_{yy}}{2} - \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \sigma_{xy}^2}, \quad \sigma_2 = \mu(\sigma_1 + \sigma_3)$$

where $\bar{\sigma}$ is the equivalent stress; σ_1 and σ_3 are the maximum and minimum principal stresses, respectively; σ_2 is the middle principal stress; μ is Poisson's ratio.

The distribution characteristics of the equivalent stress of coal and rock under the comprehensive effect of equivalent load are obtained, as shown in Figure 11.

As shown in Figure 11, the equivalent stress is an additional stress induced by the equivalent load of the overburden, excluding the influence of natural geostress. The equivalent stress distribution range of the overburden, resulting from the comprehensive effect of equivalent loads, is wide, and the stress level is high, which has a certain impact on the protection of the roadway system in the stop-mining working face. ① At a distance of 50 m from the stop-mining line of the advanced working face, the equivalent stress of the overburden reached about 10MPa. ② The equivalent stress decays along the direction of the coal seam, but the decay rate is slow. At a distance of 200 m from the stop-mining line of the advanced working face, the equivalent stress of the coal seam roof and floor remains at around 2 MPa. ③ The farther away from the coal wall of the working face, the less attenuation of equivalent stress along the y-axis direction (towards the coal seam and its floor), and the greater the depth of influence; ④ The equivalent stress distribution along the coal seam strike well reflects the bimodal distribution characteristics of the advanced abutment pressure curve of the working face.

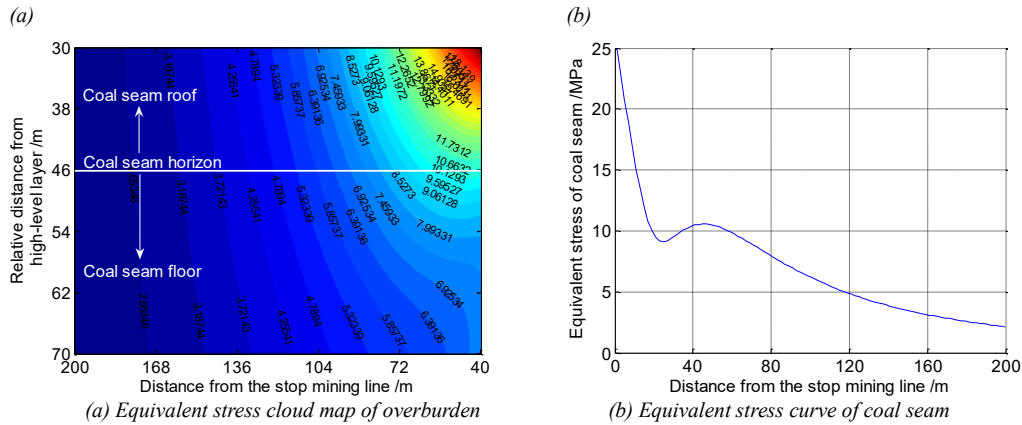


Fig.11. Distribution characteristics of equivalent stress in coal and rock.

Analysis of overburden stress after advanced roof cutting

Roof cutting without retaining the coal pillar

When there is no coal pillar left between the stop-mining line and the cutting line of the working face, the cutting line is the stop-mining line of the working face. According to equations (2) and (3), when the ratio of the fracture size of the high-level and low-level roof is taken as 1, the equivalent load of the overburden obtained from the theoretical model under the corresponding conditions is:

$$F = \frac{1}{2} \gamma_1 h_z (1 - \lambda k), \quad M = \frac{\gamma_1^2 h_z (1 - 2\lambda k)}{6} \quad (6)$$

It can be seen that when the ratio of the fracture size of the high-level and low-level roof is $n=1$ (without coal pillars), the equivalent load of the overburden decreases significantly. From the perspective of controlling the roof of the working face, roof cutting is beneficial for reducing high stress in the overburden. This is also the main reason for taking roof cutting measures in advance of the working face. In this way, the transmission path of high stress can be blocked, achieving coal body pressure relief and roadway protection. According to equation (6), the maximum equivalent loads of the overburden after roof cutting without retaining coal pillars are obtained as follows:

$$F = \frac{1}{2} \gamma_1 h_z, \quad M = \frac{\gamma_1^2 h_z}{6} \quad (7)$$

When the ratio of the fracture size of the high-level and low-level roof is 1, there is no suspended plate in the overburden of the working face after mining cessation. According to equation (7), the relationship between the maximum equivalent load of the overburden and the size of the roof fracture is obtained, as shown in Figure 12.

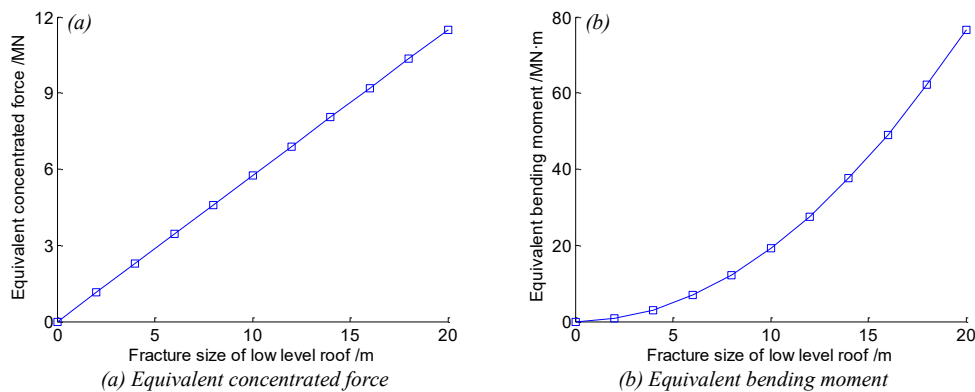


Fig.12. Relationship between equivalent load of overburden and fracture size of roof.

As illustrated in Figure 8, the equivalent load of the overburden decreases sharply under the condition of roof cutting without retaining coal pillars in the advanced working face, significantly weakening the suspended plate effect of the overburden. However, the linear relationship between the equivalent load of the overburden and the

fracture size of the low-level roof has not changed: the relationship between the equivalent concentrated force and the fracture size of the low-level roof still maintains a linear increasing correlation. As the fracture size of the low-level roof increases, the equivalent bending moment of the overburden also increases. The length of the periodic weighting of the working face is 8 to 20m, the corresponding equivalent concentrated force of the overburden is less than 12 MN, and the equivalent bending moment of the overburden is less than 80 MN·m. To further clarify the influence of overburden suspended plate length on the stress of coal seams, the ratio of the fracture size of the high-level and low-level roof is taken as 1, 3, and 5, and the equivalent stress distribution curves of the coal seam are obtained, as shown in Figure 13.

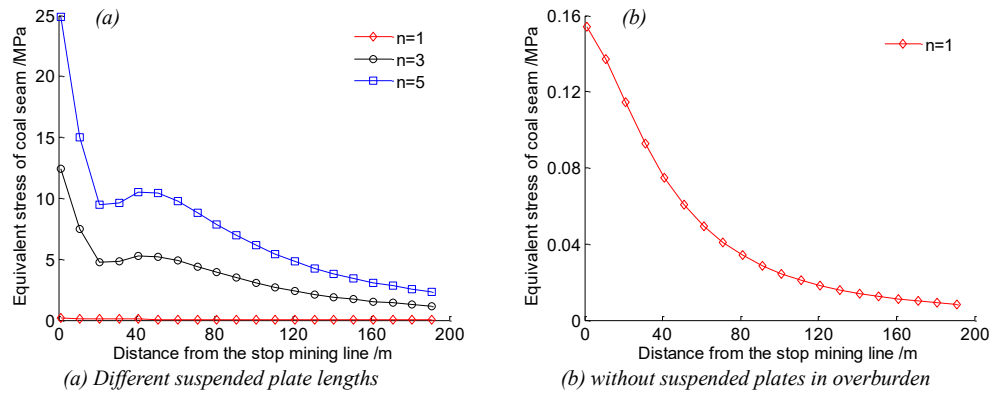


Fig. 13. Influence of suspended length of overburden on equivalent stress of coal seam.

When the ratio of the fracture size of the overburden at the high-level and low-level roof is 3 and 5, the equivalent stress in the coal seam is relatively high, showing a typical bimodal distribution characteristic. It effectively reflects the distribution characteristics of the advanced abutment pressure of the working face. When the ratio of the fracture size of the roof is 1, the bimodal distribution characteristics can not be obtained from the equivalent stress of the coal seam, and the stress level is relatively low, generally below 160 kPa. From the perspective of roof control, it is evident that roof cutting in the advanced working face and actively reducing the ratio of high-level and low-level roof fracture sizes are extremely beneficial for reducing the mining pressure intensity of the working face. This is also the theoretical basis for roof cutting and pressure relief of the working face.

Roof cutting with the retained coal pillars

To achieve effective roof control during the support dismantling process in the stop-mining working face after roof cutting, without retaining coal pillars, roof cutting with retained coal pillars in the advanced working face is adopted. Specifically, a certain size of coal pillar is retained between the stop-mining line and the roof cutting line of the working face, that is, the interval pillar (as shown in Figure 14). This pillar is left to block the transmission of mining-induced stress in the working face and improve the stress environment of the roadway surrounding rock in the working face after mining cessation.

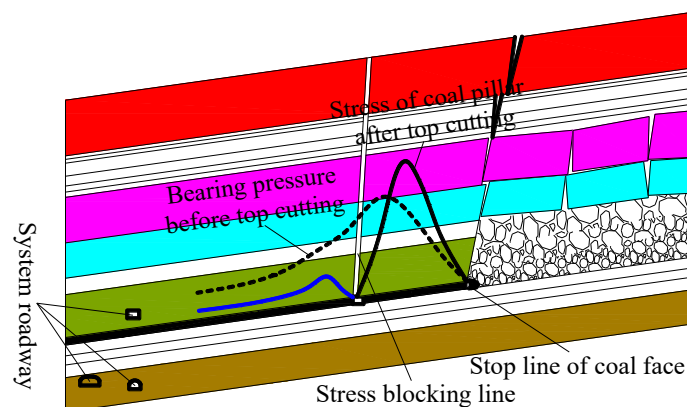


Fig. 14. Roof cutting with the retained coal pillars in the advanced working face.

When roof cutting is conducted with the retained coal pillars in the advanced working face, the roof fracture forms a discontinuous structure, and the theoretical results based on the continuum mechanics mentioned above

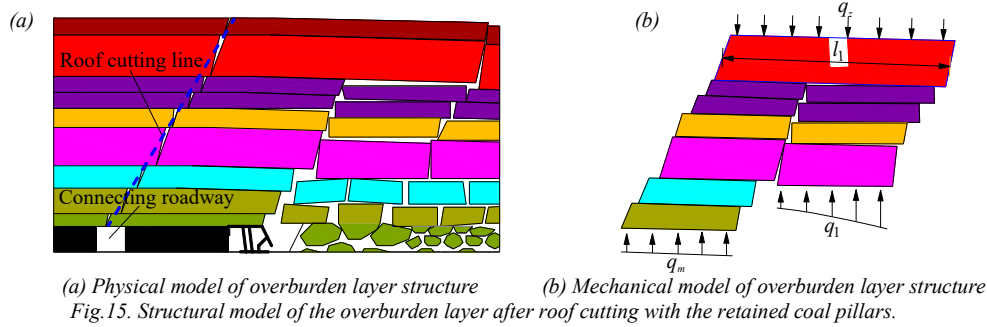
are no longer applicable. Based on this, a structural mechanics model of the overburden layer is adopted (as shown in Figure 15) to reveal the stress transfer mechanism of overburden under discontinuous roof structures.

To simplify the mechanical vectors between the fractured blocks of the overburden, the energy variational method is used to obtain the given load of the overburden under the condition of layer structure (Kuang, 2021):

$$q_m = \gamma \zeta (H_d + 3H_z + nH_g) - 2\kappa L/3 \quad (8)$$

and

$$H_d = \sum_{i=1}^m h_i, \quad H_z = \sum_{i=1}^N h_i, \quad H_g = h_d$$



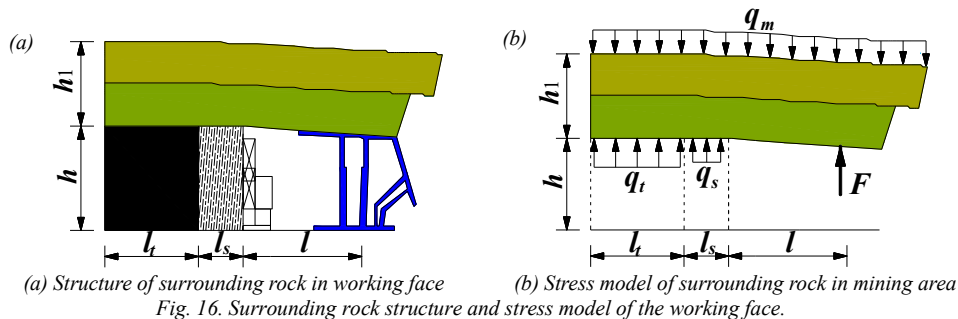
where q_m is the given load on the overburden; H_d is the thickness of the first plate of the overburden; H_z is the sum of the thicknesses of the second and third plates of the overburden; H_g is the thickness of the fourth plate of the overburden; κ is the support coefficient of gangue; ζ is the energy consumption coefficient of the overburden block; L is the effective support length of gangue; h_d is the thickness of the high-level key layer (including the overlying weak layer); m is the number of layered roof panels of the first plate; N is the number of layered roof panels for the second and third plates.

In equation (8), H_d , H_z , and H_g represent the total thickness of different overburden plates, and the difference in coefficients reflects different mechanisms of overburden plate mining pressure, corresponding to different mining pressure intensities.

The coefficient n , representing the ratio of fracture sizes between high-level and low-level roofs, intuitively reflects the influence of high-level roof movement on mining pressure in the mining area. The longer the high-level roof block, the greater the given load on the overburden.

From the perspective of roof control, timely roof cutting in the advanced working face can reduce the suspended plate length of the high-level roof, which is beneficial for controlling the mining pressure in the mining area.

The given load on the overburden of the stop-mining working face is applied to cut and protect the interval pillar and the support above the working face. For convenience, the stress on the top interval pillar is further subdivided into an elastic-plastic bearing zone, and a stress model of the surrounding rock of the working face mining area is obtained, as shown in Figure 16.



Based on the principle of minimum potential energy, the stress equilibrium conditions of the surrounding rock in the mining area under any dynamic equilibrium state of the overburden are obtained as follows (Yu et al., 2019):

$$\frac{f(l_s)}{f(l_t)} = \frac{\eta}{2} - 1, \quad F_z = \frac{4E_s l_1 f(l_s)}{\pi A \sin[(\pi l_z)/(2l_1)]} \quad (9)$$

and

$$\varphi(x) = \frac{32q_m}{EIh} \left(\frac{l_1}{\pi}\right)^4 \left(1 - \frac{2}{\pi}\right) \left(1 - \cos \frac{\pi x}{2l_1}\right), \quad f(x) = h\varphi^2(x)[1 - \varphi(x)], \quad A = \frac{32q_m}{EI} \left(1 - \frac{2}{\pi}\right) \left(\frac{l}{\pi}\right)^4$$

where $f(x)$ and $\varphi(x)$ are variable functions; F_z is the support force of the working face bracket; h is the thickness of the coal seam; η is the ratio of coal's elastic-plastic modulus; E_s is the plastic modulus of coal; l_z is the position of the support force point.

on the support force of the working face support, assuming that the size of the plastic zone of the coal body remains unchanged, $E_s = 1.3$ GPa, $l_s = 10$ m, and $\zeta = 0.2$ are taken into Equation (9) to obtain the relationship between the support force of the working face support and the fracture size of the low-level roof, as shown in Figure 18.

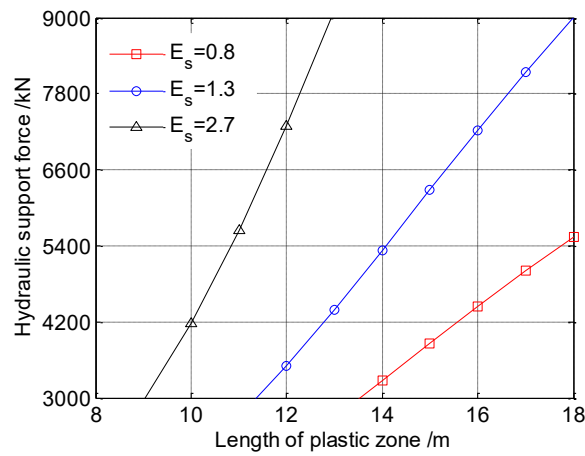


Fig.17. Coordination relationship between the plastic zone of the coal pillar and support force.

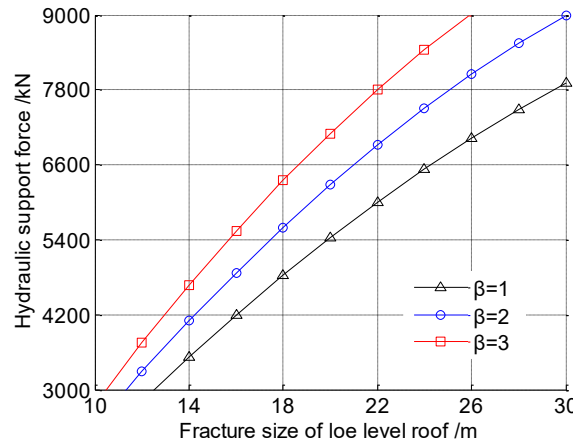


Fig.18. Relationship between the support force and fracture size of low-level roof.

It can be seen that the smaller the plastic modulus of the coal body, the poorer the bearing capacity, resulting in a higher support force of the working face bracket and a larger plastic zone of the coal body. As the fracture size of the low-level roof increases, the support force of the working face bracket increases linearly. The influence of high-level roof movement on the support force of the bracket is reflected by the ratio of the fracture size of the high-level and low-level roofs. When the fracture size of the low-level roof remains unchanged and the high-level roof cutting is insufficient ($n > 1$), the support force of the working face bracket increases significantly. Based on this, roof cutting in the advanced working face is adopted to promote the ratio of the fracture size of the high-level and low-level roof to approach 1, which has a significant effect on actively reducing the support force of the working face bracket.

Effect of overburden roof cutting and pressure relief

The aforementioned theoretical research indicates that without roof cutting in the advanced working face, the disturbance stress of the surrounding rock in the roadway is around 2 MPa, which is not conducive to the stability of the roadway. Roof cutting in the advanced working face can effectively block the transmission path of mining-induced stress, improve the stress environment of the surrounding rock of the roadway, and eliminate the disturbance stress of the overburden. ① When roof cutting with interval pillars is conducted in the advanced working face, the size of the interval pillar left at the stop-mining working face can be reduced to below 20m according to the relationship between the support force of the bracket and the plastic zone size of the interval pillar, as shown in Figure 17. ② When roof cutting without retaining interval pillars is conducted, the roadway has the best pressure relief effect according to the relationship between the suspended plate length of the overburden and the equivalent stress of the coal seam, as shown in Figure 13. From this perspective, it is recommended to cancel the retention of interval pillars for cutting the roof of the working face after mining cessation. However, considering the safety of dismantling the bracket from the working face, roof management techniques should also be supplemented to ensure the stability of the overburden during the dismantling period.

To ensure the normal use of the roadway during the cessation period of the working face 1311 (1) in Guqiao Coal Mine, deep hole blasting and roof cutting operations were carried out in the haulage roadway of the working face to block the stress transmission path of the working face, reduce the stress intensity of the roadway surrounding rock, and avoid large deformation of the roadway. Referring to the impact range of mining operations on the adjacent working face 1312 (1), the advancement of the working face 1311 (1) was stopped at a distance of 60m from the haulage roadway, that is, an interval pillar with a width of 60m was left to ensure the overburden stability during the dismantling the bracket from the working face. To clarify the height of the mining disturbance in working face 1311 (1), the method of measuring the height of the water conducting fracture zone was adopted to determine the height of the mining disturbance. According to the geological exploration conditions, the actual drilling reached 582.9m, and the circulating fluid leaked completely for the first time, with a leakage rate greater than 15m³/h. The water conducting fracture zone extends from 631.0m to 582.6m, with a height of 48.4m. Based on the comprehensive distribution characteristic of the borehole column and the convenient drilling construction, the depth of the roof-cutting borehole in the haulage roadway is 46m, and the elevation angle of the borehole is 85°. The deep hole blasting equipment and borehole layout are shown in Figure 19.

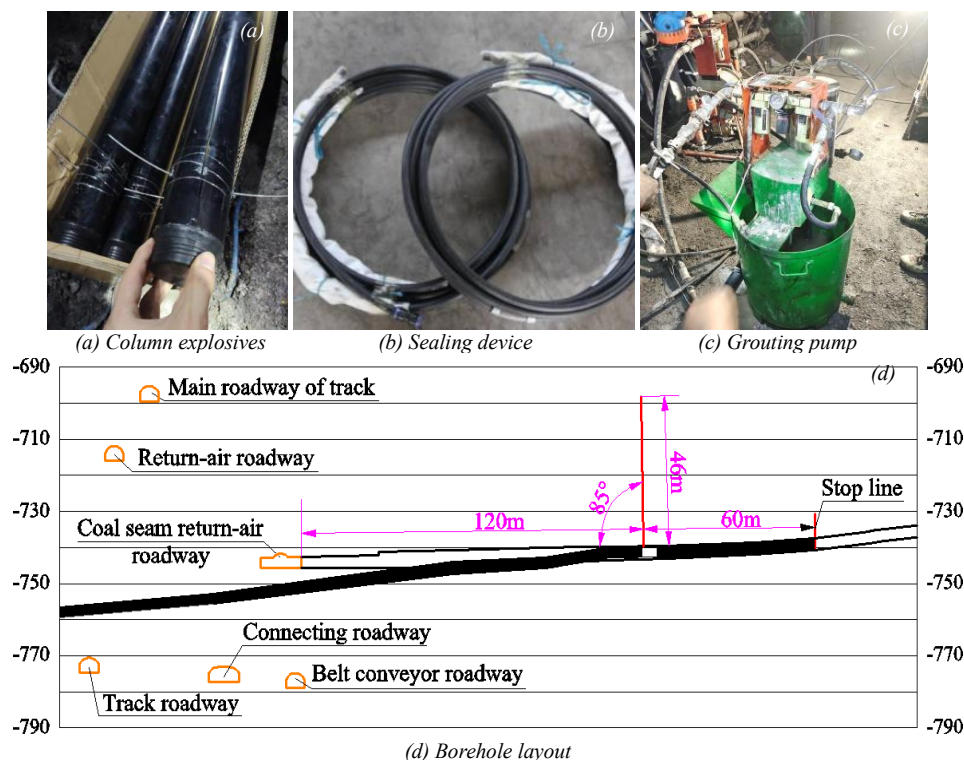


Fig.19. The deep hole blasting equipment and borehole layout.

For the convenience of large-angle deep hole charging, coal mine permissible column explosives with a diameter of 63mm are used, meeting the requirements of large diameter and large charge blasting. The water gel explosives used have the third security level and high explosive power, and the energy utilization rate of the

explosion inside the hole is high. Using a "two plugs and one injection" sealing device and cement slurry for long-distance sealing operations.

Deep hole blasting and roof cutting were carried out in the working face 1311 (1) in the haulage roadway, and the deformation of the roadway surrounding rock was effectively controlled. The deformation observation of the surrounding rock of the return airway of the North 2-11-2 coal seam (closest to the working face) was conducted, as shown in Figure 20a. It can be found that: ① With the advancement of the working face, the cumulative deformation of the roadway surrounding rock increases; ② The relative deformation of the roadway roof and floor is relatively large, and the deformation of the floor is dominated, and its maximum deformation does not exceed 140 mm, as shown in Figure 20b. ③ The interval pillar is left with a width of 60m to ensure the stability and reliable use of the roadway. However, due to the stress concentration in the interval pillar, the roadway deformation of the working face is large, as shown in Figure 20c.

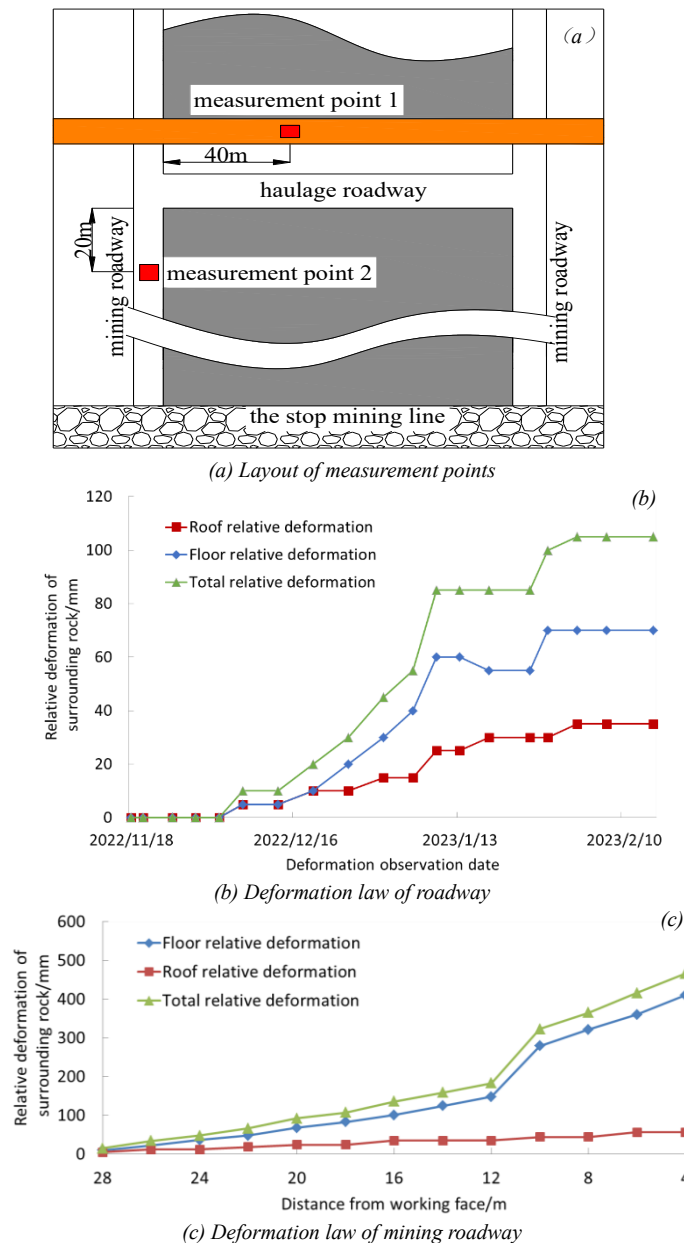


Fig. 20. Deformation law of the surrounding rock in the roadway after roof cutting.

Summary

The structural characteristics of the overburden in the working face before and after mining cessation are analyzed, and it is determined that the suspended plate and balanced arch abutment pressure of the overburden were the main causes of large deformation in the roadway. By establishing a mechanical model of the overburden

structure of the working face after mining cessation, the bearing law of the overburden before and after roof cutting is explored, and the mechanism of roof cutting and pressure relief of the working face mining cessation is revealed.

The equivalent stress index is utilized to analyze the stress distribution law of coal and rock before and after roof cutting, revealing the stress transmission mechanism under the action of an overburden suspended plate and reflecting the bimodal distribution characteristics of the coal and rock abutment pressure curve. This study explores the bearing relationship between the interval pillar and the working face support, and provides a reference for the selection of the roof cutting line position for the working face.

When an interval pillar with a width of 60m is retained, the roadway deformation in the working face is effectively controlled, and the maximum deformation of the roadway is less than 140mm. Based on theoretical research results, it is recommended to reduce the interval pillars to below 20m and consider canceling their retention, provided that the working face roof is effectively managed, to improve the recovery rate of coal resources.

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