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Research on the Influence of the Stability of the Rock Surrounding a Mine Roadway under Directional Pre-splitting Blasting

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Abstract: Lateral roof cutting technology, used in gob-side entry retention, would to a certain extent destroy the structure of the roof of the mining roadway, which affects the stability of the roadway. This study aimed to assess the stability of the mining roadway, considering the combined effects of the different sealing lengths and the mining stresses. The FLAC3D numerical simulation method was adopted to investigate three conditions: no roof cutting, incomplete roof cutting, and complete roof cutting. The deformation and stress distribution of the surrounding rock in their cases were compared and analyzed. The results show that directional pre-splitting roof cutting can cut off the stress transfer between the roofs, but it also destroys the integrity of the roof, thereby reducing the bearing capacity of the roof. The stresses on one side of the roof can be reduced via incomplete roof cutting, and this method can also maintain the strength of some of the surrounding rock. The peak advanced abutment pressure will increase as the penetration value of the directional roof cutting increases and the stress concentration area will move away from the roadway. The results of this study provide a reference for the determination of the roof cutting parameters in gob-side entry retaining.

1. Introduction

Coal pillars within the conventional mining approach lead to significant coal resource wastage, cause a high stress concentration, and affect the stability of the mining roadway. Gob-side entry retaining requires no coal pillars to protect the mining road. While reducing the waste of coal resources, this method can also solve the problem of tight mining replacement [1]. He Manchao [2] proposed a method for cutting roofs and relieving pressure in a self-forming tunnel that can automatically create tunnels once the roof of the goaf is excavated using energy-gathering explosions. Structural control and stress optimization can stabilize the surrounding rock of the gob-side entry retaining. Before mining coal mine, it is necessary to conduct pre-split blasting on the leading section of the roadway. After the advanced roof cutting, the connection state of the roof structure will change on both sides of the seam. In the leading section of the roadway, the surrounding rock's stress state will change, and the roadway's deformation characteristics will also change within the range of the advanced abutment pressure [3]. Wang Yajun [4] examined the mine pressure's distribution traits along the length of the working section using numerical simulations and conducted zoning. Bai Jianbiao [5] investigated the characteristics of the stress and deformation during the four stages of the comprehensive process of high water filling in gob-side entry retaining. However, research on how advanced roof cutting impacts the surrounding rock of the roadway's advanced section is limited. Therefore, studying the effects of pre-splitting and cutting on the stress evolution of the surrounding rock in the advanced section of the roadway, the deformation traits of surrounding rock [6,7] and the stability of the advanced support under advanced roof cutting conditions has considerable theoretical significance and practical application value.

However, when a two-way shaped tension blasting method for roof cutting is employed, it is essential to ensure that the blast-generated detonation wave is concentrated within the shaped tube wall, thereby creating a tangential tensile stress capable of effectively executing roof cutting [8]. After charging, it is crucial to seal the blasting mud at the base of the blasting hole. The length of the sealing hole plays a significant role in determining the possibility of hole punching or collapse, as well as the quality of the cracks formed during the blasting process. According to the general situation, the length of the sealing hole during deep hole blasting should be 25–30% of the hole depth [9], Blasting hole sealing will lead to the fact that the cutting surface cannot penetrate the roadway roof. In prior investigations, the assessment of whether the roof cutting was adequate solely depended on the partitioning of the vertical extent of the cut [10], and the effect of sealing the blasting hole on the adjacent geological structures of the mining passage was not considered.

Therefore, adopting the 32021 roadway of Liangbei as the engineering context and employing numerical simulation, in this study, we investigated the characteristics of the stress evolution and the shifting patterns of the overlying geological layer under the effect of advanced abutment pressure, particularly when advanced pre-splitting and cutting tactics were implemented in roof cutting and retaining passage operations. Three numerical models were established: no roof cutting, incomplete roof cutting, and complete roof cutting. The analysis explored the surrounding rock's stress evolution traits and the surrounding rock's deformation and failure patterns in the advanced section of the roadway after roof cutting. The results of this study reveal the stability mechanism of the surrounding rock before and after roof cutting in the advanced pressure zone.

2. Background of the Project

2.1. Overview of Coal Mining Face

In the Liangbei Coal Mine, the Permian 21 coal seam, which is characterized by its significant thickness, is currently being excavated. The coal seam thickness across the entire mine is 4.77 m, while the coal solidity coefficient is 0.15–0.33. The coal seam is extremely soft. Owing to the deep burial and low strength of both the roadway and the surrounding rock, significant and rapid deformation occurs in the roadway. This can easily result in floor uplift, which in turn exacerbates the deformation on both sides of the roof, widens the area of loosening, and makes the mine pressure apparent. The 32021 coal extraction working face stands as the initial mining face within the 32 mining areas and has a burial depth of 506 m. In the strike direction, the mining face extends for a length of 1235 m, while in the inclined direction, it stretches for 230 m. The immediate roof consists of sandy mudstone and is 3.0 m thick. It has a low strength and is comparatively fragmented. The fundamental roof is comprised of sandstone, measuring 11.5 m in thickness. The coal thickness averages 5.3 meters, with an average dip angle of 7 degrees. The mining height is full at one time, and a detailed histogram is presented in Figure 1. Utilizing roof cutting technology is employed to maintain gob-side entry in order to reduce the time needed for mining roadway excavation and enhance production efficiency.

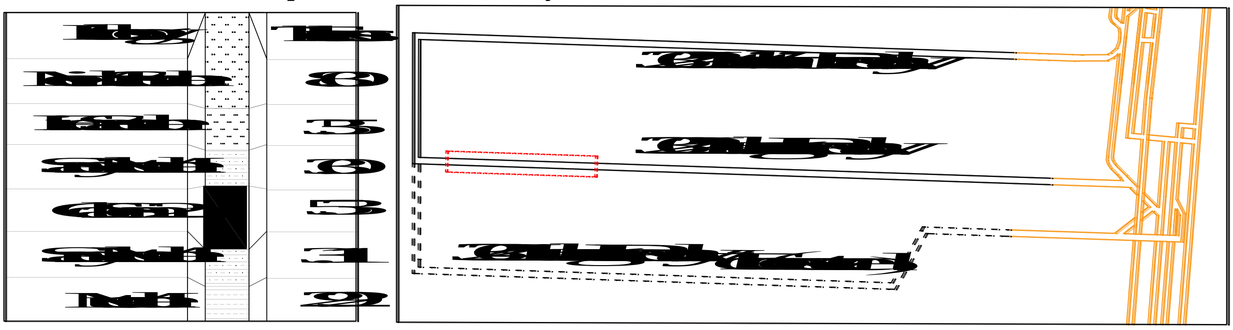


Figure 1: Comprehensive stratigraphic column and layout of mining face.

2.2. Shaped pre-splitting Blasting Roof Cutting

The technique of power aggregation through detonation [11] triggers the power accumulation impact on the explosive outcome via the energy-storing mechanism. This results in the power consolidation stream in a predetermined route and induces tensile stress intensity to establish a pre-splitting plane via tension breakdown of the roof layers in a specifically guided pathway (Figure 2). Furthermore, the presence of the energy-gathering blasting tube lessens the explosion product's direct impact on the borehole wall and hampers the growth of fractures in the non-predefined direction. This helps to minimize the harm inflicted on the rock mass in directions other than the predetermined one. The energy accumulation apparatus is composed of high-strength polyvinyl chloride (PVC) pipes. The design strength of this device varies based on the rock's lithology.

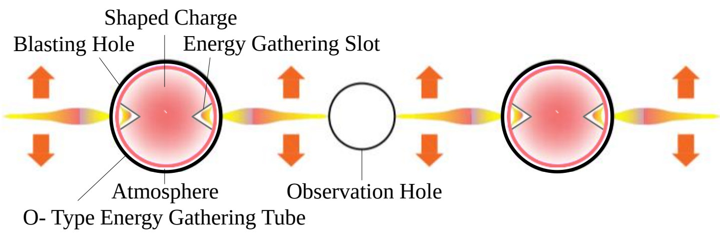


Figure 2: Schematic of the principle behind bidirectional energy-harvesting tensile hole blasting.

2.3. Abutment Pressure in Each Stage of Gob-side Entry Retaining

Prior research has shown that gob-side entry retention must go through four specific phases [12]: excavation of the roadway, dealing with increased pressure on the abutment, adjusting and stabilizing the surrounding rock of the roadway, and reusing the adjacent working face. Once the mining face has extracted the coal seam, the strata overlying the stope produce large-scale movement and cause continuous adjustment of the stress, forming a mining stress field [13],The mining roadway is positioned in proximity to the work face and adjacent to the goaf, making its roof susceptible to the effects of the mining pressure field.

In consideration of the mine's specific geological and production conditions, and the characteristics of the mine pressure. Gob-side entry retaining construction is segmented into six sections, namely the reinforcement support area for the roof and two sides, roof cutting drilling construction area, directional cracking area, advanced support area, gob-side entry retaining dynamic pressure influence area, and gob-side entry retaining stability area (Figure 3). It should be noted that under pressure reduction procedures, the deformation patterns of roadway within the advanced directional fracturing zone differ. Under the influence of advanced cutting, the transformation in the roof is not only a conventional expansion but is closer to rotational sinking deformation.

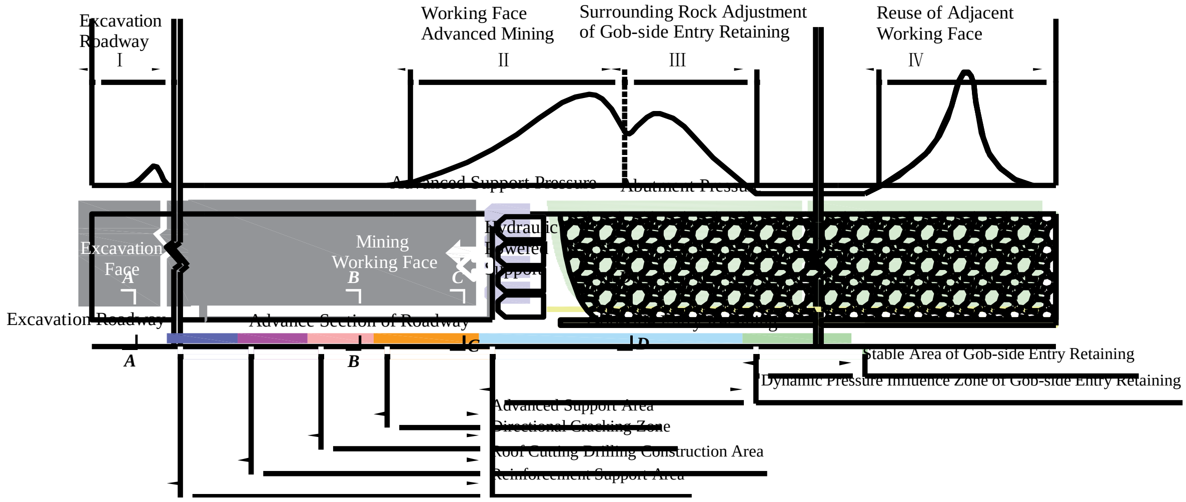
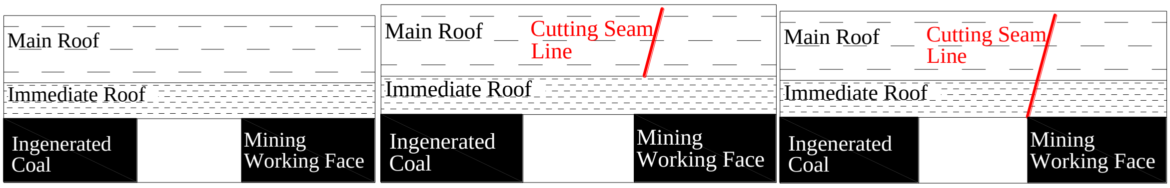


Figure 3: Regional distribution of gob-side entry retaining affected by mining stress.

3. Numerical Simulation of Stability of Advanced Pre-Splitting Roof Cutting Roadway

When the roadway is subjected to energy-gathering blasting and roof cutting, the blasting mud needs to be used as filler at the termination of the blasting hole after the explosive is filled to guarantee the effect of the cumulative blasting. The end of the hole is not filled with explosives, so the end of the hole is not penetrated after cutting the roof. Under normal conditions, after coal extraction, the collapse of the goaf roof causes it to rotate and sink along the cutting surface. At this time, the flexural moment is been generated on the cutting surface. Because of the rotary flexural moment's influence, the blast hole efficiently penetrates the cutting surface, achieving both roof cutting and pressure relief [10]. During field observations, it was noted that the roof above the roadway experiences increased subsidence after blasting for roof cutting. In the local roadway section, due to the low strength of the direct top of the sandy mudstone, the cutting seam sealing section often penetrates in advance in the leading section of the roadway. In addition, the phenomenon of punching often occurs during the blasting operation. The poor sealing effect of the borehole leads to the release of the explosion waves along the blast hole to the free surface, leading to fragmentation of the nearby rock in the shallow part of the blast hole. To investigate the stress change and deformation mechanics of the rock surrounding the roadway in the advanced support section under pre-splitting cutting seam penetration, three cases of no roof cutting, incomplete roof cutting (the cutting seam surface is not penetrated), and complete roof cutting (the cutting seam surface is penetrated to the roadway roof) were simulated. Figure 4 shows the scheme for cutting the roof.

To simulate the impact of the cutting seams on the mining roadway during mining, we conducted a complete process simulation of the mining operations. This involved excavation, pre-splitting of the roof, and mining.



(a) no roof cutting (b) incomplete roof cutting (c) complete roof cutting.

Figure 4: Schematic of advanced roof cutting simulation scheme:

4. Modeling

A FLAC3D model was developed for the 32021 mining area in Liangbei Mine, focusing on the coal seam strata conditions. The model's size was 300 m in length, 120 m in width, and 60 m in height. Its motion was constrained by the side and bottom boundaries, with the top boundary experiencing a vertical pressure of 13.75 MPa to replicate the weight of a burial depth of 500 m. The side pressure factor was 1, and the horizontal stress was also 13.75 MPa. The mine height was 5.3 m, and the coal bed inclination was 7 °.To reduce the computational requirements, the mine face was 80 m long in the simulation (Figure 5).Table 1 presents the characteristics of each rock layer.

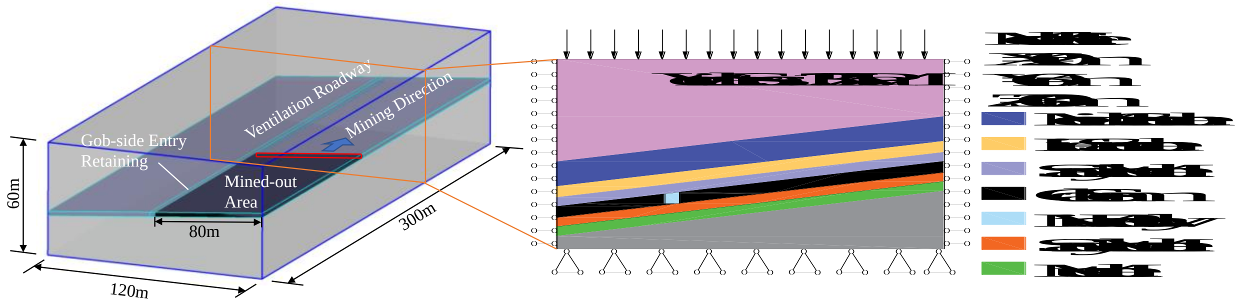


Figure 5: Numerical model and boundary conditions.

The rock layers in the model were all solid elements, and the Mohr-Coulomb constitutive model was employed to conduct the numerical analysis. The interface structural component was employed to replicate the characteristics of the cutting surface, and the structural element was given normal stiffness and shear stiffness to simulate the contact effect after cutting. The simulation was performed in the order of roadway excavation → support → roof cutting → mining. In the simulation, cyclic excavation was adopted. Each cut of the face was advanced by 5 m, and 600 steps were calculated. If the cut did not penetrate, the cut penetrated the roof after mining.

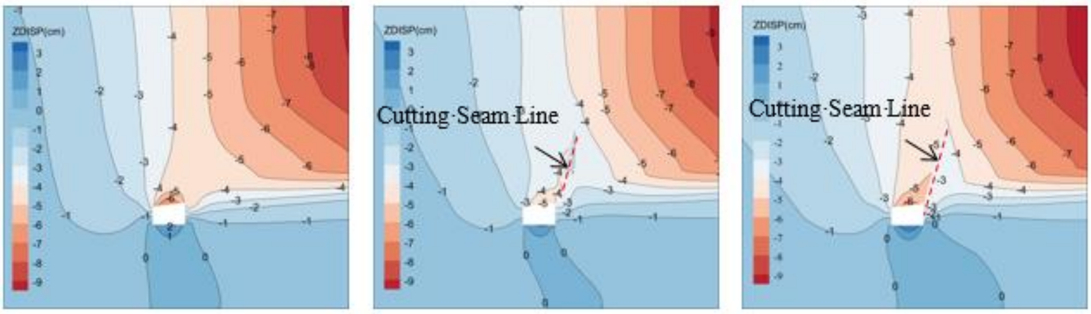
Table 1: Physical and mechanical parameters of rock strata.

Lithology	Thickness (m)	Density (kg m^{-3})	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Internal friction angle (°)
Medium sandstone	8	2750	6.3	3.5	2.6	40
Fine sandstone	3.5	2450	5.5	2.5	3.5	45
Sandy mudstone	3	1800	5.5	2.3	2.3	23
Coal seam 2	5.3	1400	4.5	1.7	1.8	25
Sandy mudstone	3	1750	5.5	1.9	2.5	25
Mudstone	3	1950	4.8	2.0	2.4	24

4.1. Displacement Evolution of Surrounding Rock of the Retained Roadway after Advanced Pre-Splitting Blasting

The deformation behavior of each rock layer in the roof is illustrated in Figure 6, both before and after the roof cutting and pressure relief.

① Prior to roof cutting, the roof strata at the location 5 m from the roadway had varying degrees of subsidence, and they rotated toward the mining face side as a whole. The deflection of the leading roadway roof was influenced by the deflection of the goaf. The rotary subsidence of the leading roadway roof was greatly reduced. After the roof cutting. The highest settlement of the roadway roof decreased from 79.3 mm before roof cutting to 46.3 mm. The main roof's maximum deflection decreased from 75.1 mm to 48.8 mm at a distance of 15 m from the road's center on the left side after cutting the roof. The reason for this was that the roof of the roadway was converted from a long arm beam to a short after cutting, which reduced the cantilever load and benefited the roadway stability [14]. ②With increasing depth from the roadway roof, the upper strata of the roadway began to separate. The rock deformation of the roof on either flank of the roadway was essentially the same as when the kerf was not penetrated. The deformation of the central position of the basic roof sandstone roadway above the roof of the roadway increased from 32.2 mm before kerf penetration to 44.5 mm, and the direct roof deflection increased from 46.1 mm to 57.8 mm. After the top surface of the pre-split cut was penetrated, the roadway roof changed from extrusion expansion deformation before penetration to right rotary sinking deformation. ③Because the immediate roof was soft, the deformation was the largest, and the roof separation was serious. After cutting the roof of the advanced roadway, the weak roof under the mining face collapsed. The additional stress generated by the cantilevered overburden at the back of the face was reduced, and the caving gangue provided support for the high-lying overburden. In addition, it destroyed the integral nature of the overlying rock in the goaf, changing the deformation mode of the high-overlying rock and low-overlying rock, and subsequently impacted the roof of the advanced section of the mining face, i.e., from the original overall coordinated deformation to non-coordinated deformation[15].



(a) no roof cutting (b) incomplete roof cuttin (c) complete roof cutting

Figure 6: Displacement cloud diagram of the roadway roof at the location 5 m ahead of the mining face

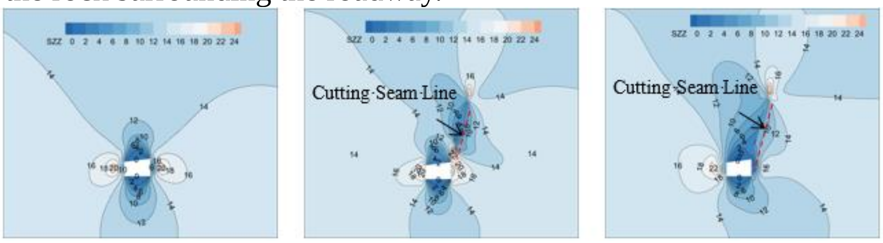
Figure 7 shows the maximum deformations of the roof strata under different roof cutting degrees at the location 5 m in the advanced mining working face. The order of maximum deformations from high to low was no roof cutting > incomplete roof cutting > complete roof cutting. In terms of the maximum deformation, the deformation of the carriageway roof was smallest where the roof was not completely cut.Yet, the stress distribution around the roadway should also be taken into account.

Figure 7: Comparison of the maximum deformations of the rock strata in the advanced roadway roof.

4.2. Stress of Roadway Roof before and After Advanced Pre-Splitting Blasting

When advanced roof cutting blasting is performed, it is generally performed dozens of meters ahead of the mining face, which also involves the area not affected by the dynamic pressure. Figure 8 shows a contrast of the vertical stress cloud diagram at a distance of 50 meters in front of the mining face, beyond the influence area of the advanced support stress.

Compared with the uncut roof, if the roof cut was not complete, the stress concentration on both sides of the roadway was not significantly improved. Although a large stress reduction area was generated around the cutting seam, the area of the stress concentration zone on the right-hand side of the road increased, and the perimeter rock around the roadway was still unstable, which was not suitable for roadway support. When the roof cut was complete, there was a 2 MPa increase in peak stress on the right side of the roadway, but the stress concentration on the left side decreased, and the overall stress around the roadway was reduced, which was more favorable for control and maintenance of the rock surrounding the roadway.



(a) no roof cutting (b) incomplete roof cutting (c) complete roof cutting

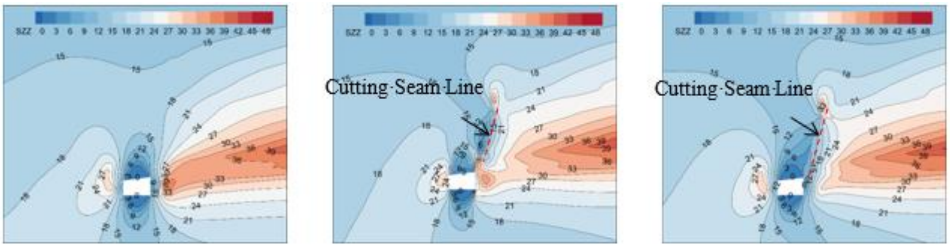
Figure 8: Vertical stress cloud diagram of the roadway outside the influence area of the advanced bearing stress.

The vertical and horizontal stress cloud map and the maximum principal stress cloud map of the roadway roof at the location 5 m ahead of the mine face as depicted in the Figure 9. The vertical stress evolution of the advanced roadway affected by mining was obtained, by analyzing the stress cloud diagram of the roof.

When the roof is not cut, the vertical stress in the roof is decreased to 0 MPa due to excavation of the roadway, leading to the release of the initial stress in the superficial roof. As the distance from the roof increases, the initial pressure in the rock gradually returns. When the roadway is excavated, stress concentration occurs on one side of the roadway. The excavation results in an asymmetrical distribution of stress concentration areas on both roadway edges. In addition, due to the lack of advanced pre-splitting and the large hanging range, the roof stress over the adjacent area on the left edge of the roadway increases to 29.8 MPa. Currently, stress concentration zones are present on both sides of the roadway, and the rock surrounding the roadway is susceptible to deformation;

When the cut surface of the seam is not fully penetrated, a stress reduction zone appears near the cutting seam. , but the stress is concentrated in the unpenetrated part of the cut surface and the vertical stress experiences a rise to 32.4 MPa. On the left side of the roadway, the area of stress concentration zone decreases. On the right side of the roadway, the stress concentration area and maximum stress decrease, and are closer to the right side of the roadway. The roof stress of the roadway is not fully released. At this time, the right side of the roadway is still in the stress concentration zone, and it is still a possibility of the surrounding rock undergoing deformation. In accordance with the field observations and numerical simulation results, stress concentration occurs in the unpenetrated part of the roof cutting surface. It is inferred that in practical engineering applications, due to the low strength of the sandy mudstone immediately adjacent to the roof, the sealing part of the cutting surface undergoes plastic deformation under shearing stress and gradually penetrates the roof.

When the cutting surface is completely connected, the stress transfer of the roof strata on both sides of the slit is interrupted, and the area of the roof stress reduction area increases, the stress in every layer of the rock in the roof within the cutting area decreases, and the adjacent rock tends to stabilize. The areas of the stress concentration zones on the side of the mining face decrease. The peak stress moves to the deep part of the working face, so that the roadway side is in the stress reduction zone, and the peak of the stress in the roof increases from 46.7 MPa before roof cutting to 48.7 MPa.



(a) no roof cutting (b) incomplete roof cutting (c) complete roof cutting

Figure 9: Cloud diagram of the roadway stress under the influence of advanced support stress: (a) no roof cutting

Based on the aforementioned analysis of the stress distribution pattern of the surrounding rock in the roadway both before and after pre-splitting cutting, it can be concluded that the pre-split seam can interrupt the stress transmission of the roof, minimize the effect of the mining stress on the deformation; increase the area of stress reduction in the roof of the advanced section of the roadway, and effectively avoid deformation of the rock surrounding the gob-side entry retaining and its advanced section. When the cutting surface in the advanced section is not fully penetrated, the stress surrounding the cutting surface is reduced, and the stress transfer can be interrupted. The stress of the rock that surrounds the roadway roof superficially is not completely released. In addition, the phenomenon of stress concentration occurs in the unpenetrated part of the cutting surface.

5. Conclusion

(1)The deformation law of the roof of a mining roadway before and after the dynamic pressure after pre-splitting roof cutting is clarified. After roof cutting, the hanging roof area of the goaf is reduced, and the roof deformation of the advanced roadway in the area affected by the dynamic pressure is significantly lower than that before roof cutting. By penetrating the cutting, the displacement of the roadway roof gradually evolves from expansion of the roof to deformation of the right rotation subsidence, and the separation of the rock strata above the roadway and the roof of the mining face is obvious.

(2)The stress distribution of the surrounding rock in the advanced section of the roadway under different advanced roof cutting conditions is revealed. Within the region influenced by the advanced abutment pressure, the stress level and stress concentration area on the right side of the roadway increase greatly when the roof is not cut. If the roof is not complete cut, the effect of improving the stress environment around the roadway is general, and only the stress transfer of the roof can be cut off. When the roof is completely cut, the high stress transfer between the roof rocks is cut off, and the vertical and horizontal stress values around the roadway are reduced to the lowest. Pre-splitting roof cutting leads to an increase in the maximum value of the advanced mining stress, and it moves toward the deep part of the mining as the penetration value of the directional roof cutting increases.

(3)The factors influencing the roof stability under different roof cutting conditions inside and outside the area influenced by the dynamic pressure are analyzed. Outside the range of influence of the pressure of the abutment, whether the pre-splitting cutting seam is connected or not is the key influencing factor. In the area influenced by the advanced abutment pressure, whether the top is cut is the key influencing factor.

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