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Retracement Ground Pressure Appearance and Control of the Working Face under the Overlying Residual Pillar: A Case Study

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Abstract: On the working face below shallow and close coal seams, there are residual pillars. The mine's ability to operate safely is constrained by the coal pillars' vulnerability to sudden instability and powerful ground pressure disasters during withdrawal. This paper uses the 31,106 working face of the Huoluowan coal mine as its research backdrop and employs field observation, theoretical analysis, and numerical simulation to examine the strong dynamic load mechanism of the overlying coal pillars. According to the analysis, the residual pillar's stress diffusion angle is 29 degrees after mining the working face above it, which has an impact on the main roof's stability above the working face's retracement roadway. The main roof is impacted by the excavation disturbance and the remaining pillars during the working face's final mining phase, displaying a complex stress superposition state. The retracement roadway is significantly deformed as a result of the plastic zone of the surrounding rock changing from small-scale damage to extensive damage. The proposed "hydraulic roof cutting + reinforcement support" prevention technology is based on the prevention idea of weakening important rock strata, changing the stress transmission path, and strengthening adjacent rock. Field testing shows how hydraulic fracturing reinforces the roof structure, lessens the heavy dynamic load on the supporting pillars of overlying residual coal, reduces rock deformation in the retracement roadway, and ensures the stability of the working face during withdrawal. The study's findings are significant for the secure removal of a working face under similar circumstances.

Keywords: residual pillar; retracement roadway; rock pressure; hydraulic fracturing

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1. Introduction

To achieve the safe and quick retracement of the working face during mine production, many nations use pre-driven retracement roadway technology [1,2]. The load of the hydraulic support increases significantly under the combined influence of the high static load of the long hanging roof and the high dynamic load of the high roof collapse during the final mining period when there is a thick and hard roof or legacy coal pillar above the retracement roadway [3–6]. The working face, which is vulnerable to strong mine pressure such as roof fall, spalling rib, and water and sand inrush, will also be impacted when the overlying coal pillar is removed due to its high roof and stress concentration [7–9]. Additionally, dynamic mine pressure phenomena like roof cutting and support crushing, support column being crushed, and column damage [10–14] will occur, which increases the likelihood of roof disasters. Oyler [15] gathered 131 pre-driven retracement roadway application cases from various countries, including 13 unsuccessful cases brought on by roof disasters. Effective treatment is required to ensure safe mining because roof disaster has always been a significant safety hazard during the withdrawal of the working face.

In the mining regions of Shendong and Northern Shaanxi in China, there are multiple layers of recoverable coal resources, which are the geological occurrence form of the coal seam group [16–18]. The occurrence characteristics of coal seams include shallow coal seams, which are typically buried at a depth of 200 m or less. Due to the limitations of geological conditions, mining technology, and equipment level, specific safety protection coal pillars must be set up during the coal seam group mining process. This causes the stress concentration phenomenon to form in the rock stratum under the coal pillar, posing a serious safety risk to the mining of the working face below the coal pillar.

Numerous studies have been conducted on the migration law of the overlying strata in shallow coal seam mining by academics from various nations. B. Hobelwait, an Australian, observed the behavior of the law of mine pressure in the working face. After the working face was mined from the open-off cut, it was discovered that the bedrock roof of the coal seam along the coal wall and the edge of the goaf was broken along the vertical direction. It was noted that the broken block was not a part of the hinged bridge arch form [19]. Numerous experiments have been conducted in the study of shallow coal seam mining in some South American and Indian nations. Many researchers today hold the view that because of the bedrock roof's high fracture angle when it breaks, surface subsidence is directly impacted, and the pressure strength of the working face is high and challenging to control [20–22].

The stress in the nearby rock goes through stages of increasing, decreasing, and stabilizing as a result of mining of the coal seam. The stress is gradually transferred from the coal pillar to the floor rock layer as well as the working face and roadway of the lower coal seam, which results in the stress concentration phenomenon and affects the stability of the nearby rock. The stability control of the working face and coal pillar during the mining process has been extensively researched. Yue et al. [23] built a structural mechanics model of the "elliptical stress arch" of the boundary coal pillar of the overlying coal seam and made note that the roadway's additional stress is influenced by the roadway's horizontal offset, coal seam spacing, and mining height. In order to control mine pressure, Roman Dychkovskyi et al. [24] examined the internal stress–strain state of the rock mass in front of the working face and coal pillars of the Lvivvuhillia SE mine using the distribution law of abutment stress. By analyzing the internal development characteristics of the coal pillars in inclined coal seam mining at the Zhairemskoye field, Daulet Takhanov et al. [25] established the parameters of coal pillar stability in the process of coal seam mining and achieved the safe and effective mining of the coal mine. The issue that the residual pillars of the upper coal affected the working face of the lower coal and caused difficulty with road maintenance was resolved by Shi et al. [26]. The law of mine pressure behavior of the working face under coal pillars is obtained through investigation of the typical working face under the influence of coal pillars in China. By examining the roof pressure of the surrounding rock in the working face, Vu [27] was able to control rib spalling and roof fall.

Tu et al. [28–30] studied the potential overburden deformation and damage caused by the mining of the close coal seam with a fully mechanized working face under the shallow room pillar goaf, the mechanism of impact weighting and frame pressing caused by the accumulation of elastic energy of rock mass, the law of surface movement, and the law of underground movement in light of the mechanism and prevention technology of the instability of the residual pillar in the goaf and dynamic load rock pressure. The law of coal pillar blasting, roof caving, and pressure relief is another factor. Plans for surface borehole sand injection to fill coal rooms and reasonable mining height control were proposed. Additionally, it should be noted that the fully automated top coal caving roadway underwent severe deformation due to the stress coupling effect brought on by the upper coal pillar and the coal mining in this layer, which is consistent with the fully automated top coal caving roadway's appearance under the upper residual coal pillar according to the law of ground pressure. At the same depth of the floor rock stratum, the stress increase coefficient is largest at the center line of the coal pillar, followed by the lower edge of the coal pillar, while the surrounding rock deformation of the roadway beneath the goaf is minimal. It was suggested that pillar width be reduced in distinct sections and that mining roadways be organized logically. The mining process caused instability in the overlying concentrated coal pillar and sudden rotation instability in the key bedrock block, which destroyed the hinge structure and caused sliding instability to transform into a dynamic pressure accident, according to Yang et al.'s [31] analysis of how the fully mechanized working face of the 3–1 coal seam in Shigetai coal mine passed through the goaf and coal pillar of the overlying room. Zheng et al. [32] used simulation techniques to study the working face of the Sanhejian coal mine's mining conditions and came to the conclusion that the high-stress concentration area of the coal pillars is susceptible to rock burst disasters. According to Feng et al. [33] and Zhang et al. [34], the stress in the floor strata under the coal pillar is thought to have a non-uniform distribution, be greatest under the coal pillar, and decrease quickly as it spreads to both sides of the coal pillar. The mining roadway in close proximity to coal seams is more likely to be deformed and damaged, and the support structure is more susceptible to localized overload and damage that could cause instability. The non-uniform effects of the coal pillar stress as well as the high stress of the coal pillar should be considered in the design of the mining roadway. The stress change rate is recommended as a way to choose a road's position that is reasonable.

The studies mentioned above put forth a reasonable staggered distance in light of the theory and preventive measures proposed by the aforementioned researchers under the condition of the overlying residual pillar and the room-and-pillar mining gob [35–39] during the routine mining process of the fully mechanized working face as well as the impact of the overlying coal pillar on the lower coal seam roadway. However, for the lower coal seam entering the final mining phase, less work is required for the theoretical calculation and numerical simulation of the analysis of the influence of the overlying residual pillar on the retracement roadway of the fully mechanized working face.

In order to prevent damage to the surrounding rock caused by the influence of coal pillars on the withdrawal channel during the final mining phase of the double retracement roadway of the 31,106 working face, we will use the Huoluowan coal mine as our engineering reference. The stability of the protective coal pillar, the stress propagation law of the coal pillar floor, and the failure mode and stress distribution characteristics of the overburden during the final mining of the working face are all examined using the method of combining theoretical calculation and numerical simulation, and the mechanism of the dynamic load pressure above the withdrawal channel is clarified. The field engineering test of the proposed weakening technology of the strong mine pressure area during the withdrawal of the working face under the overlying coal pillar has produced outstanding results by weakening the key strata, altering the stress transfer path, and strengthening the surrounding rock.

2. Geological Overview and Engineering Problems

2.1. Geological Overview

The Huoluowan coal mine is located in the Shendong mining area, which is a typical shallow coal seam with a short distance. The main coal seams are 2–2 and 3–1 from top to bottom, with an average thickness of 5.4 m and 3.7 m, respectively, and a layer spacing of 37.1 m. A nearly horizontal coal seam would be consistent with the two coal seams' dip angle of 1–3°. The mining of the 2–2 coal seam leaves behind a variety of residual pillars, including boundary coal pillars, small room coal pillars, and coal pillars in the mining area, which could pose safety risks when mining the 3–1 coal seam in the lower layer.

The majority of the roof and floor lithology of the first mining of the working face 31,106, which is located in the south wing of the main roadway, is composed of sandstone and mudstone. The working face has a 230 m average burial depth, a 3300 m strike length, and a 240 m dip. The working bread of the 31,106 consists of two headgates and one tailgate. After mining is complete, the equipment is moved using a double retracement roadway that has already been dug, including the main retracement roadway (MRR) and auxiliary retracement roadway (ARR). The stopping and retracement roads have section sizes of 5.4 m and 3.7 m, respectively, and the protective coal pillar has a width of 20 m. These are all pushed along the surface of the coal seam. After mining, several working faces leave goaf and coal pillars of the 2–2 coal seam on the 31,106 working face. The remaining coal pillar in the mining area is 20 m wide and is located 15 m from the stopping line of the 31,106 working face. The upper and lower working surfaces are shown in Figure 1a.

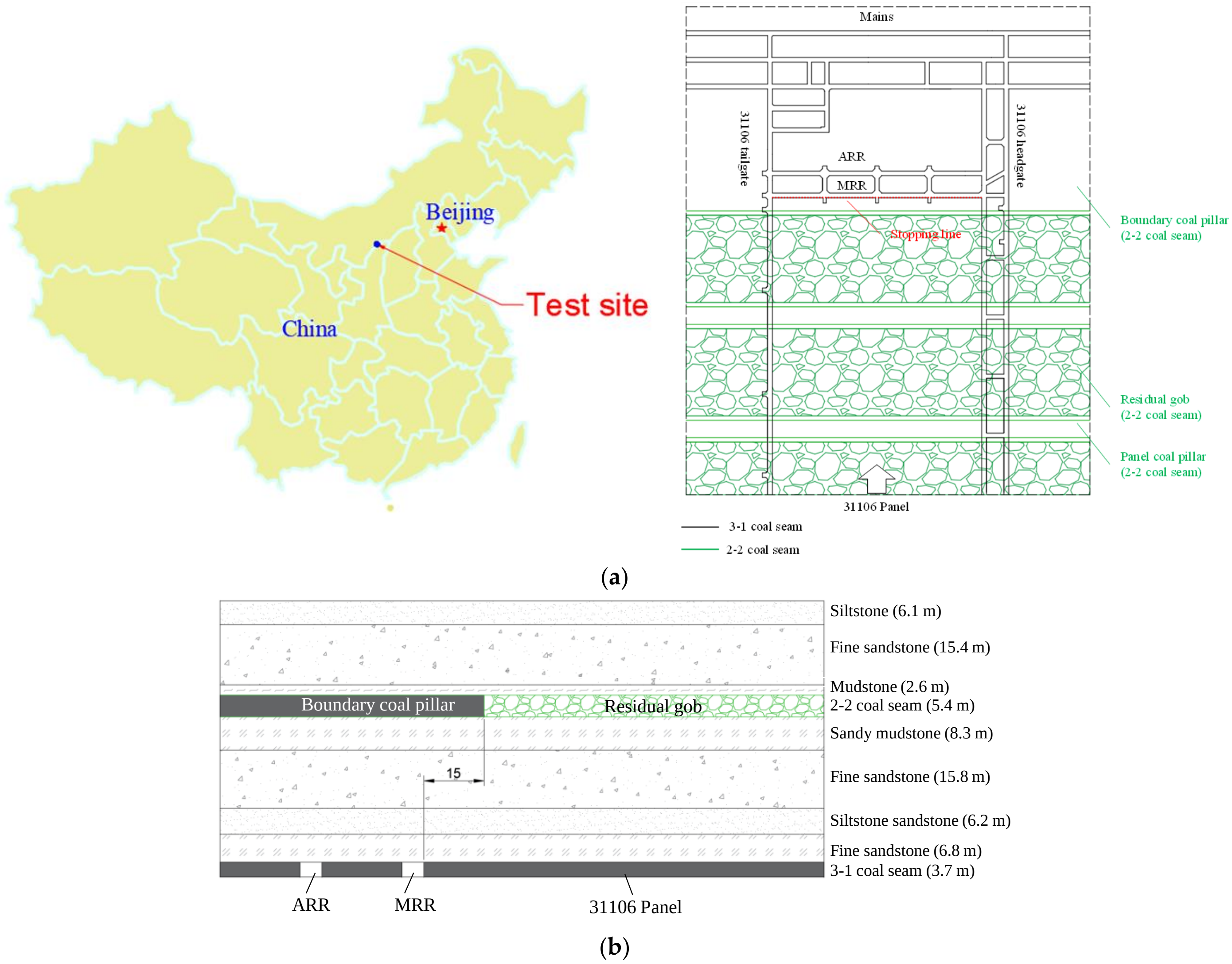


Figure 1. Overview of working face 31,106: (**a**) The layout of the 31,106 panel and 2–2 residual coal seam; (**b**) section of the relative position of the retracement roadway and the residual pillar of working face 31,106.

2.2. Potential Engineering Problems

During the final phase of mining, there was a problem with the 31,104 and 31,105 working faces covering the residual pillars or goaf in the north wing of the main roadway, respectively. In comparison with the working face in the overlying goaf (31,104 working face), the 31,105 working face experienced a significant number of serious ground pressure issues, including the pressing frame, serious wall spalling, empty roof, etc., of the working face, significant deformation of the main retracement roadway, and failure of the support body, etc. The comparison of ground pressures is shown in Table 1. The comparison results show that the overlying residual coal pillar is what causes the floor stress concentration, and that the working face's normal advancement is also what causes the leading bearing stress and the lateral bearing stress of the retracement roadway. Due to the superposition of various types of stresses, the final mining area and the main retracement roadway (MRR) of the 31,105 working face exhibit extremely high ground pressure. Figure 2 depicts severe damage to the surrounding rock and the road. Understanding how surrounding rocks affect the MRR and the law of the working face appearance at the completion of the mining pressure phase is crucial.

Table 1. Comparison of mining pressure behavior at the completion of the 31,104/31,105 working face.

Comparison	31,104 Working Face	31,105 Working Face
Distribution of residual pillar	40 m in the stopping line	10 m outside the stopping line
Average support pressure of working face	35.4 MPa	41.5 MPa
Gangue leakage between working face frames	Local	Entire working face
Roof fall of working face	A few	Entire working face (see Figure 2)
Pressing frame condition of working face	Nothing	1 support press frame
Coal wall flaking	Local	Entire working face
Roof condition of main retracement roadway	The subsidence is 40~60 cm	The subsidence generally exceeds 1 m
Side condition of the main retracement roadway	Partial spalling and bulging	Serious spalling
Deformation of auxiliary retracement roadway	Almost no deformation	The roof sinks slightly, with few side walls
Damage of support	3 anchor cables and 2 anchor bolts	The number of damaged bolts and anchor cables exceeds 100
Measures taken	Nothing	Reinforcement support, wooden crib support, blasting forced caving

(**a**) (**b**)

Figure 2. 31,105 ground pressure behavior during final mining retracement of working face: (**a**) roof fall of working face; (**b**) the retracement roadway is severely deformed.

3. Establishment of Numerical Model of Residual Pillar and Analysis of Stress Propagation

3.1. Materials and Methods

Flac^{3D} software is a three-dimensional numerical simulation software suitable for geotechnical calculation, which can be used for the excavation calculation of the working face in a coal mine. The circumstances are more difficult because the roadway excavation and working face mining of the two-layer coal seam are involved in moving the 31,106 working face forward. Therefore, the stress concentration brought on by the underlying residual pillar is examined using Flac^{3D} numerical simulation software. The model created in this study employs the Mohr–Coulomb criterion.

The model is built based on the working face's overburden condition (31,106): (a) It includes two coal seams (3–1 coal seam, 2–2 coal seam) and seven actual rock layers in the height direction (see Figure 1b). A total of 20 m of overburden and underlying rock layers are added above and below the model in the direction of advancement in order to offset the influence of the upper and lower boundaries. (b) In order to ensure accuracy, it is necessary to take into account the relative positions of the residual pillar and the retracement roadway in the direction of advancement and to take into account that the goaf range of the 2–2 coal seam is greater than 120 m [40]. (c) In terms of trend, a model with a certain thickness can be established, and the middle section can be used for ground pressure analysis because the 31,106 working face is the first mining face at the south wing of the main roadway, there is no influence of lateral stress in adjacent the goaf, and the ground pressure behavior in different areas is similar. The model height is 109 m, the strike length is 270 m, and the dip length is 40 m, in total.

The global initial size of the model is 1 m, with 1,194,200 cells. A vertical stress of 2.8 MPa is applied vertically above the model, and a vertical zero displacement constraint is applied laterally and at the bottom. The model's parameters are established using indoor experiments and earlier research [38]. Mechanical parameters of model are shown in Table 2. The simulation is divided into four sections: primary rock stress balance; 2–2 coal seam mining; 31,106 retracement roadway excavation; and 31,106 working face mining. The model after the initial balance of rock stress is shown in Figure 3.

Table 2. Mechanical parameters of model.

Rock Stratum	Density (kg/m^3)	Bulk Modulus (GPa)	Shear Modulus (GPa)	Cohesion (MPa)	Tensile Strength (MPa)	Internal Friction Angle (°)
Siltstone	2267	6.94	3.97	2.24	2.80	30
2–2 and 3–1 Coal seam	1263	2.16	1.42	1.45	0.80	24
Fine sandstone	2358	13.60	5.86	3.65	3.60	44
Mudstone	2356	3.55	2.34	0.89	0.79	26
Sandy mudstone	2400	3.85	2.42	1.66	1.20	26

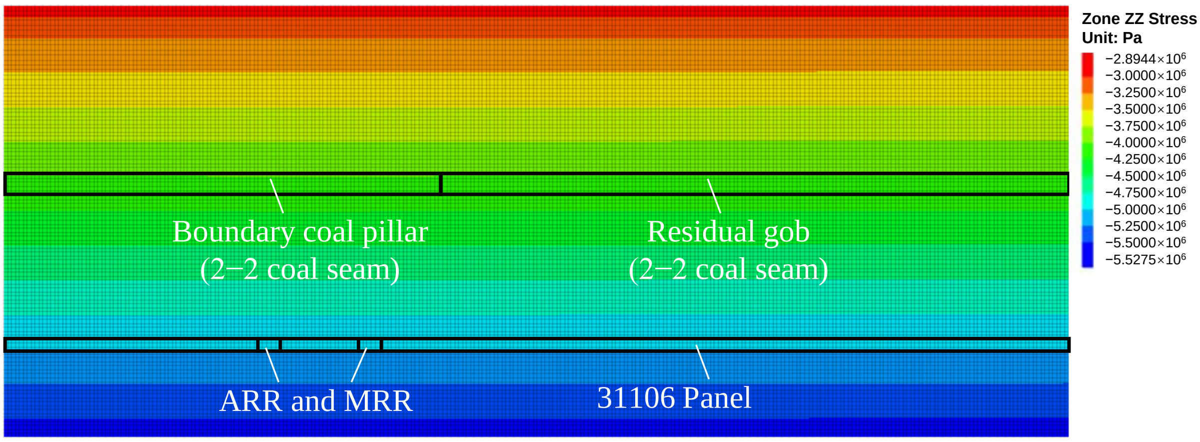


Figure 3. Schematic diagram of numerical model for mining under residual pillar (vertical stress cloud chart).

3.2. Analysis on the Stress Propagation in the Lower Floor of the Residual Pillar

In order to accurately represent the working face of 31,106's geological conditions, the paper first simulated the stress distribution of the surrounding rock. The stopping line is currently 15 m horizontally away from the last coal pillar. The simulation results are shown in Figure 4. The pressure relief area, which is beneath the goaf and has a stress level lower than the original rock stress of the layer containing the 2–2 coal seam (4.1 MPa), is depicted in the figure. The stress is concentrated in the middle of the coal pillar, as well as the area of the roof and floor. The local stress has decreased due to the excessive load on the remaining coal pillar's edge, indicating that the elastic bearing in this region has changed to a plastic bearing. The elastic bearing area is where the coal pillar's peak stress (31.5 MPa) first appears, and as the vertical distance from the coal pillar floor increases, the floor's stress gradually decreases. The stress diffusion angle of the underlying residual coal pillar is 29°, as can be seen by comparing the stress nephogram with the original rock stress. Therefore, if the layer spacing is 37.1 m, the lower roadway must be positioned 20.6 m outside the residual pillar's perimeter to avoid being impacted by the floor stress concentration.

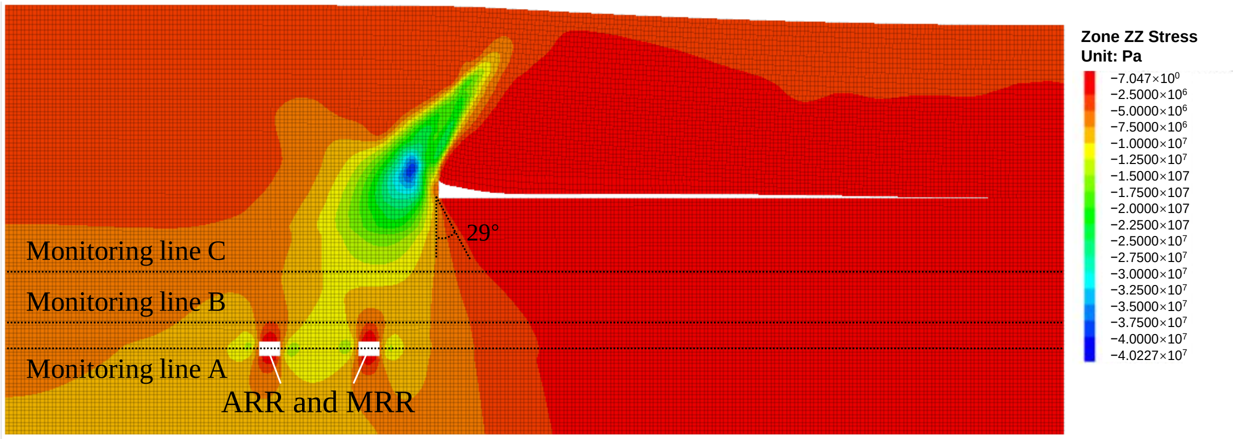


Figure 4. Cloud chart of surrounding rock stress under the action of residual pillar in working face 31,106.

In the middle of the 3–1 coal seam, the upper fine sandstone is the immediate roof and the siltstone is the main roof, and the model has three sets of measuring lines (Line A/B/C). The distribution of stress in the three coal/rock layers is shown in Figure 5. The model's coordinate in the x direction is represented by the horizontal position of the curve in this illustration. The minimum value is 0, the maximum value is 270, and the unit is m. The horizontal position of the coal pillar distribution range is 70–90 m, the horizontal position of the coal pillar stopping line (coal wall on the right side of the MRR) is 95. 4 m, and the horizontal position of the right boundary of the overlying residual coal pillar is 110. 4 m.

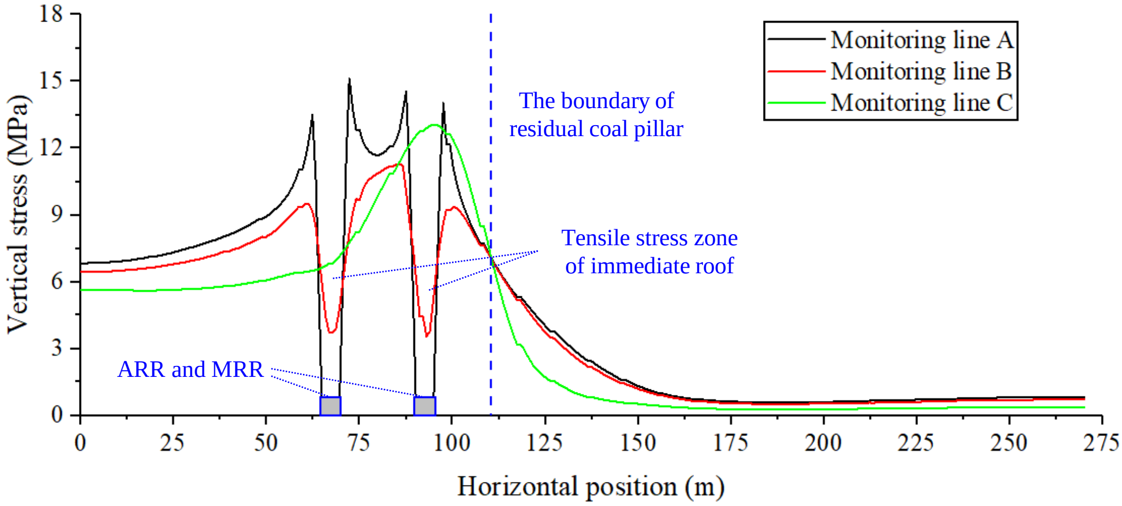


Figure 5. Stress monitoring results of measuring line.

The stresses on Line A and Line B in the retracement roadway's coal pillar region are not exactly symmetrical. Line C makes it abundantly clear that the residual pillar directly contributes to the stress concentration of the retracement roadway's roof and that the goaf has a pressure relief effect on the coal seam mining below. Accordingly, as shown by the three groups of curves, the stress distribution of the surrounding rock of the retracement roadway is influenced by the stress of the floor of the underlying residual coal pillar and the bearing stress brought on by tunneling. The coal seam, immediate roof, and main roof all experience maximum stresses at a horizontal position of 72.2 m (15.1 MPa), 84.0 m (11.9 MPa), and 93.9 m (13.0 MPa), respectively. In double heading, the roof of the retracement roadway's peak stress point typically appears above the coal pillar. However, because of the residual pillar's influence, the peak stress in Line C appears outside the coal pillar's range, indicating that the residual pillar's stress has a more significant impact on the surrounding rock of the retracement roadway.

3.3. Research on Influence of Residual Pillar Floor Stress on Retracement Roadway

The horizontal and vertical distances, in accordance with Reference [41], play a major role in the stress propagation of the floor of the remaining coal pillar. In the Huoluowan coal mine, several working faces have a coal seam spacing between 35 and 40 m, with little variation in the vertical distance. However, there are significant differences in the distribution positions of the remaining coal pillars across the various working faces. This paper focuses on the surrounding rock stress concentration of the retracement roadway beneath the remaining coal pillar because the horizontal distance between the stopping line of the lower working face and the remaining coal pillar varies. The study's conclusions have theoretically significant implications for the design and maintenance of each working face's retracement roadway in coal seam 3–1's north wing.

The stability of the immediate roof directly affects the deformation of the surrounding rock and the damage to the support body during the service period of the retracement roadway, whereas the stability of the main roof affects the overall stress distribution of the retracement roadway and the appearance of the ground pressure during the final mining withdrawal. The model further simulated the stress distribution of the residual pillar edge at these additional horizontal distances of 30 m, 20 m, 10 m, 0 m, 10 m, 20 m, and 30 m from the stopping line. The Line B and Line C stress distributions are shown in Figures 6 and 7, respectively.

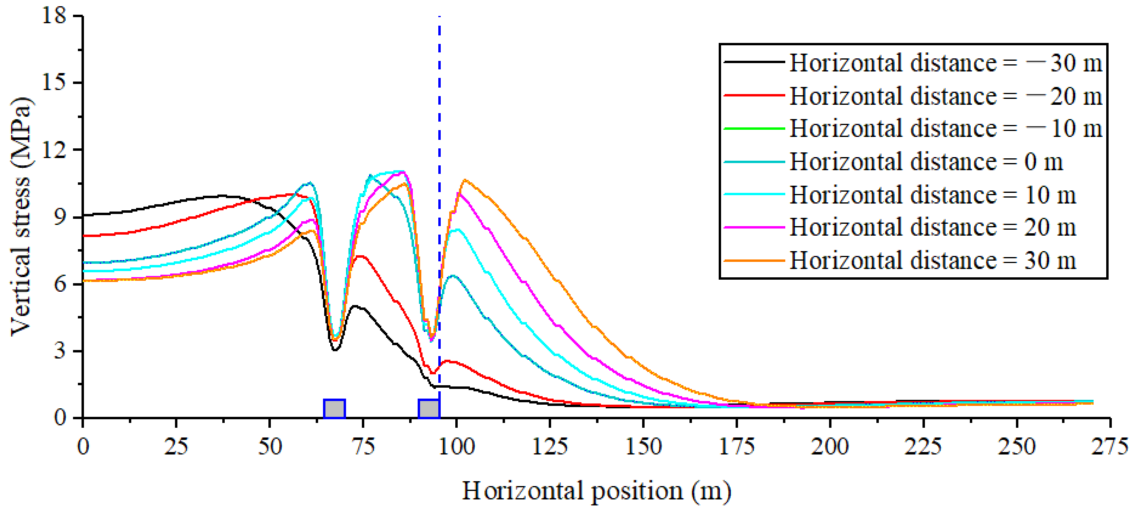


Figure 6. Distribution of immediate roof stress at different horizontal distances.

The immediate roof's stress distribution is shown in Figure 6. The phenomenon of pressure relief above the seven groups of curves occurs generally. The peak stress above the coal pillar is higher than that above the road, and the MRR and ARR are typically depressurized above seven groups of curves. As the horizontal distance increases from −30 m to 30 m, the stress level significantly decreases both in the retracement roadway and above the coal pillar. This is due to the fact that after the residual pillar's position was moved to the left, the MRR was less affected by the residual pillar's stress concentration. For instance, when the horizontal distance is −30 m, as shown in Figure 7, the retracement roadway is already present in the pressure relief area underneath the entire goaf. The minimum stress of the MRR immediate roof is decreased from 3.67 MPa to 1.41 MPa, a decrease of 53%, and the peak stress of the immediate roof above the coal pillar is decreased from 10.52 MPa to 5.03 MPa, a decrease of 62%. This demonstrates that the distribution position of the remaining coal pillar plays a significant role in the stress environment of the floor of the remaining coal pillar, which serves as the basis for the stress distribution of the surrounding rock after excavation of the retracement roadway. The distribution of the main roof stress in Figures 5 and 7 demonstrates that the main roof is typically less disturbed by the support stress of the retracement roadway. The distribution area of the peak stress and the location of the last coal pillar are directly correlated.

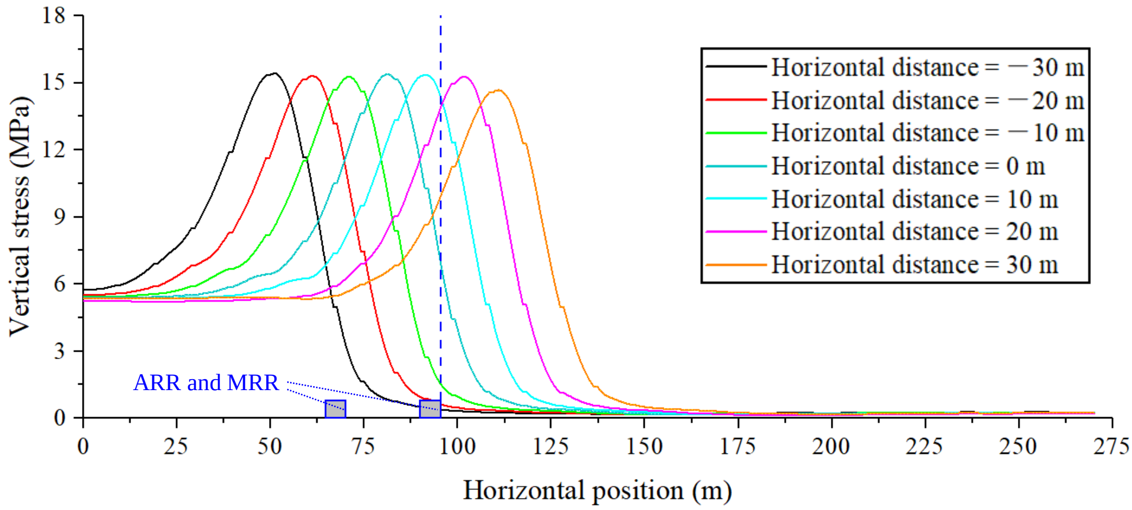
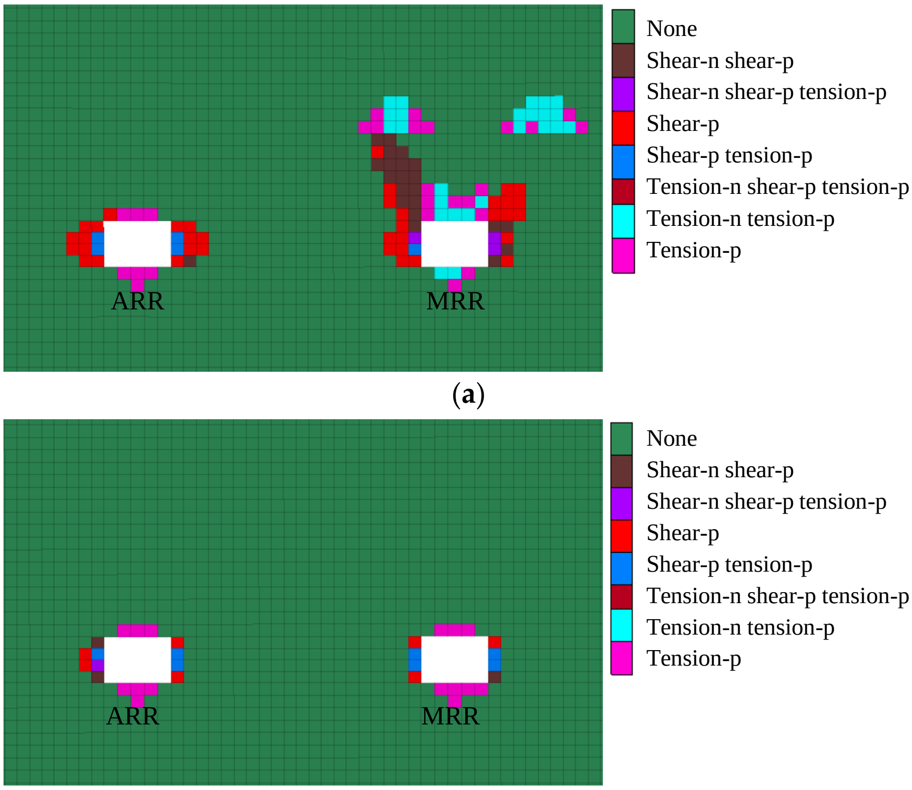


Figure 7. Distribution of main roof stress at different horizontal distances.

The stress environment is worse when the retracement roadway is located at the outer side of the residual pillar than at the inner side of the residual pillar, which can be inferred from the relative positions of the stress concentration area and the retracement roadway. In particular, the stress environment is worse when the retracement roadway is located at the outer side of the residual coal pillar than at the inner side of the residual coal pillar when the residual pillar is 10–20 m outside, the surrounding rock plastic zone area is laxer, and the surrounding rock stress concentration of the retracement roadway is higher. Figure 8 shows how the retracement roadway's plastic zone is distributed between horizontal distances of 15 and 30 m. In 31,106, the boundary of the left coal pillar and the working face are separated by a horizontal distance of 15 m, which is just within the range of 10–20 m. Additionally, the coal and rock mass will be simultaneously affected by the upper concentrated stress and the advanced mining dynamic stress when the last few meters of the working face are mined. This will present risks to the working face's mining efficiency and safety.



(**b**)

Figure 8. Distribution of plastic zone of surrounding rock of retracement roadway: (**a**) horizontal distance = 15 m; (**b**) horizontal distance = −30 m.

4. Study on Control Mechanism of Ground Pressure under Residual Coal Pillar in 31,106 Working Face

The research in Section 2 indicates that during the final mining withdrawal, the 31,106 working face =experienced multiple stress superpositions. This section will study in greater detail the issue of ground pressure appearance and control technology during the final working face mining stages while being influenced by pillars of residual coal.

4.1. Superimposed Influence of Mining-Induced Stress during the Last Mining Period in 31,106 Working Face

According to data from the field stress measurement points at Huoluowan coal mine, the peak stress point of advance mining is between 5 and 8 m in front of the working face, and the mining impact range is between 40 and 60 m. When there is no overlying residual coal pillar, the ground pressure of a 3–1 coal seam working face typically rises between 30 and 50 m before the stopping line and enters the final stage of mining. According to the stress distribution of the surrounding rock beneath the residual coal pillar of working face 31,106 in Figure 4, the influence range of the residual coal pillar stress concentration is 20.5 m outside the stopping line. Based on a thorough simulation and actual field conditions, this section will examine the ground pressure behavior at the final 30 m of the last mining face while atop residual pillars.

The retracement roadway and the overlying residual coal pillar both have an effect on the immediate roof of the working face of 31,106, but the overlying residual pillar has the biggest effect on the main roof, according to the stress analysis in the preceding section. Mining in the working face of 31,106 causes the nearby roof to be disturbed as a result, exposing a complex state of stress superposition. The working face's immediate roof stress curve in the simulation at 30 m, 20 m, 10 m, and 0 m before the stopping line is shown in Figure 9. As the working face approaches the stopping line, the leading stress on the working face intensifies and superimposes itself more intensely, raising the peak stress level. Prior to the working face's stopping line, a 30 m section experiences peak stresses of 12.32 MPa, 13.97 MPa, 16.55 MPa, and 22.81 MPa, respectively. The leading stress of the working face, the lateral bearing stress of the retracement roadway, and the stress on the floor of the remaining coal pillar intensify their superposition, which is what causes the continuously rising peak stress level.

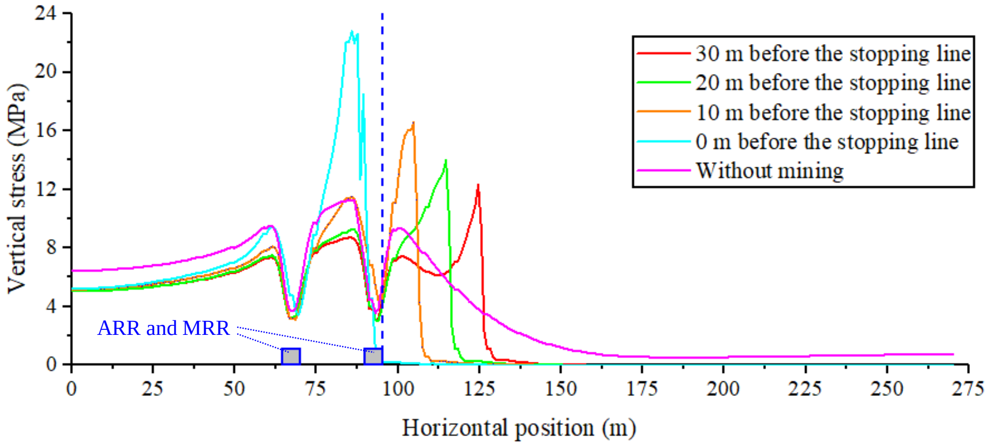


Figure 9. Distribution of immediate roof stress during the final mining period of working face 31,106.

When it has been advanced to the stopping line, the working face becomes completely connected to the retracement roadway. As the top directly above the main retracement roadway is destroyed, the peak point of the bearing stress is transferred to the top of the coal pillar. Peak stress in this area is 10.91 MPa higher than the stress curve of the untapped 3–1 coal seam, which has a significant effect on the roof and the retracement roadway below. This is also the reason for the severe deformation of the retracement roadway that occurred during the final stage of mining on the 31,105 working face. The retracement roadway of the working face beneath the residual pillar must be strengthened in order to increase the coal pillar's bearing capacity and the structural integrity of the roof.

4.2. Overburden Failure and Subsidence Law during the Connection of Working Face and Retracement Roadway

The overlying collapsed rock stratum and the interlayer rock stratum's dead weight load act as the lower working face pressure when the 31,106 working face is in the normal push mining stage. The high roof and the overlying remaining coal pillars will lose stability synchronously with the subsidence of the 3–1 coal when it reaches the final stage of mining and lies over the remaining coal pillars, in addition to the issue of stress concentration. This causes a sudden increase in the dynamic load and a dynamic pressure accident [14,31].

As shown in Figure 10, the simulation can express the bearing capacity and deformation of the rock stratum through the evolution of the plastic zone. The main plastic area is dispersed throughout the recovered 2–2 coal seam area after the retracement roadway is excavated, and the retracement roadway is only damaged after the excavation simultaneously impacts the local surrounding rock and the underlying residual coal pillar. Following the completion of the 3–1 coal seam mining, which transforms localized surrounding rock damage into significant plastic damage, the roof of the retracement roadway is the first to be destroyed. The plastic zone expands to the upper left along the 23° dip direction after the roof of the lower retracement roadway is damaged and subsides, which exacerbates the damage to the upper roof and the remaining coal pillar.

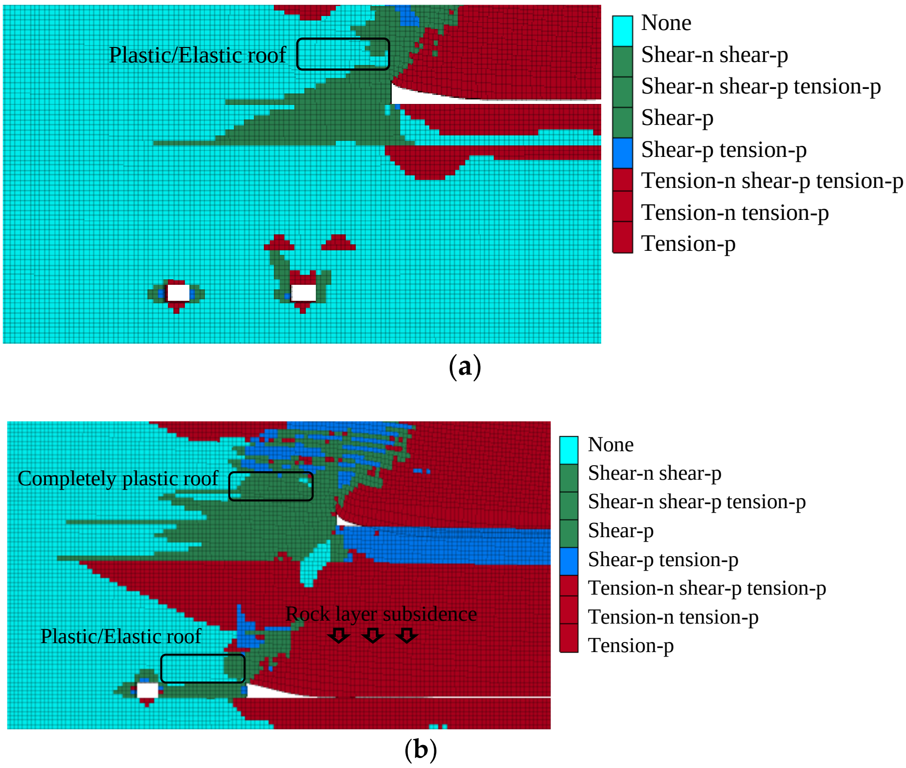


Figure 10. Distribution of plastic zones in different mining stages: (**a**) after mining of the 2–2 coal seam; (**b**) after the working face 31,106 is connected with the retracement roadway.

Figure 11 provides details on roof displacement at various mining stages. In general, the goaf space of the 2–2 coal seam is further reduced, the roof subsidence is further increased, and the mining disturbance range is further enhanced after the 3–1 coal seam is mined. This type of uneven subsidence will result in shear failure of the rock mass, reduce the roof's load capacity, and exacerbate the support of body damage. The displacement of the hanging roof area gradually decreases to zero along the horizontal direction. The plastic zone type in the suspended ceiling area of Figure 10 also illustrates this trend. Because the critical point distance of 0.5 m vertical displacement after the mining of the 2–2 coal seam and the 3–1 coal seam is 17.1 m and the critical point distance of 0.05 m vertical displacement is 10.3 m, it is likely that the mining of the 3–1 coal seam also affects the above-ground residual coal pillar and its roof.

To summarize the displacement analysis of the plastic zone and rock stratum, the combined instability of the roof of the 3–1 coal seam and the roof of the 2–2 coal seam will occur between the last mining of the 3–1 coal seam and the connection with the retracement roadway, posing a dynamic load risk to the lower working face and the retracement roadway.

4.3. Determination of the Pressure Relief Area of the Final Mining Roof in 31,106 Working Face

According to prior studies, the dynamic load effect of stress concentration and synchronous instability of multi-layer rock strata exposes the 31,106 working face to the risk of frame pressing and other accidents during the final mining phase. The available literature shows that using pretreatment techniques for the rock mass, such as blasting and hydraulic fracturing [42–46], to treat the roof beforehand can achieve the effect of roof cutting and pressure relief at the same time, and is an important way to eliminate the risk during the withdrawal of the last mining phase in the 31,106 working face. For the site to be used for roof cutting and pressure relief of the strata above, two conditions must be satisfied: (A) The site of the construction must be near complete rock strata. The rock mass pretreatment technology cannot achieve the effect of roof cutting because the rock mass in the plastic area or the damaged area has lost its bearing capacity. (b) The construction location should be as close to the stress concentration area as is practical. At this point, blasting or hydraulic fracturing-produced cracks can be expanded to lessen the stress concentration.

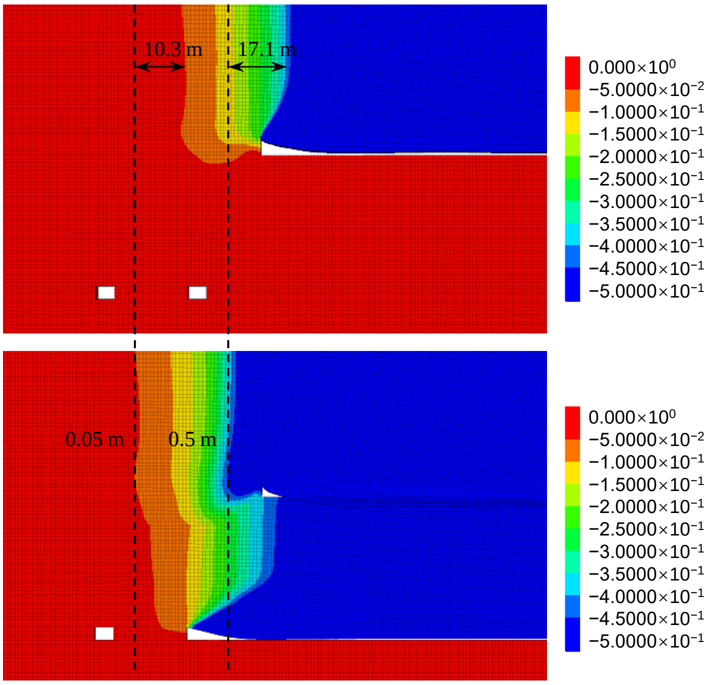


Figure 11. Distribution of roof displacement in different mining stages.

To lessen the effect of the overlying residual pillar on the pre-excavation double retracement roadway, roof cutting and pressure relief must be used after the mining of the 2–2 coal seam but before the 3–1 coal seam enters the final mining stage. After the mining of the 2–2 coal seam, the roof above the remaining protective coal pillar reaches its peak stress, the edge of the coal pillar may have a suspended roof, and the concentrated stress is transferred to the 3–1 coal roof through the coal pillar, according to the analysis above. The rock stratum in this area's stress environment and medium state must be changed as a result. Therefore, it is decided that the elastic bearing area in the main roof of the fine sandstone above the final coal pillar will serve as the first section of top-cutting pressure relief location (see Figure 12).

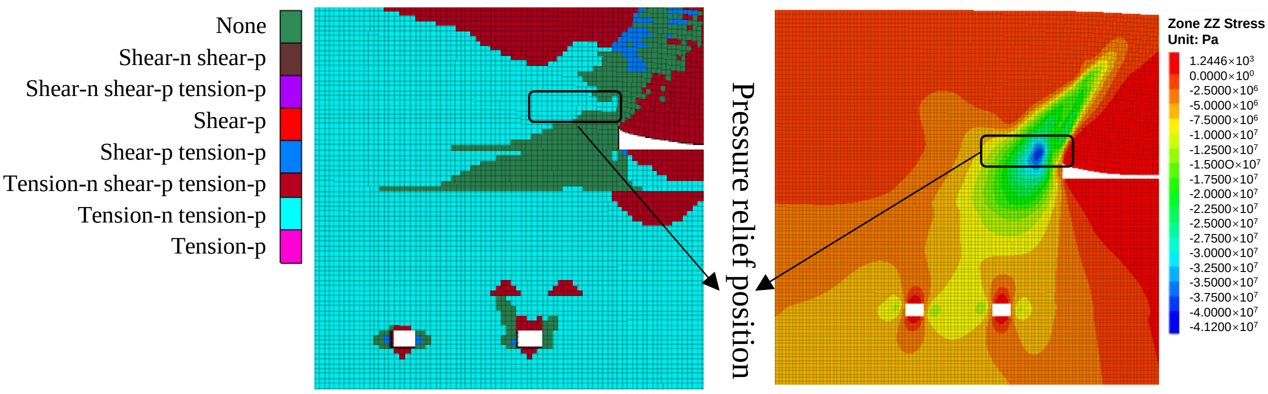


Figure 12. Top-cutting position at the first stage.

The hard roof above the coal seam is easily produced in the final stages of mining on the working face 31,106 due to the instability of the overlying residual coal pillar and the impact of mining-induced superimposed stress, and the roof of the retracement roadway is easily damaged. Even after the working face has been removed, the protective coal pillar and the main roadway continue to be affected by the main roof's hinged structure due to a variety of forces. Now, outside of the stopping line, the main roof breaking position must be set up above the 3–1 coal seam. On the one hand, the roof structure is relatively stable, and the retracement roadway is currently the main recipient of the roof's static load [47–50]. On the other hand, the concentrated stress transmission path through the upper residual pillar can be completely blocked, effectively controlling the ground pressure behavior to protect the retracement roadway. The top cutting position of the second stage is shown in Figure 13.

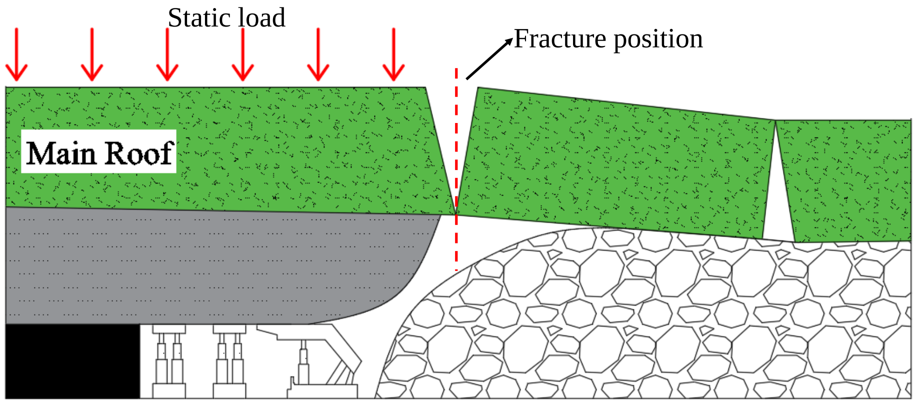


Figure 13. Top cutting position at the second stage.

In order to prevent the impact of the superposition of mining stress and coal pillar concentrated stress on the retracement road, it is necessary to use multi-stage roof cutting and pressure relief at the same time to eliminate the stress transmission path within the range of concentrated stress of the remaining coal pillar and hard roof overlying the retracement roadway, avoid the blind area of pressure relief, achieve the blocking, and positively protect the MRR.

5. Ground Pressure Control Scheme in the Final Mining Period of 31,106 Working Face

During the final mining stage, the non-isopiestic dynamic superimposed stress field affects the surrounding rock of the retracement roadway, causing it to no longer be stable under the original support conditions. To control the deformation of the surrounding rock of the retracement roadway, the stope's overlying rock structure must be adjusted to appear less under pressure when the working face is connected. This led to the development of a dual technology that combined hydraulic roof cutting with pressure relief and improved support for both the roof and the retracement roadway. It is suggested to fix the retracement roadway's deformation issue and guarantee the stability of the MRR and ARR.

5.1. Scheme for Strengthening Support of Retracement Roadway

During the final mining phase, the main retracement roadway is subjected to a complex stress environment, the coal pillar's stress is consistently distributed asymmetrically, and a sizable amount of plastic failure occurs at the side. The ARR places little regional stress on the roadway, which is also relatively stable. The ARR's short service life means that the surrounding rock's deformation is minimal. Additionally, because the plastic zone can only expand so far, the support's initial strengthening is sufficient to support the load from the outside. In order to ensure the stability of the surrounding rock during the working face's late mining phase, the MRR needs to be strengthened and supported prior to the forced mining of the working face. It is decided to employ the W-steel tape, anchor cable, wire mesh, and hydraulic chock combined support mode. The top plate of the MRR is made to reinforce one row of grouting anchor cables, consisting of three sets, each with a diameter of 21.6 mm, a length of 12,000 mm, and a row spacing of 2300 mm × 3000 mm, based on the original anchor (rod) cable support. Along the retracement roadway, a W steel strip with a specification of W230 × 3 mm is used to connect the three adjacent anchor cables. The support for roof reinforcement is shown in Figure 14.

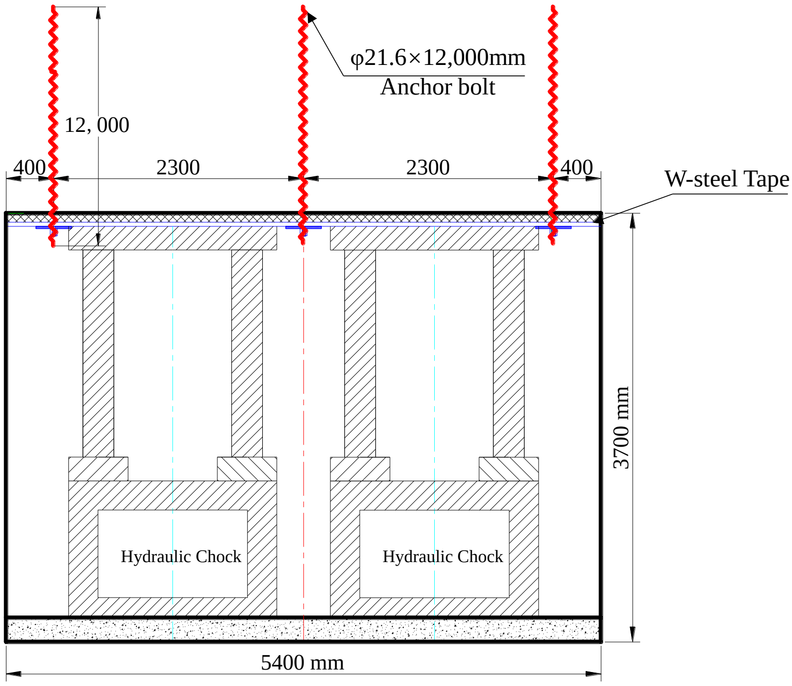


Figure 14. Schematic diagram of roof reinforcement and support of main retracement roadway.

The auxiliary wall of the main retracement roadway is provided with support and secondary reinforcement. One group of the "anchor cable + anchor bolt + steel tape" combined support (shown in green in Figure 15) is built longitudinally and evenly spaced apart on the original support foundation. The main retracement roadway's steel strip is 3.7 m long, with a row spacing of 2.4 m. The top three rows are anchor cable specifications, measuring φ17 × 87,000 mm with a 1000 mm spacing. The bottom row is deformed steel anchor bolts, which are specified as φ22 × 2400 mm, with a spacing of 1100 mm from the anchor cable (the purple part in Figure 15). The three resins are φ23 mm × 600 mm, the additional anchor cable is a 300 mm × 300 mm × 16 mm tray, and the steel strip is specified as W230 × 3 mm. The anchor bolt and cable from the original support are shown in red in Figure 15 for the wall support for the main retracement roadway.

5.2. Roof Fracturing Scheme

According to the aforementioned study, the fundamental roof rotation movement and the internal concentrated stress of the underlying residual coal pillar are superimposed, which affects the working face of 31,106's final mining phase. It is suggested that hydraulic fracturing technology be used to develop a fracture network in the roof rock strata, undermine its structural integrity, address the problem of stress concentration in the residual pillar, deteriorate the roof structure of the working face, change the stress transmission path, and achieve the transfer of high stress to the deep fracturing section. Furthermore, hydraulic fracture of the main roof within the predetermined range above the retracement roadway that was dug before it was placed beneath a stable main roof beam will increase the stability of the surrounding rock around the roadway. This will stop the natural rotation and fracture of the main roof from having an impact on the retracement roadway. On the basis of this, the roof fracturing parameters are created to achieve stability control of the ground pressure appearance during the last stage of mining for the working face of 31,106.

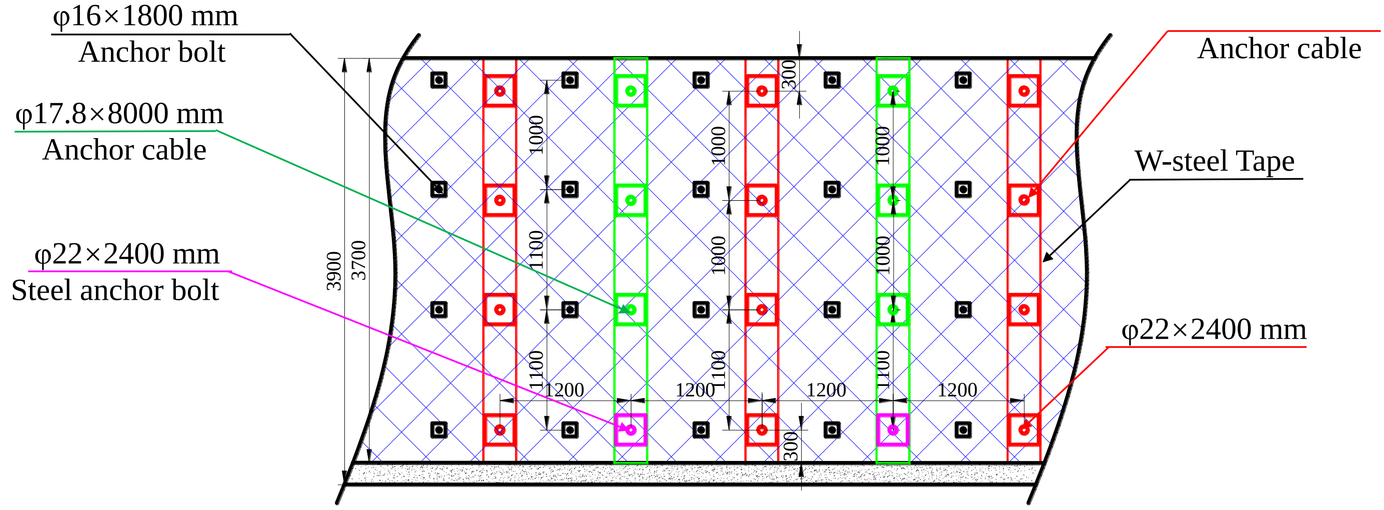


Figure 15. Secondary reinforcement and support of auxiliary wall of main retracement roadway.

For hydraulic top cutting and pressure relief, high- and low-level holes are used in the retracement roadway of working face 31,106, in accordance with Section 3.3. Taking into consideration the length and interval of the hole packer in the borehole, drilling and fracturing are carried out in the primary retracement roadway to the working face side. There are a total of 29 hydraulic fracturing boreholes in the working face's retracement roadway, including 15 P (high) and 14 Q (low) boreholes, respectively. The placement of the fracturing boreholes on the retracement roadway's roof is shown in Figure 16. The construction is vertical to the axial direction of the road, the length is 47.7 m, and the angle of the hole P is 70°. The construction is vertical to the axial direction of the road, the length is 25.9 m, and the angle of the hole Q is 50°. From the retracement roadway's shoulder angle to the designated layer, the P and Q holes are built and are spaced alternately along the working face trend. The drilling intervals are 8 m.

5.3. Evaluation of Fracturing Implementation Effect

The hydraulic fracturing top-cutting pressure relief operation is completed at the roof of the retracement roadway, on the working face of 31,106. The fracturing hole's average fracturing pressure is 17.5 MPa, while the stable pressure is roughly 12.4 MPa. The integrity of the deep surrounding rock around the fracturing hole is good, and the fracturing position is accurate, as shown by the fact that the pressure of the deep fracturing section is higher than that of the shallow fracturing section while the rock is fractured. The middle and shallow sections of the fracturing release a significant amount of water, indicating that the cracks in the nearby rock are continuing to grow and extend throughout the fracturing process and are connected to the roof anchor cable borehole. The ground pressure appearance of the working face and the retracement roadway at this point is improved when the working face advances because it can effectively encourage roof collapse, reduce roof breaking load, and reduce working resistance of the cribbing support. In order to confirm the construction effect after fracturing, Figure 17 shows the peeping of the roof fracturing boreholes. The peeping results show that after construction, hydraulic cracks are found in the fracturing boreholes. The majority of these hydraulic cracks ran parallel to the borehole's axis, which seriously weakened the surrounding rock and jeopardized the stability of the nearby roof.

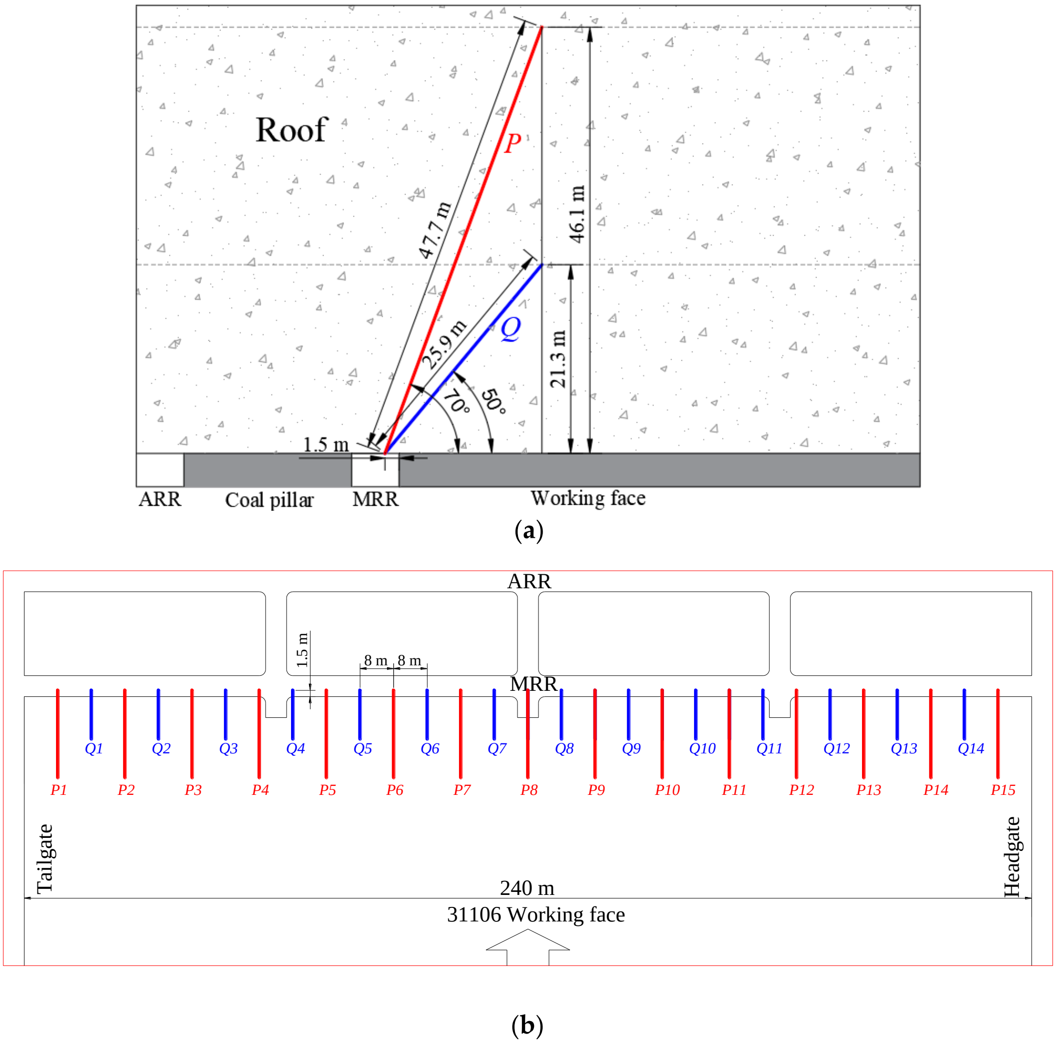


Figure 16. Roof fracturing scheme of retracement roadway: (**a**) fracturing borehole profile inside the main retracement roadway; (**b**) borehole layout.

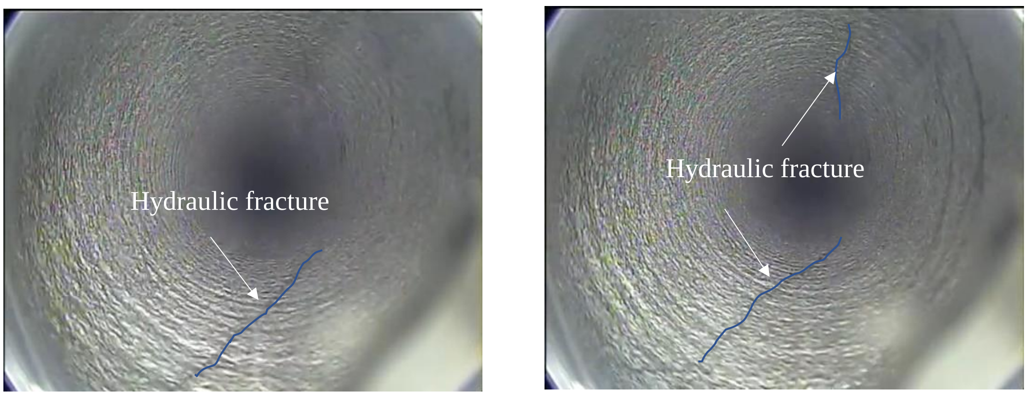


Figure 17. Fracture distribution characteristics of hydraulic fracturing boreholes.

The coal wall of the working face is complete and the support has a good roof connection effect, without gangue leakage or roof leakage, when the working face is advanced to the point where it is nearly through and adopts the measures of advanced roof cutting and pressure relief. The roof does not significantly sink, the anchor bolt and anchor cable do not break and fail, and the auxiliary wall in the retracement roadway is also unharmed. As shown in Figure 18, the hydraulic chock's load of 23~31 MPa is consistent with the load when it is first installed, showing that the roadway is less impacted by the advancement of the working face. The retracement roadway of working face 31,106 demonstrates the use of the hydraulic roof cutting and pressure relief method, which significantly reduces the deformation of the surrounding rock and achieves stability control under the influence of multiple stresses superimposed on the overlying residual pillars.

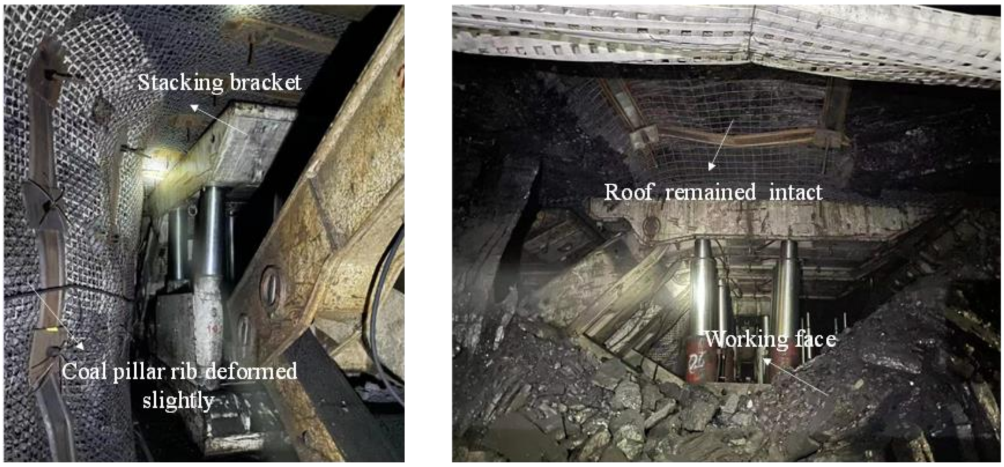


Figure 18. Illustration after the evacuation channel is completed.

6. Conclusions

In order to study the poor stability of the surrounding rock of the retracement roadway during the final mining period as a result of the influence of the overlying residual pillars on the 31,106 working face of the Huoluowan coal mine, this paper conducted a systematic study on the deformation and failure mechanisms of the surrounding rock of the working face under the residual coal pillars during the final mining period using on-site observation, theoretical analysis, numerical simulation, and field measurements. It is suggested that hydraulic roof cutting and pressure relief be used for the roof above the retracement roadway in order to lessen roof stress. The technique is used in engineering projects, and successful outcomes from industrial tests are obtained. The main conclusions are as follows:

1. After the retracement roadway has been excavated, the position of the overlying coal pillar determines the stability of the main roof and the distribution of stress within it. When the horizontal distance between the boundary of the overlying residual pillar and the stopping line is 15 m and the overlying residual pillar's stress diffusion angle is 29°, the stress environment of the surrounding rock of the retracement roadway is severely disturbed by the stress of the floor of the residual pillar, and the plastic area is increased, leading to serious deformation.
2. Due to the presence of overlying residual coal pillars, mining disturbs the fundamental roof after the mining of the 31,106 working face, exposing a complex stress superposition state. Peak stress on the working face gradually rises to a maximum value of 22. 81 MPa in the final 30 m before the stop line. The peak point of the supporting stress shifted to the top of the coal pillar when the working face was connected to the retracement roadway, causing the retracement roadway's roof to subside and extensive plastic damage. It is noted that the ground pressure appearance of the retracement roadway can be decreased by using multi-stage roof cutting and pressure relief to block the stress transmission path of the remaining coal pillar and hard roof overlying the retracement roadway.
3. Based on extensive numerical simulation calculations and actual field conditions, a high and low hole fracturing scheme was developed for the roof of the retracement roadway, and an industrial test was carried out. The results show that hydraulic fracturing strengthens the roof structure, reduces the intensity and duration of incoming

pressure during the final phase of mining on the working face, and lessens the heavy dynamic load on the adjacent residual coal pillar. While moving the retracement roadway to the coalescence of the working face, the roof does not significantly subside and the surrounding rock deformation is generally stable. The fact that the roof did not significantly sink increased the safety of withdrawal and the efficiency of equipment removal. The findings of the study can offer a specific solution for the secure removal of a working face under comparable geological circumstances.

The final mining phase of the working face beneath the remaining coal pillars is examined in this paper, along with the distribution law and mine pressure control technology. The stress propagation properties of unevenly distributed coal pillars and the parameter system design of hydraulic roof cutting scheme can be further investigated on the basis of this paper.

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