

Mechanism and Control Technology of Workface Pressure Manifestation under Different Types of Overlying Coal Pillars

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Abstract

Based on the relative spatial characteristics of overlying coal pillar and underlying mining faces, three types of coal pillar mining workfaces were classified as vertical coal pillars, parallel coal pillars, and oblique intersecting coal pillars. Taking the geological conditions of comprehensive mechanized caving mining face under the overlying coal pillars in Buertai Mine Shendong Coal Group as an example, the characteristics, occurrence mechanisms, and prevention and control technologies of mine pressure manifestation under three types of coal pillar mining workfaces were studied. According to the mine pressure manifestation data of the 4-2 coal seam mining face in Buertai Coal Mine, it was found that when there is stress concentration caused by the remaining 2-2 coal pillars in the overlying coal seam, the pressure manifestation on the 4-2 coal seam mining face varies from strong to weak as follows: mining-out of the parallel coal pillars, mining-in of the parallel coal pillars, and vertical coal pillars in the middle area of the mining face. Based on the geological characteristics of the strata between the 2-2 coal seam and 4-2 coal seam, the fracture evolution characteristics, such as “O-X” shape, of the 4-2 coal mining face roof were analyzed. It was pointed out that the spatial stability of the “fan-shaped lever” under the stress concentration of the overlying coal pillars is the main control factor determining the load of the mining face shield, which is the mechanism of the pressure manifestation of the underlying mining face when mining under the parallel coal pillars. For the vertical coal pillars overlying the mining face, a coal pillar stress transfer model based on the foundation beam was proposed, which revealed the composite fracture mechanism of rock mass between the overlying vertical coal pillars and the underlying coal pillars. Taking the pressure prevention and control in the mining faces 42106 and 42108

under the coal pillars in Buertai Coal Mine as cases, the strong mine pressure prevention and control technology under the overlying coal pillars was introduced. The on-site pressure prevention outcomes were good.

Keywords

Overlying Coal Pillar, Workface Pressure Manifestation, Ground Control, Multi-Seam Mining

1. Introduction

The Shendong coal group is rich in coal resources and serves as a crucial area for the high-quality development of China's coal industry [1] [2]. The coal seams in this area are characterized by high thickness, shallow burial depth, thin bedrock, and close proximity to the surface [3]. These geological features lead to various manifestations of mine pressure within the Shendong mining area. One of the typical mine pressure challenges is the stress concentration effect caused by the residual coal pillars left in the goaf of overlying coal seams, which affects the mining face of the underlying coal seam during multi-seam mining operations. Regarding the issue of pressure manifestations on the mining face beneath the residual coal pillars of overlying coal seams, previous scholars' research mainly falls into two directions:

The first one is the study of the spatial structure and stress distribution characteristics between the overlying coal pillars and the mining face below. For example, Huang *et al.* [4] [5] believe that the concentrated stress transmitted by the coal pillars is borne jointly by the coal wall ahead of the mining face and the roof structure above the support. The load transmitted by the coal pillars is mainly borne by the coal wall in the coal entry stage and gradually shifts to the support in the coal exit stage. Song *et al.* [6] believe that the fractured rock blocks of the roof form a "main control layer-weak layer" composite structure that bears the load synergistically, and the impact load from the overlying strata affects the stability of this composite structure. Yan *et al.* [7] point out that the failure characteristics differ between the "dislocated stacked beams" area and the "compressed fractured rock" area in the overlying strata, with rock failure height increasing exponentially as the face advances under insufficient mining conditions. Xu *et al.* [8] [9] proposed that the load from the overlying strata could directly affect a single key layer structure, revealing the instability mechanisms and support failure modes of key layers, along with corresponding prevention and control strategies. Overall, these studies show that the spatial structure of the rock layers between the overlying residual coal pillars and the mining face below significantly influences the mine pressure in the surrounding rock.

The second research direction focuses on the methods for preventing mining induced pressure. Support resistance and various roof-cutting measures are proactive methods of mine pressure prevention. In terms of mining technology, Hou *et al.* [10] used 31201 fully mechanized face at Shigetai Mine as an example, where

they achieved safe production through techniques such as blasting residual coal pillars, shortening the face length. Ju *et al.* [11]-[14] noted that there are two types of pressure manifestation when the face mines through overlying coal pillars: 1) when the distance between the cut line and the coal pillar boundary is greater than the initial fracture distance of the key layer above the pillar, periodic fracture of the key layer occurs, forming an unstable three-hinge structure with the goaf. The excessive load transferred by the relative rotational movement of this structure is the fundamental cause of support failure. 2) When the distance is between the initial and periodic fracture distances of the key layer, cantilever-type fracture of the key layer occurs, and the large fracture span causes excessive load on the shield. Chi *et al.* [15], using the 22307 fully mechanized face at Bulianta Mine as the research object, proposed several safety measures, including a reasonable distribution of advancing and maintenance times, appropriate mining height, replacing and verifying safety valves, adjusting the face angle, and strengthening mine pressure monitoring. These measures effectively prevented severe support compression, roof collapse, sidewall failure in the roadway, and injuries from bolts or cables when the face passed through concentrated coal pillars in the overlying strata.

Most of these studies focus on a specific type of overlying coal pillar, and there is a lack of comprehensive research on mining techniques under the conditions of thick coal seams, shallow burial depth, thin bedrock, and multi-seam mining in the Shendong mining area. In response to this issue, this paper aims to analyze the characteristics of mine pressure problems in mining faces beneath overlying coal pillars in the Shendong mining area, classify the mechanisms of mine pressure manifestations, and study corresponding prevention techniques.

2. Different Overlying Coal Pillars at Buertai Coal Mine

The Shendong mining area includes 13 mines. Through classification and statistical analysis of mine pressure phenomena observed during the production process in these mines, it was found that the pressure manifestation from upper coal pillars exists in most of the mines [16]-[18]. It is clear that prevention of pressure associated with upper coal pillars has become one of the key issues affecting safe mining in the Shendong mining area. This paper takes Buertai Coal Mine as a case study to analyze the mechanisms of pressure manifestations and control techniques for mining faces beneath overlying coal pillars.

Taking the mining face beneath coal pillars in Buertai Coal Mine as an example, this section analyzes the pressure manifestations beneath parallel coal pillars in the overlying strata. In the southeastern and western parts of the Buertai Coal Mine, the 4-2 coal seam bifurcates into two layers. In some areas, the burial depth of the 4-2 coal seam exceeds 400 m, and the 2-2 coal seam goaf lies above it, with an interlayer spacing of about 70 m. The immediate roof above the 4-2 coal seam contains a thick, hard roof layer. Due to the influence of the residual coal pillars in the 2-2 coal seam above, pressure manifestations were observed during the recovery of the workface in the 4-2 coal seam, including severe floor heave, sidewall

spalling in the roadways, and occurrences of support jamming and hydraulic cylinder explosions [19].

Based on in-situ stress measurements at 22206 and 42109 workfaces at Buertai Coal Mine, there is substantial tectonic stress present in the 4-2 coal seam. The maximum principal stress, σ_1 , ranges between 9.07 and 9.79 MPa, with an average value of 9.43 MPa. The azimuth ranges from NE55° to NE77°, with an average azimuth of NE66°. The direction of tectonic stress is roughly perpendicular to the roadway axis of the first panel of the 4-2 coal seam and parallel to the roadway axis of the second panel of the 4-2 coal seam.

Due to technical reasons, 22106 and 22107 workface leave behind parallel coal pillars, as shown in **Figure 1**. The width of the parallel coal pillar in the 22106 face is 201 m, and the distance from the head of the open cutting on the 42106 face is 654 m. Along the dip of the coal seam, it primarily affects partial parts of 42106 face and 22107 face. The parallel coal pillar in the 22107 face is 337 m wide, and the distance from the head of the open cutting on the 42107 face is 582 m. It affects about 200 m of the 42107 face and approximately 131 m of the 42108 face. The skip-mined parallel coal pillars in the overlying 2-2 coal seam have a significant stress concentration effect on the recovery of the underlying 4-2 coal seam.

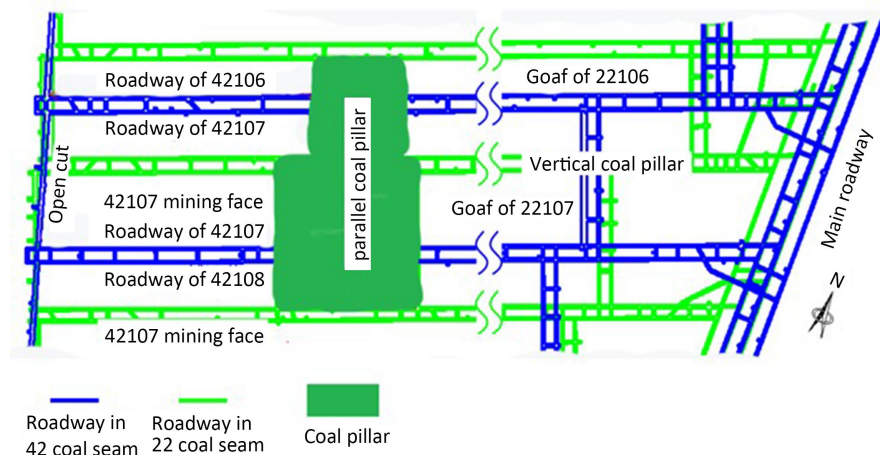


Figure 1. Plane position relationship of parallel coal pillars of 2-2 coal seam and 4-2 coal seam workface in Buertai Coal Mine.

3. Classification of Overlying Coal Pillar Types

Based on the relative orientation between the layout direction of the working face and the long axis direction of the overlying coal pillar, the mining conditions where the layout direction of the working face is parallel to the long axis of the overlying coal pillar are defined as parallel coal pillars, while the conditions where the layout direction is perpendicular to the long axis are defined as vertical coal pillars. For conditions where the layout direction of the working face forms a certain angle with the long axis of the coal pillar, these are termed oblique coal pillars [20]. The mechanisms of mine pressure manifestation for oblique coal pillars can be categorized as either parallel or vertical coal pillar conditions.

Based on on-site measured mine pressure data and the characteristics of mine pressure manifestation, there are significant differences in the manifestation of mine pressure between working faces with parallel coal pillars and those with vertical coal pillars. Overall, the mine pressure manifestation is strongest when passing through parallel coal pillars, while the pressure manifestation caused by vertical coal pillars is weaker. This is closely related to the differences in the spatial distribution of the different types of coal pillars and the structure of the overburden fractures [21].

When the working face passes through parallel coal pillars, the roof breaks to form a “seesaw” structure, which has two supports: one main support located within the coal wall and one auxiliary support provided by the hydraulic supports. When the underlying coal seam’s working face extracts the coal pillar, the stress concentration and pressure zone is located beneath the edge of the coal pillar on the side of the mined-out area, while the coal wall side of the basic roof block is protected by the upper sub-key layer forming a load relief zone. Therefore, the stability of the roof block deteriorates, making it prone to rotation toward the mined-out area, which may cause severe pressure manifestations such as sinking of the working face [22]-[24]. This observation is consistent with the pressure manifestation in the 4-2 coal seam at Buertai Mine when passing through parallel coal pillars, see **Figure 2(a)**.

Conversely, when the working face passes through vertical coal pillars, a pressure concentration zone is formed directly beneath the coal pillar due to stress concentration. On both sides of the coal pillar, the protective effect of the key block creates symmetrical load relief zones [25] [26]. Further, due to the contact with the key blocks, a re-load zone is formed, but the mining pressure in this area is less than that in the load increase zone directly beneath the coal pillar. At this time, there is significant mine pressure manifestation within the support range of the load increase zone beneath the vertical coal pillar. On-site monitoring data indicate that the supports within this range maintain high pressure throughout the mining process, see **Figure 2(b)**.

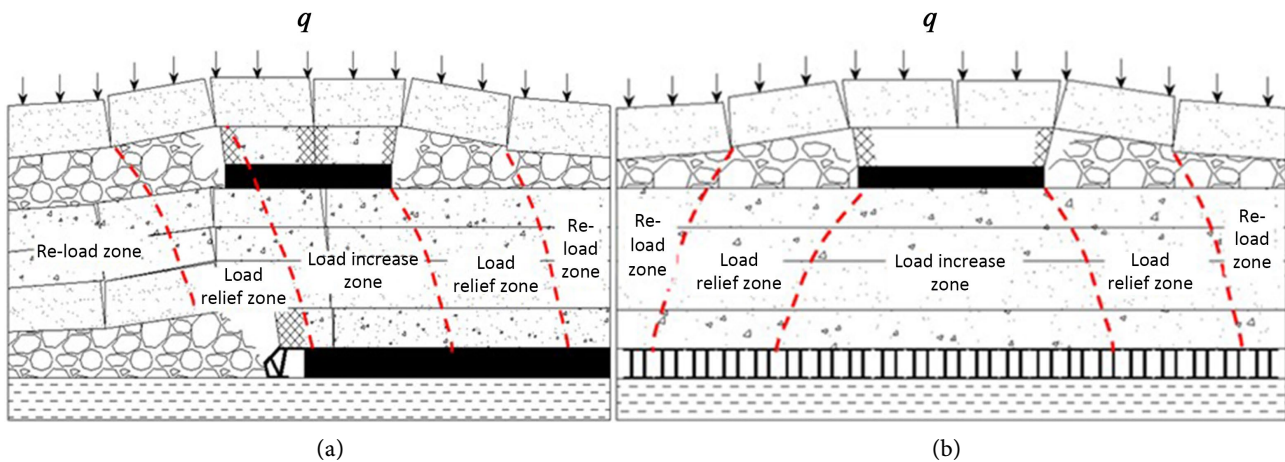


Figure 2. Models of overburden rock structures for different types of coal pillars. (a) mechanical mode of parallel and oblique intersecting coal pillar; (b) mechanical model of vertical intersecting coal pillar.

4. Pressure manifestation in Coal Pillar

4.1. Pressure Manifestation of Workface Mining through Parallel Coal Pillars

As shown in **Figure 1**, when the 42106 face enters the parallel coal pillars of the overlying 2-2 coal seam, the pressure intensity of the shield directly beneath the coal pillar weakens, while the pressure intensity and magnitude of the shield under the mined-out area of the 2-2 coal seam remain unchanged. When the 42106 face is directly beneath the center of the overlying 2-2 coal seam parallel coal pillar, the pressure on the roof becomes significant, and the depth of roof falls and the depth of side wall instability increases.

The workface experiences three major cycles of periodic pressure. The maximum pressure intensity reaches 51.6 MPa, and during the periodic pressure of the supports under the mined-out area of the 2-2 coal seam, the area of maximum load shifts towards the parallel coal pillar side, leading to a noticeable reduction in pressure on shield No.100 to No.150. When the 42106 workface exits the parallel coal pillar of the overlying 2-2 coal seam, the pressure on the hydraulic supports does not show significant changes. However, when mining-out the coal pillar by 5 m, a distinct strong mine pressure is observed, causing subsidence in the roof directly above the coal pillar, with a maximum subsidence of 300 mm and a maximum pressure intensity of 51.2 MPa.

This indicates that when the working face enters the coal pillar, there is a phenomenon of forward movement in the high-stress zone of the coal body. As the working face is located beneath the coal pillar, the resistance of the supports increases, elevating the area affected by the pressure. Conversely, when the working face exits the coal pillar, there is a backward movement of the high-stress area, although the area affected by the pressure is relatively smaller [27].

4.2. Pressure Manifestation of Workface Mining through Vertical Coal Pillars

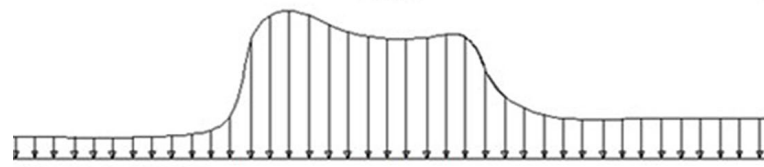
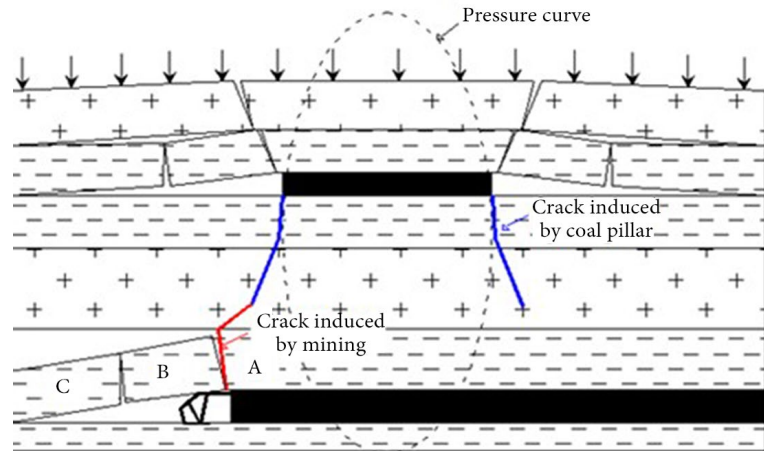
As shown in **Figure 1**, the vertical coal pillar from the overlying 22105 working face is positioned vertically relative to the 42106 working face. The coal pillar is located 88 m from the head of the 42106 working face and is situated above the shield No.45 to No.57 of the 42106 workface. During the extraction process of the 42106 working face, the vertical coal pillar above the 22105 working face does not show a significant influence on the pressure or the load on the supports of the 42106 working face. Similarly, the 42107 working face is covered by the vertical coal pillar of the 22106 workface, aligned vertically with respect to the 42107 working face. This coal pillar is located 170 m from the head of the 42107 workface.

Pressure data indicate that the vertical coal pillars above the 2-2 coal seam have minimal impact on the mine pressure in the lower 4-2 coal seam extraction working face. The periodic pressure patterns do not show significant changes, and they do not lead to serious pressure manifestation.

5. Mechanism of Pressure Manifestation in Different Types of Overlying Coal Pillars

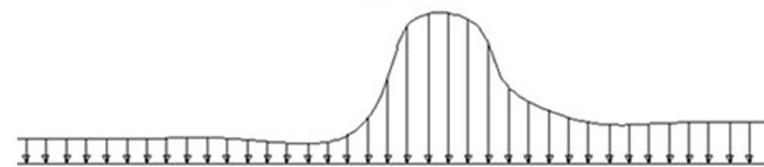
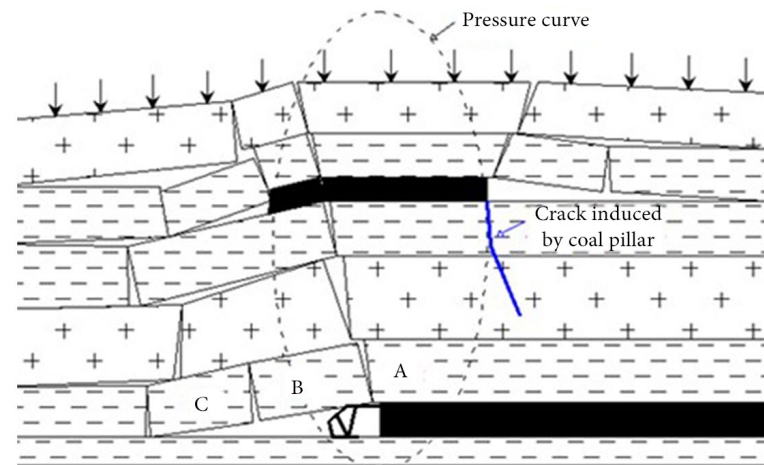
5.1. Mechanism of Pressure Manifestation in Overlying Parallel Coal Pillars

Above the 4-2 coal seam of the Buertai Mine, approximately 60 m of the 2-2 coal seam exists. During the extraction process, due to geological and mining technical



Pressure in roof of 42 coal seam

(a)



Pressure in roof of 42 coal seam

(b)

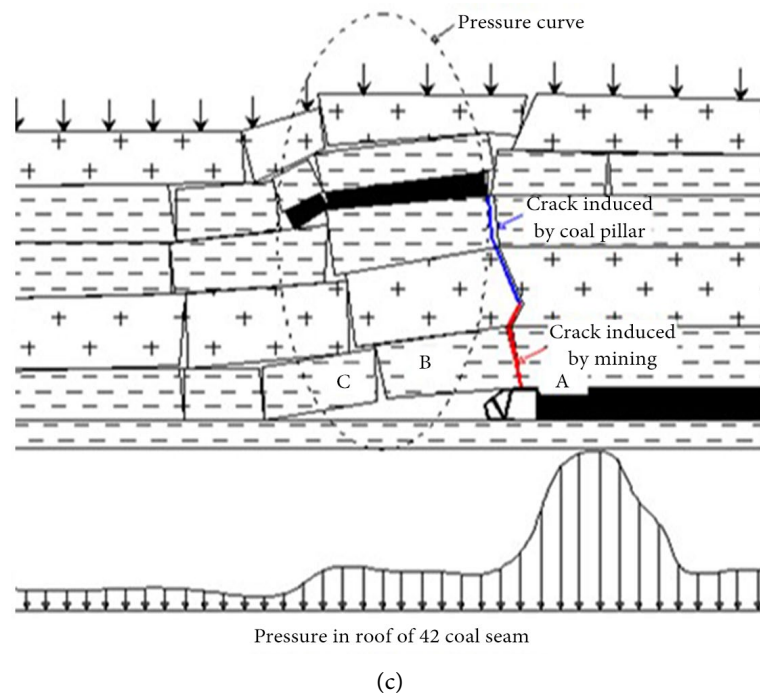


Figure 3. The features of the surrounding rock of different corresponding locations between 4-2 coal seam workplace and 2-2 coal seam pillar. (a) period as the workplace mining-in the parallel coal pillar; (b) period as the workplace mining-under the parallel coal pillar; (c) period as the workplace mining-out the parallel coal pillar.

factors, a residual parallel coal pillar was left, which is referred to as a parallel coal pillar. The manifestation of mine pressure in the 4-2 coal seam working face during extraction is influenced by the remaining coal pillar of the overlying 2-2 coal seam, and the evolution of its surrounding rock fracture can be seen in **Figure 3**.

Pressure data indicate that during the extraction of the 4-2 coal working face, the working face frequently mining-in and mining-out of the coal pillar, leading to significant effects from the stress concentration at the bottom of the coal pillar. It has been observed that there are considerable differences in the manifestation of pressure when entering and exiting the parallel coal pillar. When mining-in the parallel coal pillar, the manifestation of mine pressure is not significant; however, when mining-out the parallel coal pillar, the manifestation of mine pressure becomes extraordinarily strong, resulting in the safety valves of the hydraulic supports in the working face.

During the extraction of the 4-2 working face, the influence of the overlying parallel coal pillar from the 2-2 coal seam creates varying “O-X” patterns and stress distribution areas in the surrounding rock [28]-[32]. **Figure 3(a)-(c)** illustrate that the 4-2 coal seam working face will experience three stages relative to the parallel coal pillar from the 2-2 coal seam: “mining-in the coal pillar”, “mining-under the coal pillar” and “mining-out the coal pillar”. The different stress curves during 4-2 coal seam workplace entry and exit of 2-2 coal seam pillar are shown in **Figure 4**. The parallel coal pillar from the 2-2 coal seam also impacts the stability of the old roof’s “O-X” fracture structure in the 4-2 coal seam and the

pressure of the working face supports.

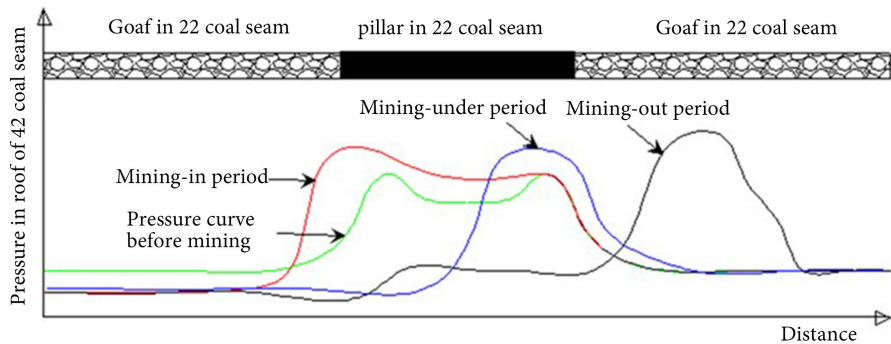


Figure 4. The different stress curves during 4-2 coal seam workface entry and exit of 2-2 coal seam pillar.

According to the general rules governing the movement of rock fractures, during the extraction of the 4-2 coal seam, the hard rock layer between it and the 2-2 coal seam will experience horizontal “O-X” fractures. This will lead to the formation of a structure resembling a “seesaw” plate above the working face, referred to as key block B. The stability of this “seesaw” structure can be analyzed using the masonry beam “S-R” theory, which allows for the determination of its instability criteria [33].

The fracture line at the base of the 2-2 coal pillar intersects with the fracture line of the overlying rock of the 4-2 coal working face, making the collapse and subsidence of the roof in the 4-2 coal working face prone to destabilizing the surrounding rock structure. When the 4-2 coal working face enters the area of the 2-2 coal pillar, the stress concentration effects from the 2-2 coal pillar lead to a stress concentration coefficient greater than 1 for the hard roof in front of the working face, while the coefficient behind it is less than 1. As a result, even with low resistance from the support, the “seesaw” structure is unlikely to undergo violent rotation, thus reducing the likelihood of support failure incidents, as illustrated in **Figure 3(a)**.

However, when the 4-2 coal working face is beneath or has extracted the 2-2 coal pillar, the stress concentration effects from the 2-2 coal pillar significantly increase the stress concentration coefficient of the hard roof behind the 4-2 coal working face. Consequently, the basic roof of the 4-2 coal seam becomes susceptible to shear failure when the coal pillar is extracted, leading to a scenario where the coal wall can no longer adequately support the roof. If the resistance of the support is insufficient, top-slicing subsidence may occur, resulting in support failure incidents, as depicted in **Figure 3(b)** and **Figure 3(c)**.

5.2. Pressure Manifestation Mechanism for Overlying Vertical Coal Pillars

The residual coal pillars from the 2-2 coal seam workface at the Buertai Coal Mine also exert stress effects on the 4-2 coal seam. Since the advancing direction of the 4-2 coal working face aligns with the long-axis direction of the residual coal pillars from the 2-2 coal seam, the influence of these residual coal pillars on the mining pressure of the 4-2 coal working face is persistent [34] [35].

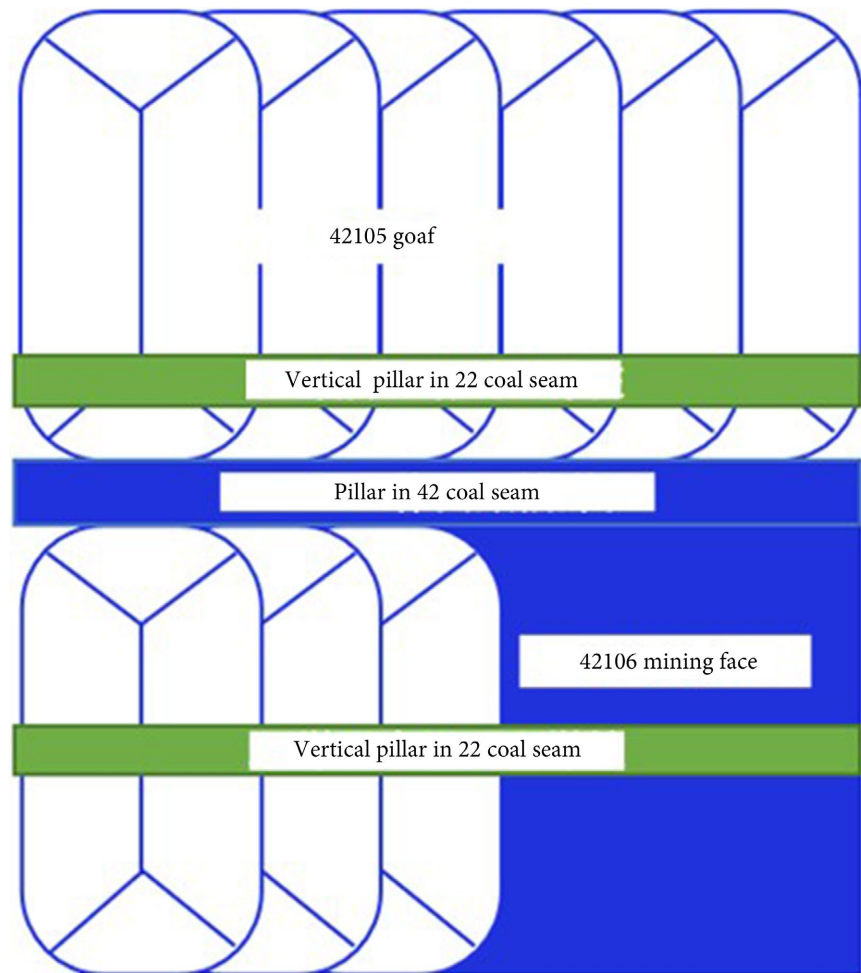


Figure 5. The layout of a vertical coal pillar.

The intensity of mining pressure manifestation varies depending on the relative positions of the 2-2 coal pillars and the 4-2 coal working face. When the segmental coal pillar of the 2-2 coal seam aligns with the arc-shaped triangular block of the 4-2 coal working face, the impact is significant. Conversely, when the 2-2 coal pillar is positioned in the middle of the 4-2 coal working face, the influence is comparatively weaker, as shown in **Figure 5**.

The 42105 and 42106 working faces at Buertai are significantly impacted by the overlying residual coal pillars of the 2-2 coal seam. The hard rock layers above the 4-2 coal seam create an unstable rock structure. The coal pillars of the 2-2 seam, located within this inverted trapezoid, transfer their load down to the underlying coal pillars of the 4-2 seam. This interaction leads to strong mining pressure manifestations in the 42105 and 42106 working faces, causing significant deformation in the surrounding rock that is challenging to control [16]-[18].

Additionally, the lateral triangular block structure formed by the primary critical layer above the 2-2 coal pillar transmits loads to the supports of the lower 42105 workface at the position of rock failure. Monitoring data indicate severe mining pressure at the end of the 42105 working face. Following the extraction of

the 42105 working face, the upper hard roof breaks and rotates, leading to intense compression of the coal pillars between the 42105 and 42106 workfaces [28]-[32].

The residual coal pillars from the 2-2 seam continue to transfer loads to the supports of the 42106 working face, exacerbating the strong mining pressure. When the 42106 working face is extracted, the upper hard roof breaks and rotates, causing intense compression on the lateral coal pillars. Furthermore, the downward movement of the rock blocks in the 42106 goaf area further increases the pressure exerted by the upper vertical coal pillars on the lower lateral coal pillars.

6. Mining Pressure Prevention Cases

6.1. Case Study on Pressure Prevention for Parallel Coal Pillars

The Buertai Coal Mine's 42108 working face extracts the 4-2 coal seams, with coal thicknesses ranging from 3.8 to 7.3 m and an average thickness of 6.05 m. There is a layer of 0.2 m of sandy mudstone mixed with gangue. The angle of the coal seam ranges from 3 to 9 degrees. The 42108 working face has a strike length of 5170 m, a width of 310 m, and a burial depth of 370 to 475 m. The roof and floor of the coal seam are interbedded sandy mudstone and fine-grained sandstone or siltstone, with the direct roof being sandy mudstone 3 - 19 m thick, averaging 12 m. The hard roof is fine sandstone, with a thickness of 7 - 38 m, averaging 22 m. The direct floor is sandy mudstone, 1 - 4 m thick, averaging 3 m. The 42108 working face is covered by a section of the 2-2 coal seam with parallel coal pillars.

In the 42108 working face, six drilling sites are arranged, each with three directional fracturing boreholes, totaling 18 boreholes. The designed borehole diameter is 96 mm, with an initial drilling to the direct roof at 96 mm, then expanding to 153 mm, and a 127 mm casing crossing 10 m of rock strata. After the fracturing process is completed, the first hole is drilled to the final borehole according to the designed trajectory, targeting the 4-2 coal seam's sandstone roof. The specific arrangement can be seen in **Figure 6(a)**.

The length of each fracturing borehole ranges from 350 to 585 m, designed for 5 to 10 fracturing segments per borehole, with a total drilled length of 8320 m and 140 designed fracturing segments. Borehole site No.1 addresses initial extraction; boreholes No.2-3 correspond to the visibility positions of the working face, while sites No.4-6 are arranged in areas deeper than 400 m. The borehole spacing is 78.25 m, with the auxiliary transportation lane and the main transportation lane also at 78.25 m. When fracturing a single borehole in adjacent positions, the spacing between the two boreholes is kept within 30 m; when both boreholes need to be fractured, the spacing is within 60 m. The preliminary design for the 42108 working face has a spacing of 30 m between fracturing segments and a segment length of 6 m, with the borehole design layout shown in **Figure 6(b)**.

The remote monitoring and recording system for fracturing collects data on parameters such as pressure and flow volume during the fracturing operation. The characteristics of pressure changes during the multi-point segmented fracturing process are shown in **Figure 7**. To compare the effects of segmented fracturing on

pressure relief, an analysis was conducted on the support loads of the 42106 working face, where no hydraulic fracturing was applied to the roof, and the 42108 working face, where hydraulic fracturing was implemented on the roof, as shown in **Figure 8**.

In the 42106 working face, where no hydraulic fracturing was performed, the applied pressure intensity was approximately 50 MPa. In contrast, after hydraulic fracturing was carried out in the 42108 working face, the applied pressure intensity was significantly reduced to about 35 MPa. Additionally, the periodic pressure relief step was minimized, effectively weakening the roof and ensuring the safe recovery of the working face within the fracturing operation range.

The average load changes of the shield during the initial mining period for the 42106 working face (without fracturing the roof), the 42107 working face (with roof fracturing), and the 42108 working face (with roof fracturing) are shown in

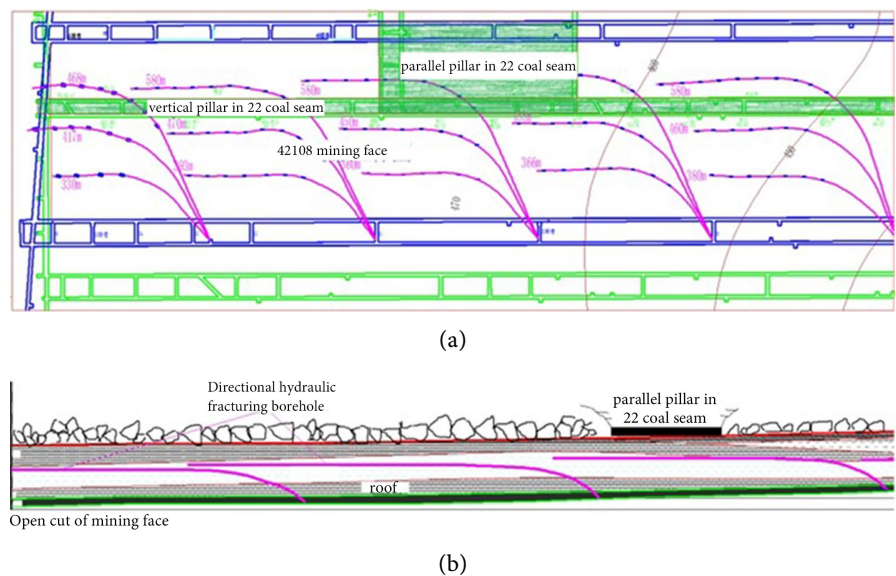


Figure 6. Layout of fracturing borehole. (a) plan layout of fracturing borehole; (b) sectional layout of fracturing borehole.

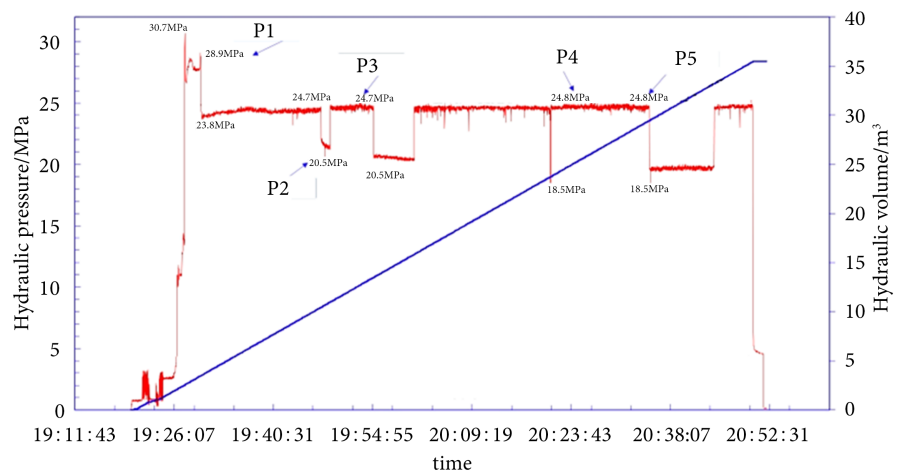
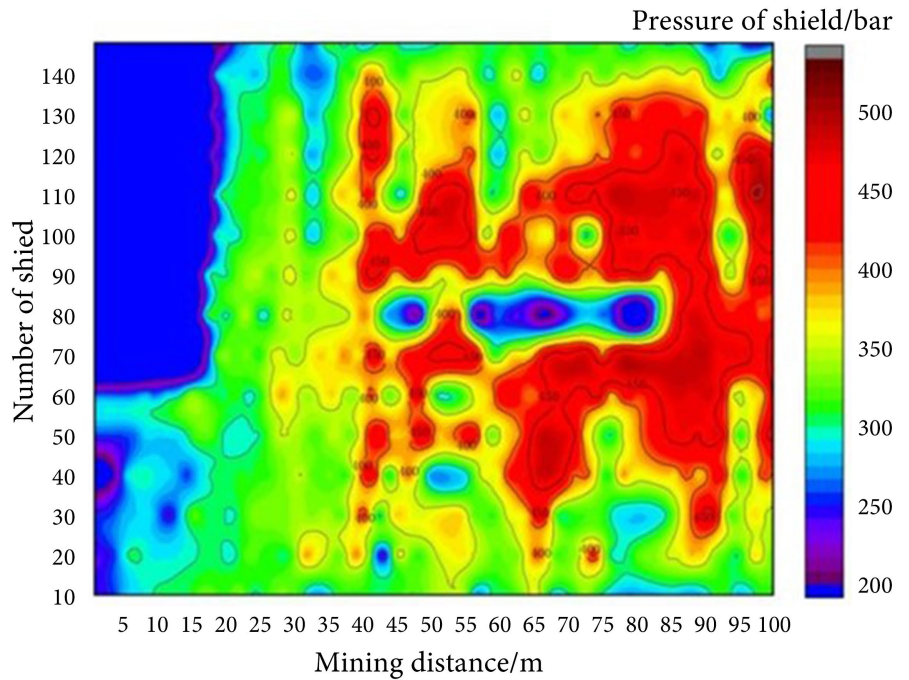
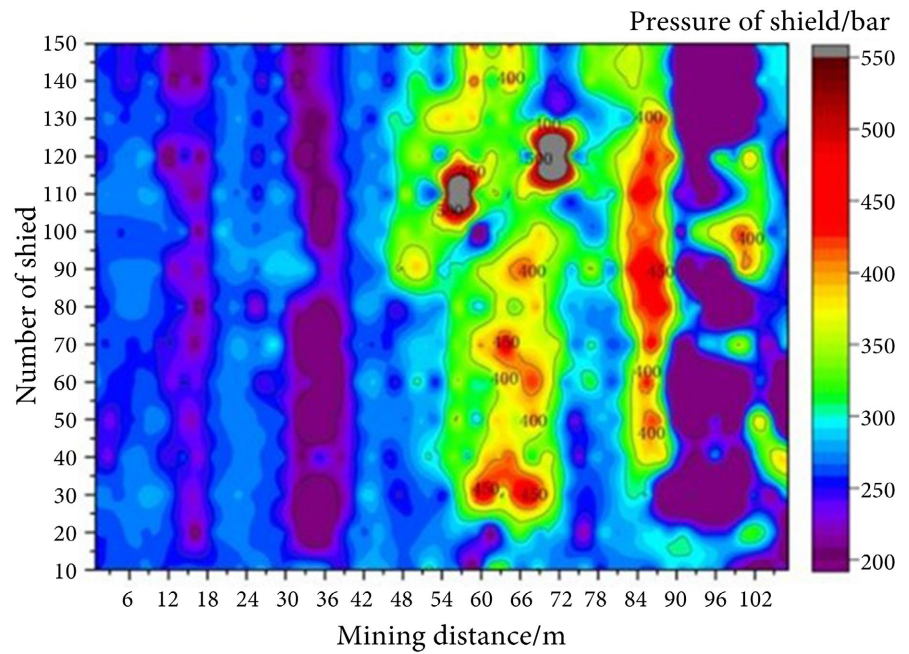


Figure 7. Pressure variation curve during staged fracturing.



(a)

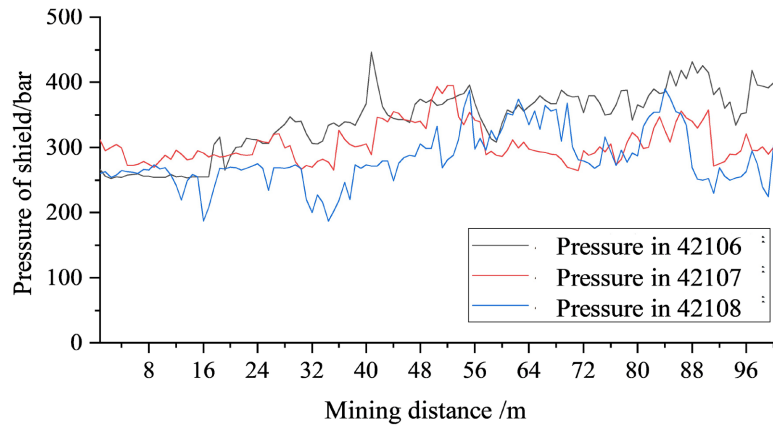


(b)

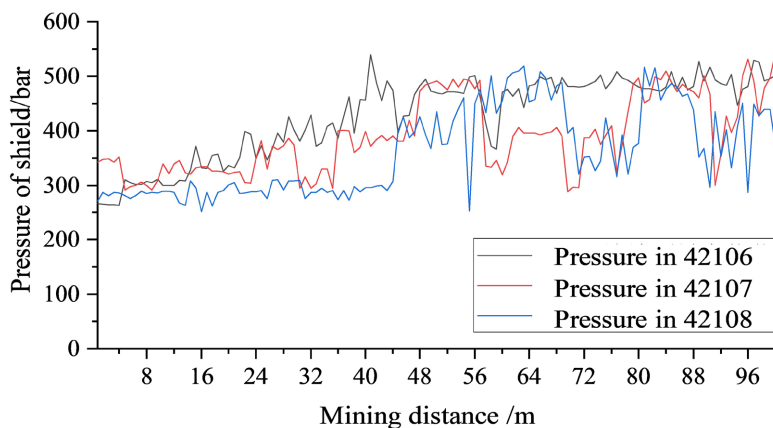
Figure 8. Comparison of shield load during initial mining between working faces with and without hydraulic fracturing. (a) stress contour map in 42106 workface before roof fracturing; (b) stress contour map in 42108 workface after roof fracturing.

Figure 9. The figure indicates that under the same geological mining conditions, the average and maximum loads of the supports in the 42107 and 42108 working faces are lower than those in the 42106 working face. Specifically, the average load of the supports in the 42107 working face is 3.67 MPa lower than that in the 42106

working face, representing a reduction of 10.45%. Similarly, the average load in the 42108 working face is 5.912 MPa lower than in the 42106 working face, indicating a decrease of 17.31%. This demonstrates that the directional long drilling segmented hydraulic fracturing technique effectively compromises the integrity of the overlying hard roof, reducing the mining pressure intensity.



(a)



(b)

Figure 9. Comparison of the stress of the shield in different workface. (a) average stress of shield in different workfaces; (b) maximum stress of shield in different workfaces.

The directional long drilling segmented hydraulic fracturing technique also weakens the hard roof of the 42108 working face, decreasing the periodic pressure relief step and range. Compared to the non-fractured areas, the periodic pressure relief step, dynamic load coefficient, and maximum pressure are reduced by 13.58%, 13.77%, and 25.49%, respectively. This effectively relieves pressure on the overlying parallel coal pillars and addresses the issue of severe mining pressure hazards during the recovery of the fully mechanized mining working face above the overlying parallel coal pillars.

Additionally, after hydraulic fracturing the roof in the 42108 fully mechanized mining working face, a total of 8075 microseismic events were detected within a

recovery range of 0 to 3683 m, with a total energy release of 1.42×10^8 J. The distribution of these microseismic events was dispersed, primarily occurring within a range of 36 to 277 m in front of the working face. During the initial mining phase, microseismic events were frequent; for instance, when the working face advanced 59 m, 10 microseismic events were recorded, releasing energy 5.39×10^5 J. When the working face progressed to 89 m, a total of 35 microseismic events occurred, with an energy release of 1.43×10^6 J. After advancing 822 m, the frequency and total energy of the microseismic events decreased, with most events falling below 5.0×10^5 J. The microseismic events were primarily concentrated near the coal pillar in the middle of the working face, indicating a successful hydraulic fracturing effect in that area, which significantly reduced the mining pressure, keeping the pressure intensity below 40 MPa. By comparing the total energy of microseismic events in the 42107 and 42108 working faces, it was found that under the same conditions, depth, working face width, and initial mining parameters, the 42108 working face, which implemented directional hydraulic fracturing technology on the hard roof, had a smaller increase in microseismic energy compared to the 42106 working face, which did not utilize hydraulic fracturing technology. The maximum energy of the microseismic events decreased by nearly 3.0×10^8 J.

6.2. Case Study on Pressure Prevention in Vertical Coal Pillars

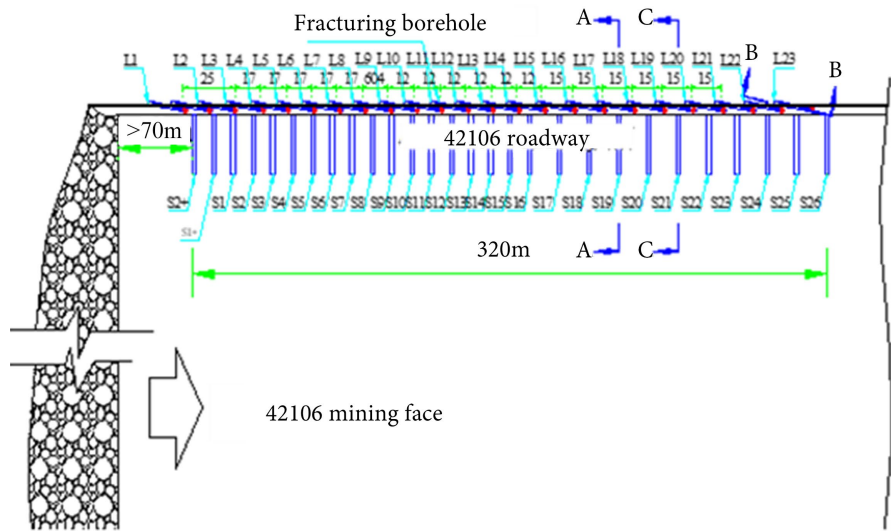
The 42106 working face of the Buertai Coal Mine is adjacent to the 42108 and 42107 working faces, and they share similar production and geological conditions. To address the issue of strong mining pressure during the extraction under the coal pillar in the 42106 working face, high-pressure hydraulic fracturing holes were constructed in the return air roadway of the working face. The arrangement and parameters of the fracturing boreholes, along with the fracturing method and hydraulic fracture propagation, are illustrated in **Figure 10**.

The 42106 working face air-return gateway was equipped with roof fracturing holes in both the solid coal rib and the adjacent empty coal pillar rib. The borehole in the solid coal rib was 40.5 m long with an inclination of 50° , while the adjacent empty coal pillar hole measured 37.5 m long with an inclination of 80° . The end of the borehole reached the upper part of the roof sandstone layer. During the fracturing process in the gateway of the 42106 working face, the following was observed: for the solid coal rib borehole, fracturing was conducted 8 to 11 times with an average pressure of 28 MPa. Water began to flow out at a depth of approximately 26 m, with a significant flow observed at a depth of 18 m, prompting the cessation of fracturing. For the conventional adjacent empty coal pillar borehole, fracturing was performed 12 to 14 times at an average pressure of 25 MPa. Water began to flow from multiple points of the roof anchor cables at a depth of around 18 m, leading to the end of fracturing.

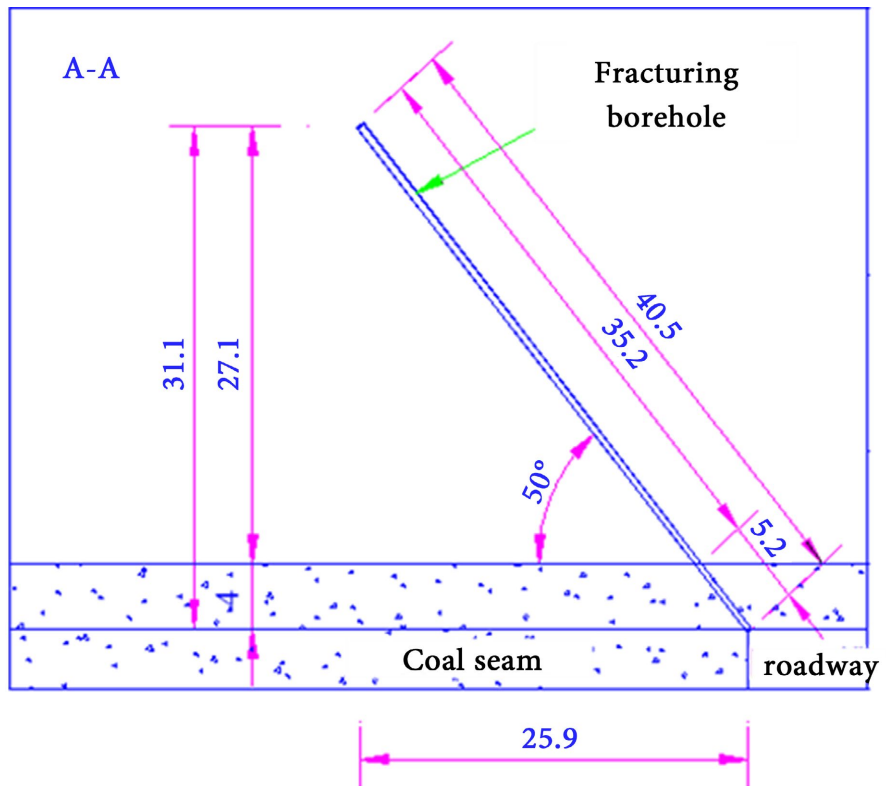
The expansion range of hydraulic fractures in the roof rock layer of the 42106 gateway is shown in **Figure 11**. By implementing hydraulic fracturing within the

roof rock layer, the propagation of fractures reduced the high stress stored in the rock layer. This release of stored elastic energy from the fractures helps to prevent sudden energy release that could cause severe deformation of the surrounding rock. The noise associated with rock bursts in the roof within the fractured area was significantly reduced.

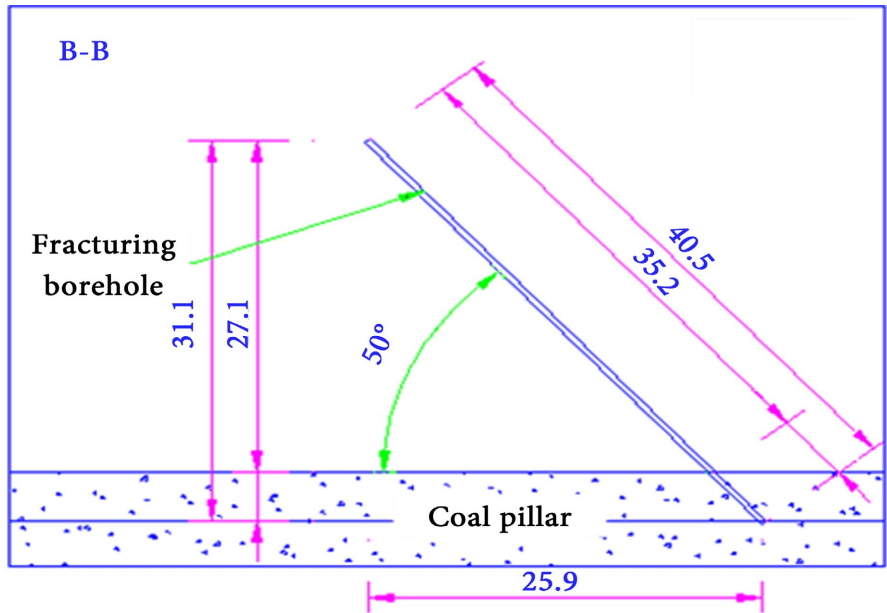
Through multiple fracturing operations on a single borehole, the hard roof was significantly weakened, leading to a substantial reduction in its strength and integrity.



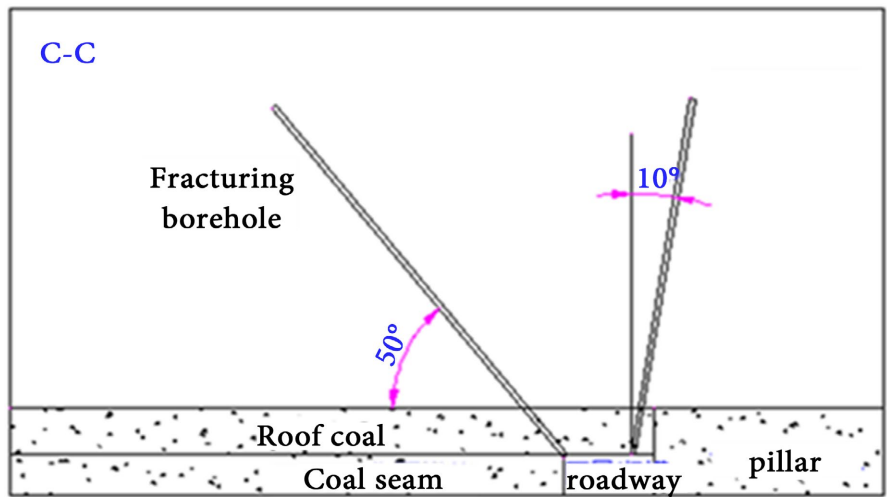
(a)



(b)



(c)



(d)

Figure 10. Hydraulic fracturing arrangement of conventional short boreholes. (a) plain layout of borehole; (b) sectional layout of borehole A-A; (c) sectional layout of borehole B-B; (d) sectional layout of borehole C-C.

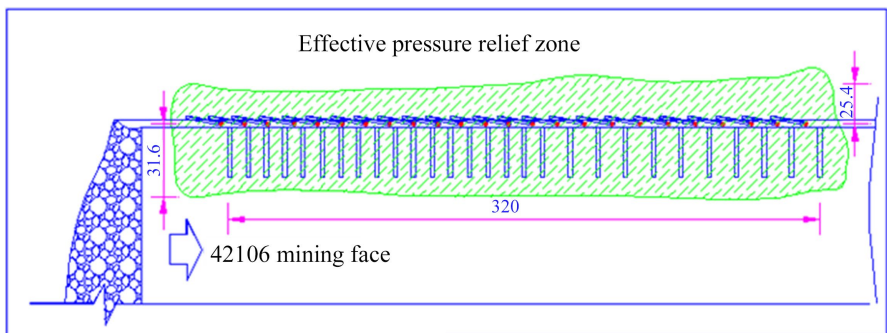


Figure 11. Influence the range of hydraulic fracturing.

As the working face advanced, the basic roof could collapse promptly, preventing the formation of prolonged overhangs and reducing the concentration of advance support pressure. The deformation of the surrounding rock in the roadway has been effectively alleviated.

In the gateway of the 42106 working face, several monitoring points for surrounding rock deformation were established. After implementing hydraulic fracturing on the roof using conventional short boreholes, significant reductions in strong pressure events were observed, and the deformation of the roadway's width and height also decreased, as shown in **Figure 12**.

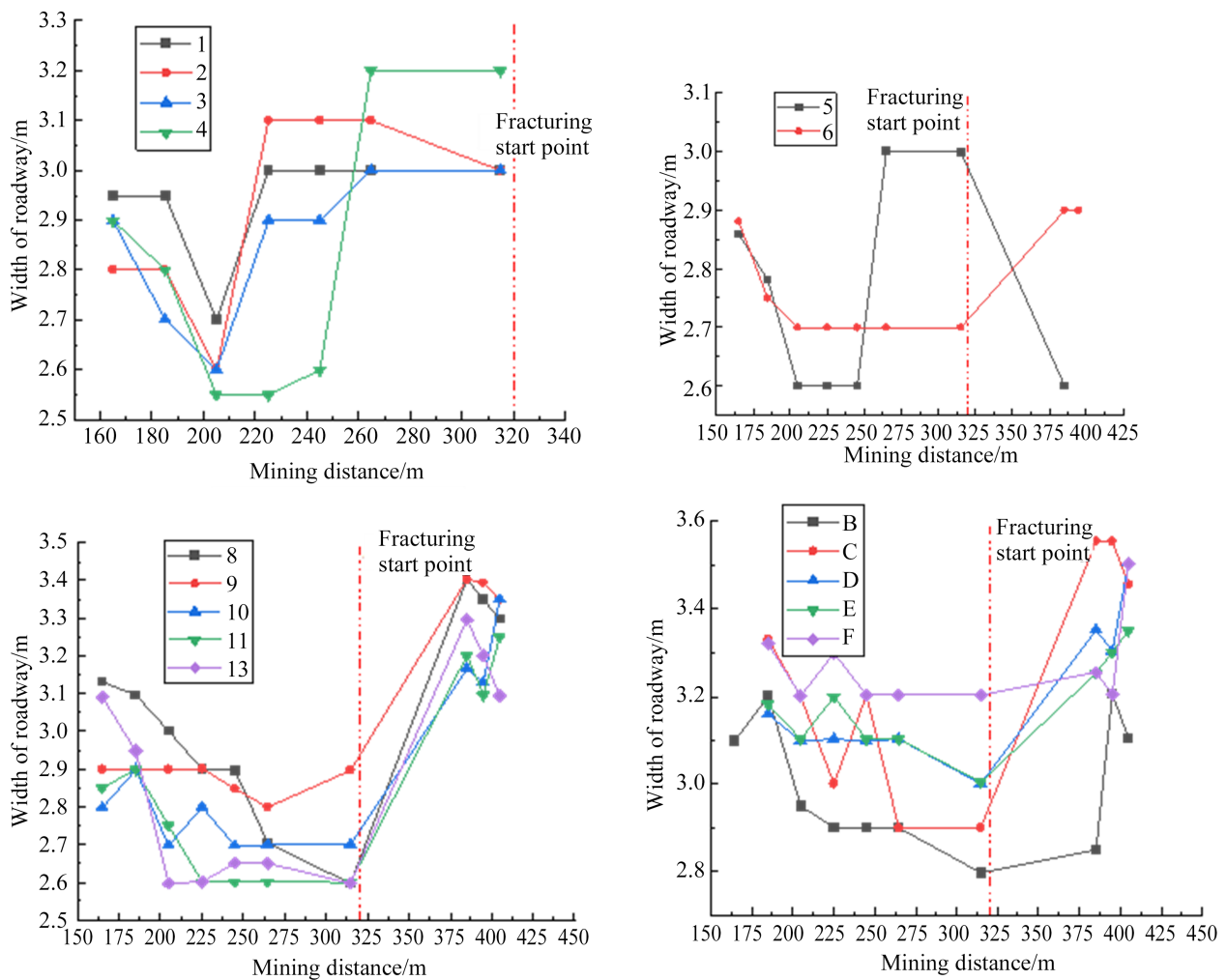


Figure 12. Variation curve of return air roadway height after hydraulic fracturing.

By employing the single hole multiple fracturing technique on the surrounding rock of the return airway in the 42106 working face, the goals of weakening the roof rock layer, shortening the length of the hard roof overhang, releasing stored elastic energy in the roof rock layer, and reducing high stress within the rock layer were achieved. This effectively mitigated the severe deformation of the return airway, leading to a noticeable decrease in the tailgate's bulging after fracturing, thereby ensuring safe production in the working face,

as illustrated in **Figure 13**.



Figure 13. Comparison of tail bottom drum before and after hydraulic fracturing.

7. Conclusions

This paper focuses on the Shendong mining area, analyzes the mining and geological conditions of the 4-2 coal seam beneath the overlying 2-2 residual coal pillars. The study examined the pressure manifestation in the working face under overburden parallel and vertical coal pillars, revealing the mechanisms of mining pressure under different overburden coal pillars. Effective measures for mining pressure prevention and control are proposed based on engineering validation. The main conclusions are as follows:

1) In Shendong mining area, nine mines have geological conditions characterized by closely spaced thick coal seams. During the extraction of coal seams, the residual coal pillars from the overlying seams lead to stress concentration affecting the lower coal recovery faces, resulting in strong mining pressure phenomena such as roof support failure and sidewall caving. Thus, the management of mining pressure under overburden coal pillars has become a typical challenge in the Shendong mining area.

2) Based on the spatial relationship between the layout direction of the lower recovery faces and the long axis of the overlying residual coal pillars, coal pillars are classified into three extraction types: parallel coal pillars, vertical coal pillars, and oblique coal pillars. Statistical data from the Buertai coal mine indicates that the mining pressure manifestation varies in time and space, ranked from strong to weak as follows: mining-out of parallel coal pillars > mining-in the coal pillars > vertical coal pillars in the middle of the mining face.

3) For mining under overburden parallel coal pillars, a “fan-shaped seesaw” mechanical model is proposed, indicating that the spatial stability of the seesaw under the stress concentration of the overlying coal pillars is the primary factor determining the load on the working face supports. This model reveals the mechanism of strong mining pressure during mining. For mining under vertical coal pillars, a coal pillar stress transfer model based on a foundation beam is introduced, unveiling the compound fracturing mechanism between vertical coal pillars.

4) Techniques for preventing mining pressure were proposed, including opti-

mizing the layout of excavation faces, using high-resistance hydraulic supports, directional drilling hydraulic fracturing, and straight-hole fracturing. Engineering cases of mining pressure prevention in the 42106 and 42108 working faces of the Buliutai coal mine illustrate the effectiveness of these techniques in managing strong mining pressure, providing valuable technical references for similar mining situations.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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