International Journal of Oil, Gas and Coal Engineering
2024, Vol. 12, No. 3, pp. 63-74
https://doi.org/10.11648/j.ogce.20241203.11

Research Article

Study on Roadway Layout and Supporting Method of High Intensity Mining Disturbance Bottom Coal Recovery Working Face (A Case Study in Xiagou Mine)

Yuqing Duan[1, 2, *], Gang Han[1, 2], Xiaoqi Hao[1, 2]

[1]Research Institute of Rock Burst Prevention, China Coal Energy Research Institute Co., Ltd., Xi'an, China
[2]China Coal Rock Burst & Water Hazard Control Center, Ordos, China

Abstract

After more than ten years of mining, the subsequent replacement resources of 4 # coal in Xiagou Mine are insufficient. In order to ensure the normal production of the mine, Xiagou Coal Mine needs to recycle the lower layer resources of 4 # coal seam. The design issue of the roadway layout and support mode for the bottom coal recovery left by the strong disturbance in the Xiagou Mine has to be resolved. Through theoretical evaluation and computer simulation, this study investigates the appropriate staggered distance of the roadway layout following upper slicing mining as well as the distributed stress law of the roadway under various staggered distances. Finally, the reasonable external offset is determined. Based on the actual working condition of 404 mining area in Xiagou Mine, the matching roadway support design is put forward. Finally, the roadway layout and support design are validated through the use of computer modeling and field monitoring. The findings demonstrate that when there is a significant disruption in the upper layer, the roadway layout of bottom coal recovery should adopt the external staggered layout and the reasonable external staggered distance is 6 m. At this time, the fluctuation degree of nearby rock stess, the non-uniformity of stress distribution and the uniformity of the roadway's deformation under disturbance meet the production needs. It shows that 6m layout and roadway supporting method are more reasonable, which has reference significance for roadway arrangement and support under similar engineering conditions.

Keywords

High Intensity Mining Disturbance, Non-Uniform Stress Distribution, Roadway Layout, Combined Support, Bottom Coal Recovery

1. Introduction

Many mines in China are limited by historical and technical conditions. There is a large thickness of bottom coal when the floor lithology is poor. Based on this, the remaining coal resources in the mine have not yet been mined, resulting in many problems such as insufficient production and mining continued tension. In addition, the high-intensity mining of super-thick coal seams in the upper layer leads to the destruction of coal seam integrity. When the lower layer mining design is carried out, it is found that the stress environment in some areas changes dramatically, which can easily lead to the

*Corresponding author: duanyuqing2@chinacoal.com (Yuqing Duan)

Received: 22 July 2024; **Accepted:** 12 September 2024; **Published:** 10 October 2024

deformation and instability of the lower layer roadway, rib spalling, roof fall and other severe mine pressure [1]. There are many mining areas with the above geological characteristics in China, such as the layered re-mining left by the Huojitu mine in Daliuta, the recovery of bottom coal under the loose roof of Xintai Xiagou Coal Mine, and the comprehensive caving and re-mining of residual coal in Jushan Coal Mine in Jincheng Mining Area [2-4].

In order to fundamentally reduce the severe mine pressure appearance and improve the support efficiency of mines under such conditions, it is necessary to study the location selection and support of roadways. Numerous academics both domestically and internationally have studied this problem from different angles and achieved fruitful results. Lu, S et al,. 1993 [5] combined with the mining situation and the rock's deformity that surrounds the roadway, calculated the location of the roadway; Jia, F et al,. 2020 [6] used the stress failure range and stress bubble theory to calculate the internal dislocation distance of the roadway. Zhang, Z et al,. 2012 [7] determined the roadway's appropriate layout placement through the floor failure depth and the stress distribution under the coal pillar. In the computer simulation system was utilized to examine the impact of different layouts of roadway on the deformation and instability of roadway. Zhang, Y et al,. 2008 [8, 9] and other pioneers proposed a method to determine the location of lower layered roadway by stress change rate, and verified it on site. For the study of roadway support of broken nearby rock, Shi, M et al,. 2008 [10] introduced the test technology of loose circle thickness based on the theory of ' combined arch ', which greatly reduced the roadway's deformation and stiffness. He, Q et al,. 2008 [11] analyzed the roadway's deformation and fracture process with composite roof, and put forward the design scheme of bolt mesh cable coupling support, which achieved good support effect. Kang, W et al,. 2010 [12-14] proposed the use of high prestress, high strength anchor cable, anchor net cable coupling support, grouting and bolt support, step-by-step pressure relief and anchor net combined support, shed and other support methods on the basis of pressure release and pressure relief.

In addition, Yuan, T et al,. 2010 [25] et al. analyzed the influence of different bottoming parameters on the stability of surrounding rock of mining roadway in fully mechanized working face. Wang, H et al,. 2020 [26] analyzed the correlation between the deformation and failure of the bottom coal and the width of the coal pillar in the roadway along the goaf, and determined the reasonable width of the coal pillar.

For different downward mining engineering conditions, the research results of experts have effectively solved the layout and support of the lower layered roadway's problems. However, under the triple influence of the damage and failure of coal pillar during the extremely close mining of the upper layer, the focus on stress of the remaining coal pillar itself, and the change of the overburden structure of the extra-thick coal seam during the upper layer mining, the reasonable layout of lower layered roadway and the corresponding support method has become an urgent problem to be solved. Therefore, aiming at the engineering conditions of recovering the remaining bottom coal in Binchang mining area, this paper uses theoretical evaluation, computer simulation, field detection and other means to study the roadway layout and corresponding support under this condition based on the overlying strata movement rules and stress bubble after the extra thick coal seam's mining, in order to provide reference for the roadway layout and surrounding rock control under such conditions.

2. Engineering Background

2.1. Engineering Overview of Re-mining Working Face for Xiagou Coal Mine

At present, 4 # coal seam is mined in Xiagou Coal Mine. According to the detection of coal seam thickness during digging, the typical coal seam's thickness in mining area is 10.70-18.50 m, with an average of 16.1 m, and the dip angle is 0-18°. The buried depth of coal seam is about 439.7-590 m. The firmness coefficient of coal seam is 2.1, and the firmness coefficient of roof is 4.1. The floor is bauxite mudstone, which is easy to expand in water and cause floor heave. Therefore, the mining needs to leave the bottom coal. Coal seam's thickness is about 12 m. The roof is managed by fully mechanized top coal caving method. The coal pillar's width between the working faces is 35 ~ 42m. At present, the upper layered fully mechanized caving mining is basically completed. After more than ten years of recovery of 4 # coal in the mine, the subsequent replacement resources are insufficient. To keep the mine operating and producing, Xiagou Coal Mine needs to recycle the lower layer of 4 # coal seam's resources.

2.2. Mining Characteristics of Upper Layer of 4 # Coal Seam

After the upper fully-mechanized's high-intensity mining caving, the section coal pillar has certain damage, and the roadway has a large deformation, as indicated in Figure 1.

Figure 1. *Deformation of upper layer transport roadway.*

The roof has obvious subsidence and the floor has obvious bottom heave, which leads to the extreme compression of the roadway section area, which is about 40% of the original section area, and the metal mesh also has shear failure.

In order to further clarify the surrounding rock condition of the lower layered roadway, the field borehole peeping experiment was carried out on both sides of the coal pillar between ZF304 and ZF4401 working faces. The characteristics of the borehole histogram of the generated failure, fracture, and complete coal are shown in the diagram., and the statistics of crack range of surrounding rock of the coal pillar are as follows:

(a) broken surrounding rock (b) strong fissured surrounding rock (c) integrity surrounding rock

Figure 2. Drilling histogram.

Table 1. Statistics of loose range of surrounding rock at edge of coal pillar (Unit: m).

Test position	1	2	3	mean value
ZF304 side wall	5.6	5.3	5.5	5.5
ZF4401side wall	5.8	5.4	5.7	5.6

Coal pillars have experienced high-intensity mining disturbance and compaction. According to the analysis of the borehole histogram indicated in figure 2, as indicated in Table 1, the failure depth of the section coal pillar reaches about 5.6 m, and the fracture depth reaches about 8.2 m, which makes the upper layer mining roadway prone to deformation and instability.

3. Layout and Stagger Distance Analysis of Lower Layered Roadway

3.1. Analysis of Rock Pressure in Lower Layered Roadway Layout

Upper slice mining leads to complex loading conditions of coal pillars. Not only is it easy to cause stress concentration on the coal pillars, but also The stress will be transmitted to the deep floor strata, resulting in the general mechanical characteristics of the roadway surrounding rock arranged in the coal seam of the floor become worse, and the deformation increases sharply [15]. Affected by the dynamic pressure of the upper coal seam mining, the bond coefficient and internal friction angle between the two sides of the coal body and the roof of the lower layerd roadway become smaller. According to the correlation analysis in 1.2, the coal and rock mass in the goaf has obvious properties of discontinuous medium fragmentation or block fragmentation.

Although the mining space of the upper layer is large, after a long period of compaction, the roof fully sinks, which not only weakens the transfer stress of the coal pillar during the lower layer mining, but also weakens the impact of the basic roof breaking on the lower layer working face and roadway. [16-19], and the compacted discontinuous block fracture body can have a certain mechanical strength under the condition of using grouting technology, so the following roadway layout scheme design can be carried out.

According to the occurrence of coal seam in 4 mining area and the existing production system, it is proved that the lower layer is arranged in the same direction as the upper layer.

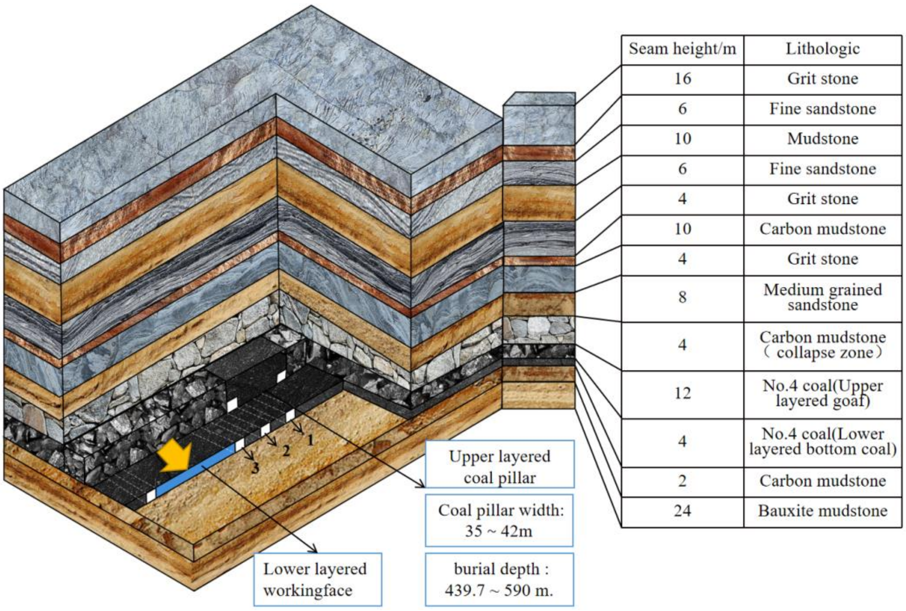


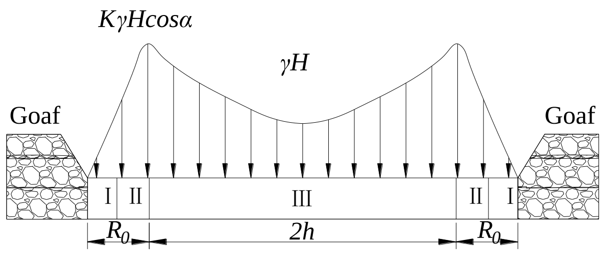
Figure 3. *Comprehensive histogram.*

There are three kinds of main roadway layout [20, 21], which are internal fault, outer stagger and overlapping layout as indicated in figure 3. The upper slice working face in the diagram has been mined out. The upper layered working face left a wide coal pillar. 1 is the outer staggered arrangement. 2 is the overlapping arrangement. 3 is the internal staggered arrangement.

Because the overlapping arrangement and the internal staggered arrangement are very close to the coal seam construction. Due to the influence of discontinuous medium fragmentation, mesh laying and passive support must be carried out, which makes the mining process of lower layered roadway cumbersome and less safe. And because the overlapping arrangement is close to the coal pillar, it will still be impacted by the concentrated stress of the upper coal pillar, which further increases the roadway's maintenance cost. The external staggered arrangement can be used for active support to improve surrounding rock strength and the efficiency of excavation and support, which can increase the working face length, reduce the loss of resources and reduce the air leakage of roadway.

3.2. Analysis of Coal Pillar Width in Lower Layered Section Roadway Layout

The research of narrow coal pillar roadway protection must be carried out. In order to further clarify the limiting conditions of the outer distance of the roadway, the coal pillar's width is analyzed. The mining activities on both sides of the lower slice working face will cause different degrees of damage to the edge of the coal pillar. A plastic deformation zone with a width of R_0 is formed on both sides of the coal pillar. When the width of the coal pillar is less than the sum of the two plastic zones, the plastic zone is penetrated and the coal pillar will lose stability.



I - fracture zone II - plastic zone III - elastic core zone

Figure 4. *Coal pillar support pressure distribution.*

The basic conditions for coal pillars to remain stable are as follows: after the plastic zone is formed on both sides of the coal pillar, the center of the coal pillar still maintains a certain width L in the ' elastic core ' of the elastic stress state, as indicated in Figure 4. The width of the elastic core is twice the height of the roadway, so the width of the coal pillar to maintain a stable state [22] should meet the condition of formula (1):

$$B \geq R_0 + 2h + R_0 \quad (1)$$

Within the equation and Figure 4: B is the appropriate coal pillar width, m; R_0 is the coal pillar's plastic zone width, m; h is the roadway's height, m; α is the dip angle of coal seam.

After the mining face is advanced, coal stress will be redistributed. From the edge of the coal pillar to the deep part, the fracture zone, plastic zone, elastic zone and original rock stress zone will appear, and the surrounding rock stress will transfer to the deep part. According to the limit equilibrium theory, the plastic zone width R_0 of the coal body around the mining face can be obtained as Equation (2):

$$R_0 = \frac{M\lambda}{2\tan\varphi_0} \ln \left[\frac{K\gamma H + \frac{C_0}{\tan\varphi_0}}{\frac{C_0}{\tan\varphi_0}} \right] \quad (2)$$

Within the equation and Figure 4: M is the thickness of coal seam mining, m, take 3; λ is the lateral pressure coefficient, $\lambda=\mu/(1-\mu)$, μ is the Poisson 's ratio, $\lambda=0.43/(1-0.43)=0.754$; φ_0 is the internal friction angle of the coal body interface, take 30; C_0 is the cohesion of the coal interface, MPa, take 15.534; K is the stress concentration factor caused by mining, taking 3.0; H is the mining depth, m, according to 515 consideration; γ is the average bulk density of the overlying strata, kN/m^3, take 25. Therefore, the width of plastic zone caused by mining can be calculated as: R_0=1.7m.

Therefore, the width of the section coal pillar should be greater than 9.4 m, which can avoid the penetration of the plastic zone on both sides of the working face. Considering a certain safety factor, section coal pillar width in the lower layered working face should not be less than 10 m.

3.3. Analysis of Reasonable Stagger Distance of Lower Layered Roadway Layout

Under the influence of mining on both sides of the upper layered coal pillar, the stress of the surrounding rock of the coal pillar is redistributed. The edge of the coal pillar will be destroyed first due to stress concentration. After that, the stress of the surrounding rock will gradually shift to the deep part. From the edge to the deep coal pillar, the fracture zone, the plastic zone and the elastic zone are gradually formed. According to Formula (1), M takes 13 m, and the width of the plastic zone caused by the upper layered mining is 7.54 m. Considering a certain safety factor, the plastic zone affected by mining is considered as 8.0 m.

The upper layer coal mining in Xiagou mine is high-intensity mining of top coal caving. The coal pillar is damaged greatly and the edge is damaged seriously. According to the theory of bolt support, the rock mass in anchorage zone must be located in 2 ~ 3 zones of broken zone, plastic zone and elastic zone., and the confining pressure can be strengthened. Considering that the roadway layout avoids high stress, when the roadway is arranged outside, the outside distance should be about 7.5 m.

4. Numerical Simulation Analysis of Roadway Layout

4.1. Numerical Model of Lower Layered Roadway Layout

In order to simulate different roadway layouts and subsequent roadway support methods, the simulation is carried out according to the geological histogram of Xiagou mine (Figure 5).

The layering of ZF4401 and ZF304 working face of 4 # coal has been completed. The lower layer working face is set to first mine the coal seam below ZF4401 working face, and then mine the coal seam below ZF304 working face. The location relationship is as indicated in figure 5 (the layout of the lower layer roadway is outer stagger), the length of the upper layer working face is 186 m, the coal pillar's width4 is 35 m, and the roadway of the lower layer working face is arranged in the outer staggered, overlapping and internal staggered. The width × height of the lower layered roadway is 4×3m, and the coal thickness is 4m. The supporting force of 1 MPa is applied to the roof of the lower roadway to simulate the supporting conditions, strengthen the mechanical strength of roadway surrounding rock during the support, and simulate the grouting rock mass [23]. The lower layered roadway and the working face area are affected by the coal pillar floor's concentrated stress, and the internal staggered and overlapping arrangement roadway support are affected by the roof fracture discontinuity.

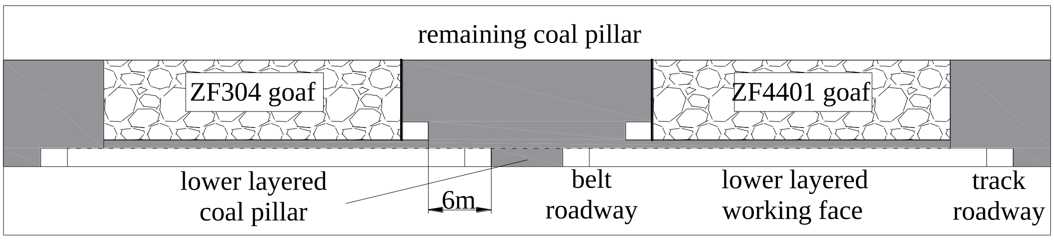


Figure 5*. Layout diagram of lower layer working face.*

Considering the boundary effect of mine rock mass, 50 m protective coal pillar is left at the boundary. The surrounding and bottom of the model are fixed constraints. The length × width × height of the model is 512 × 200 × 210m. Considering the stress transfer effect, the vertical stress is applied on the upper boundary so that the initial vertical stress in the simulated coal seam is about 13MPa. In the calculation, the Mohr-Coulomb strength criterion is used as the material yield criterion of coal rock mass. According to the results of rock mechanics test, the specific parameters of rock mass are indicated in table 2 and table 3.

Table 2. *Table of lithology and physical and mechanical parameters of roof and floor of coal seam before grouting.*

Rock	bulk modulus/GPa	shear modulus/GPa	cohesion/MPa	tensile strength/MPa	nternal friction angle /(°)	Density kg/m^3
grit stone	13.70	3.57	8.75	7.20	37	2 830
fine sandstone	4.53	4.42	2.8	3.2	33	2 500
mudstone	3.31	10.16	8.25	4.73	36	2 754
fine sandstone	4.53	4.42	2.8	3.2	33	2 500
grit stone	13.70	3.57	8.75	7.20	37	2 830
carbon mudstone	9.75	4.45	2.64	5.14	38	2 300
grit stone	13.70	3.57	8.75	7.20	37	2 830
medium grained sandstone	5	8	4.5	1.8	37	2 400
carbon mudstone	9.75	4.45	2.64	5.14	38	2 300
no.4 coal	1.57	0.61	6.8	0.61	22	1 400
carbon mudstone	9.75	4.45	2.64	5.14	38	2 300
Bauxite mudstone	3.31	10.16	8.25	4.73	36	2 754

Table 3. *Physical mechanical parameters of coal rock after grouting.*

Grouting Rock	bulk modulus/GPa	shear modulus/GPa	cohesion/MPa	tensile strength/MPa	nternal friction angle/(°)	densitykg/m^3
no.4 coal	1.57	0.61	6.8	0.61	22	1400

4.2. Analysis of Disturbance Characteristics of Upper Layer Mining to Lower Layer

After the mining of ZF4401 and ZF304 working faces is stable, the plastic zone is indicated in figure 6.

According to figure 6, the depth of the plastic zone of the coal pillar is 6 ~ 7m after the mining of the working faces on both sides. The coal pillar has an elastic core in the center. Different degrees of shear and tensile failure occurred on both sides of the coal pillar and the roof and floor of the working face on both sides after the mining was stable, and the failure depth reaches the carbon mudstone and bauxite mudstone below the coal seam. Therefore, if the lower layered roadway is arranged in internal staggered or overlapping arrangement, the roof and floor of the roadway and the rock strata of the two sides are all damaged rock strata, and the whole process of high-density mesh laying + grouting + shed support is required, with high cost and low efficiency of roadway protection. The roadway excavation and mining in the lower layer will further have a huge impact on the roadway, which will easily cause serious deformation of the roadway.

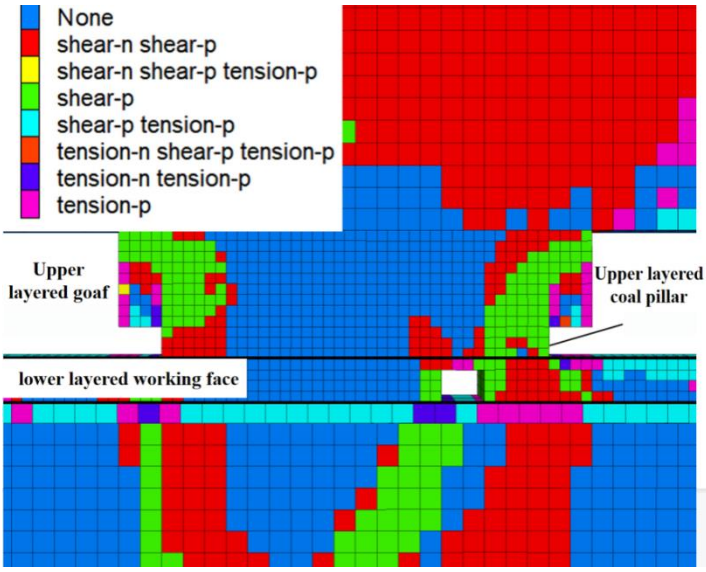


Figure 6. *Distribution map of plastic zone of surrounding rock in lower layered coal pillar.*

In order to further clarify the stress environment of the surrounding rock in the lower layered roadway [24], FLAC3D was used for simulation. When the mining of the working faces on both sides reached stability, the TECPLOT post-processing software was used to obtain the stress distribution of the coal pillar and the surrounding rock. The Isogram of surrounding rock stress distribution is indicated in figure 7.

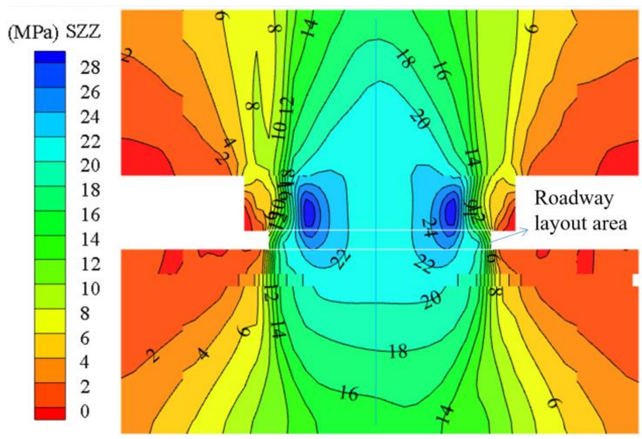


Figure 7. *Isogram of surrounding rock stress distribution at coal pillar.*

It can be seen from figure 7 that after the mining of the working faces on both sides, the stress of the roof and floor is small, which further indicates that the shallow roof and floor have been damaged and cannot bear the stress. From the point of view of whether the stress at both ends of the roadway is uniform, the roadway is on the side of the center of the coal pillar to bear the larger stress, and the side away from the center of the coal pillar to bear the smaller stress. From the density of the stress distribution contour, it can be seen that the stress change below the center line of the coal pillar is relatively gentle, and the stress change away from the center line of the coal pillar is more severe. Therefore, the layout of the outer staggered roadway should be close to the center line of the coal pillar to effectively reduce the uneven degree of stress distribution.

From the perspective of roadway layout outer stagger distance and stress distribution, the stress concentration point of coal pillar is about 7m according to the coal wall, which is consistent with the depth of surrounding rock loose circle. The roadway should be arranged near 7m.

The smaller the offset distance is, the larger the width of the lower layered coal pillar is. In order to analyze the rounding, 6m (ensure the width of the lower layered coal pillar, the support stability on the side of the roadway is poor), 8m (can meet the stability of the support on both sides and the width of the lower layered coal pillar), 10m (the support stability on both sides of the roadway is good, but the lower layered coal pillar is narrow, which is not conducive to the stability of the roadway during the mining period). Therefore, the offset distance is set to 6m, 8m and 10m respectively, and the reasonable offset distance of the roadway layout is analyzed. Therefore, the stagger distance is set to 6m, 8m and 10m1 respectively, and the reasonable stagger distance of roadway layout is analyzed.

4.3. Analysis of Reasonable Outer Stagger Distance in Lower Layer

Before the lower layer mining, the vertical stress data in the coal body are extracted to make the difference between the vertical stress of the latter node and the vertical stress of the previous node, which can represent the uniformity of the vertical stress distribution of the lower layer. The vertical stress distribution and uniformity characteristics of the coal body before the lower layer mining are indicated in figure 8, and the box in the figure indicates roadway with outer stagger distance of 6m.

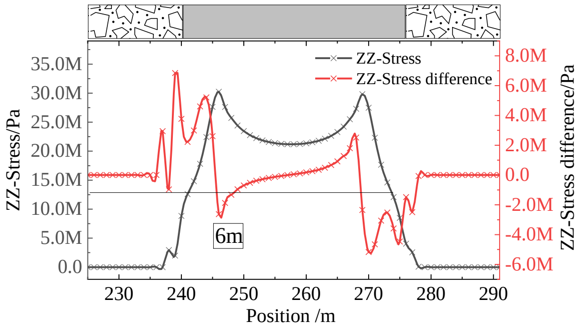
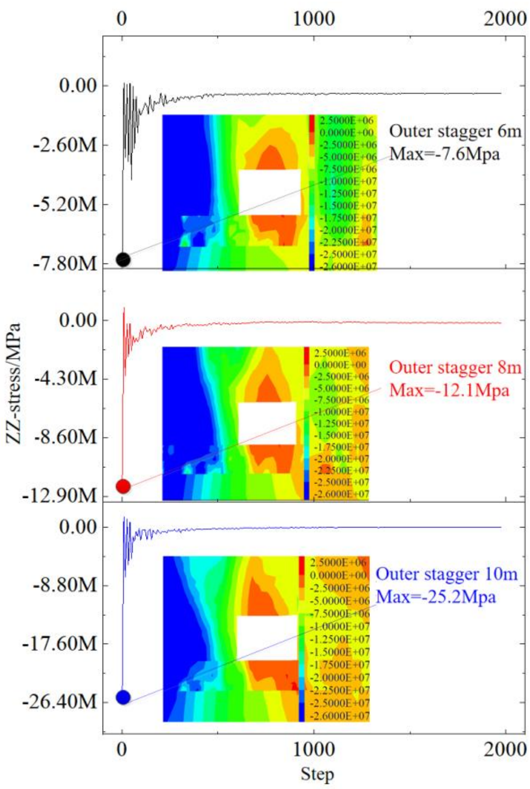
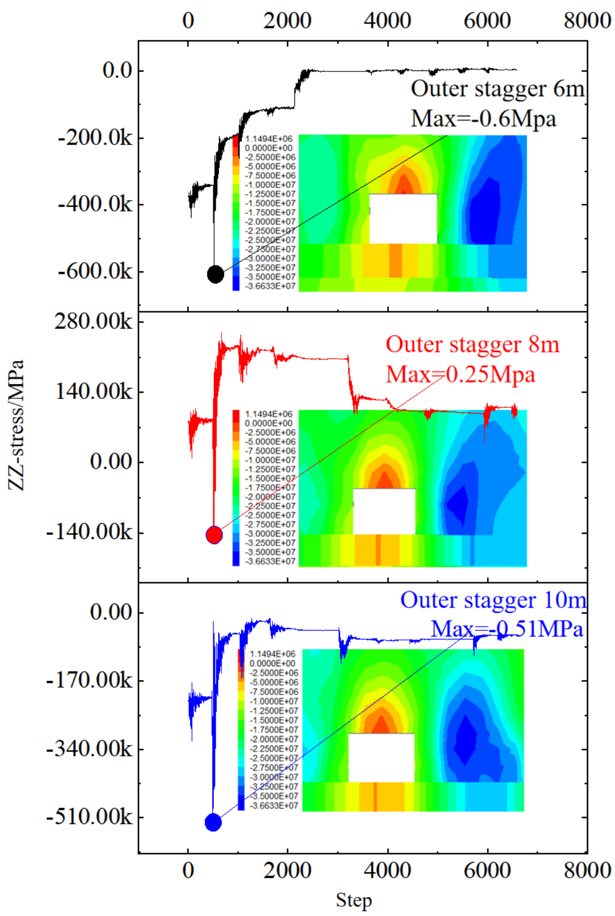


Figure 8. *The vertical stress distribution in coal body before mining and its uniformity chart.*

According to figure 8, the vertical stress of the lower layered roof is close to 0MPa, which further shows that the roadway roof with internal dislocation and parallel arrangement is in a completely broken state, which is not conducive to the stability and maintenance of the roadway in the lower layered working face. From the analysis of stress concentration degree, the stress concentration degree of 6 ~ 10 m is gradually reduced, and the stress at 10 m is at the lowest level. From the analysis of the uniformity of stress distribution, the uniformity of stress at 6 ~ 10m gradually decreases, and the uniformity of stress at 6m is the highest.



(a) Digging period



(b) Recovery period

Figure 9. *Perturbation diagram of vertical stress of roadways with different offsets in mining stage.*

Figure 9(a) illustrates that the roadway is dug after 2000 steps of operation, and Figure 9(b) illustrates that the roadway is dug 50 m ahead of the recovery period after 8000 steps of operation. Figure 9 (upper), Figure 9 (middle), and Figure 9 (lower) depict the vertical stress of the midpoint (248,120,42) of the 6 m roadway floor, the midpoint (250,120,42) of the 8 m roadway floor, and the vertical stress of the midpoint (252,120,42) of the 10 m roadway floor.

Figure 9(a) illustrates how the vertical stress of the roof of the 6–10 m roadway changes substantially in a brief amount of time during the digging period before progressively decreasing to almost 0 MPa; among them, the vertical stress fluctuation range of the roadway roof with outer stagger distance of 10m is the largest, followed by 8 m, and 6 m is the smallest. After the vertical stress is gradually stabilized, the value is also 6m, which is the closest to 0MPa. From the analysis of the uniformity of stress distribution, it is easy to see that the stress distribution on both sides of the roof with 6m is more symmetrical than that with 8m and 10m according to the vertical stress cloud diagram in figure 9.

It can be seen from figure 9 that during the recovery period, after the digging disturbance, the bearing capacity of the coal and rock of the roadway roof decreases greatly. The change law is similar to that during the digging period, from the drastic change in the early stage, and then gradually becomes smaller to a smaller stress value, and there is obvious step change. From the initial stress value, it can be seen that the coal and rock bearing capacity of the roadway roof with outer stagger distance of 6m is strong. Similarly, after the vertical stress is stable, it is also 6m closest to 0MPa.

Therefore, in the initial digging of the lower layered roadway, the initial support is prone to roof fall, so the initial support strength should be strengthened and the displacement monitoring should be strengthened. Combined with the analysis of figure 7, 8, 9, theoretical calculation and on-site drilling peep, the stress fluctuation range and stress uniformity of the roadway layout are small, and the bearing capacity of the roadway roof is strong under the influence of mining. At the same time, the roadway support at this position meets the bolt support theory.

5. Supporting Scheme Determination and Verification

5.1. Determination of Support Scheme

Together with the actual geological engineering conditions of the Xiagou Coal Mine, the strength of the broken surrounding rock should be strengthened first in order to realize the support of the broken two sides and roof of the roadway and the prevention and control of roadway floor heave. This is based on the reasonable width of the coal pillar, the reasonable selection of the roadway stagger distance, and the calculation results of numerical simulation, taking into consideration the improvement of coal recovery rate and the positional relationship between roadways. Secondly, strengthening the support of the two sides' bottom corners and floors is required. improve their shear and tensile resistance, and prevent floor heave under the dual influence of mining and geological effects [18].

According to the engineering analogy method, based on the successful experience of a large number of similar working conditions in Xiagou Mine, the roadway support design is optimized according to the current engineering conditions as indicated in figure 10.

Grouting, anchor cable, a W-shaped steel belt, and metal mesh make up the roof. The grouting material is high-water quick-setting material. The depth of grouting hole is 8m, the spacing of grouting hole is 1.5m, and the row spacing is 1.4m. After the grouting is completed, the grouting bolt is installed and finally the hole is sealed. The metal mesh adopts a double-layer metal mesh structure. The top layer adopts a diamond metal mesh to block the broken roof, and the outer layer adopts a 10×10cm steel mesh to enhance the overall rigidity and deformation resistance of the metal mesh. In the area with high crushing degree of top coal, The "anchor net cable + I-shaped steel shed" combination support approach is used; in the air leakage area caused by coal crushing, roadway grouting is carried out; the two sides are supported by grouting and anchor net support to increase the two sides' capability for support. On the one hand, the floor maintenance increases the drainage capacity of the working face and roadway, and tries to keep the floor dry. On the other hand, the floor remains about 0.5 m bottom coal to prevent floor heave.

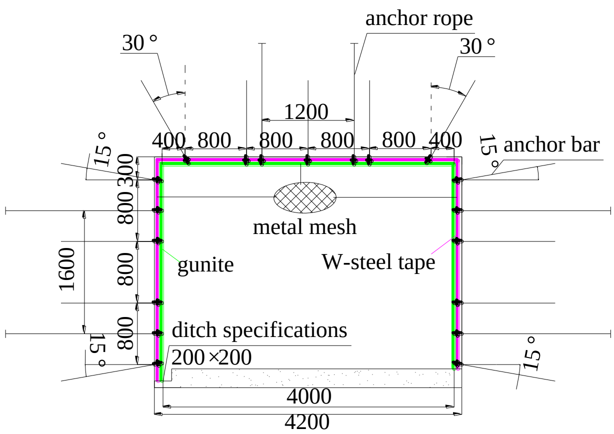


Figure 10. *Schematic diagram of roadway support scheme (unit: mm).*

The roof support bolt is made of φ20mm×2400mm left-handed non-longitudinal rebar, the row spacing is 800mm×1000mm, and the W steel strip is 3mm×280mm×3400mm in thickness×width×length. The anchor cable is made of φ22mm×7300mm high strength low relaxation prestressed steel strand, and the row spacing is 800mm×1000mm. The specification of the anchor cable of the side support bolt is the same as that of the roof, and the row spacing is 1100mm×2700mm.

Because the parameters of coal pillar have the characteristics of non-uniformity, anisotropy and time-varying, the construction can be carried out according to the initial setting support scheme, while construction, while detecting roadway surface and deep displacement, the stress of bolt and anchor cable and the separation value of anchorage zone and non-anchorage zone. Through analysis, the design scheme can be continuously improved.

5.2. Supporting Scheme Verification

After the lower layered roadway is arranged according to the design and the support is completed, the recovery of the working face at this position is carried out, and the stress disturbance cloud diagram of the lower layered roadway and its support body in the advancing area of the working face under the influence of mining is extracted as indicated in figure 11.

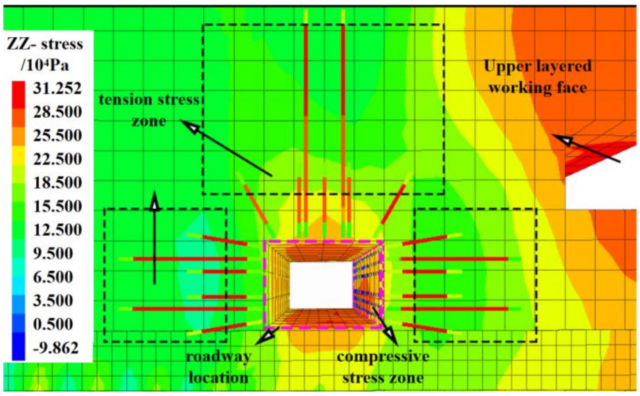
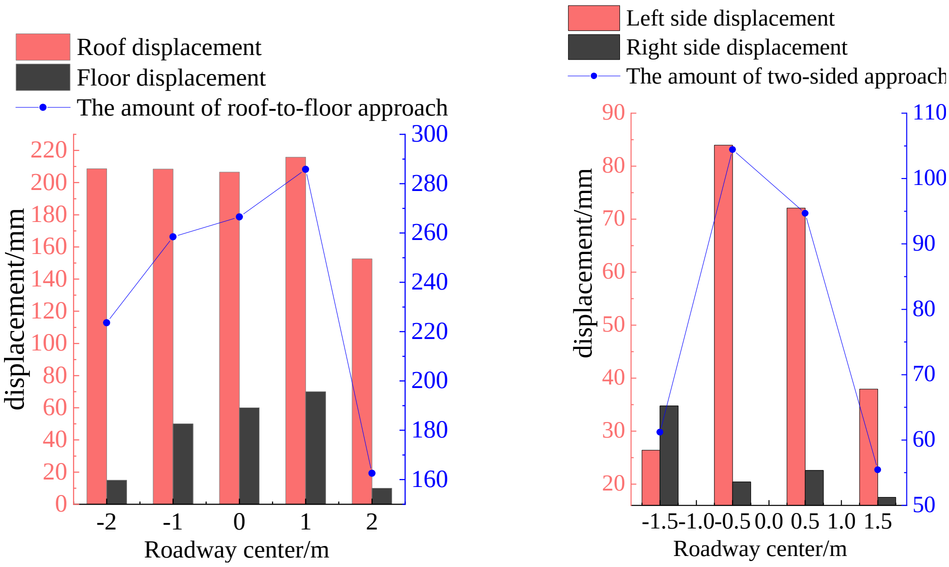


Figure 11. *The stress diagram of lower layer roadway support body.*

Due to the mining influence of the upper layered working face, the edge of the coal pillar is destroyed. The left side of the roadway is the coal pillar part with elastic core, and the right side is the coal pillar failure zone and plastic zone under the influence of secondary mining. From figure 11, it can be seen that there is a small distance on one side of the working face, that is, the compressive stress of the anchor cable in the broken zone and plastic zone of the coal body formed under the influence of mining, and gradually becomes tensile stress when it extends outward. The anchor cable on one side of the coal pillar and the roof and floor are subjected to tensile stress, indicating that the strength of the surrounding rock of the roadway is strengthened after grouting, and the anchor cable achieves the supporting effect.

The continuous mining of the working face is 80 m, and the displacement of the roadway side and the roof and floor nodes at 10 m in front of the working face is extracted for statistics as indicated in figure 12.

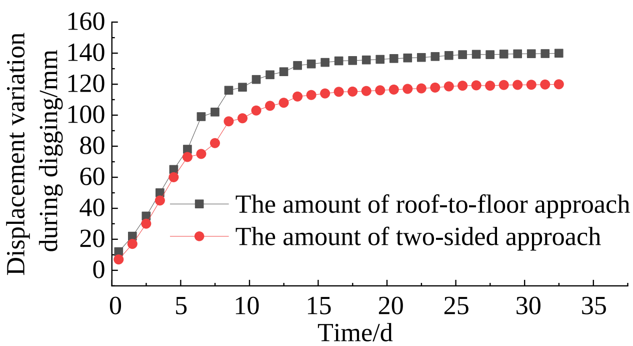


(a) Displacement of roadway roof and floor (b) Displacement of two sides of roadway

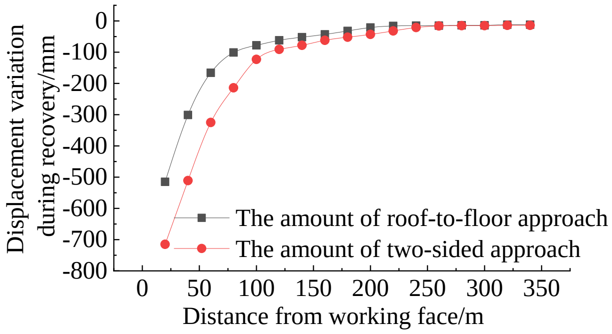
Figure 12. *Statistical Chart of Roadway Displacement in Front of Work.*

Figure 12 illustrates that when the roadway is set up with an outer stagger distance of 6 meters, the maximum displacement around it is less than 220 mm. Additionally, the maximum displacement of the floor and roof is less than 300 mm, the maximum displacement of the two sides is less than 110 mm, and the overall displacement of the surrounding rock is minimal. The road's maximum floor displacement difference between its left and right sides is less than 50 mm, the worst roof displacement value between its left and right sides is less than 70 mm, and the maximum displacement difference between its left and right sides is less than 85 mm, and the overall displacement of the roadway is relatively uniform.

To confirm the reasoning of the lower layer roadway layout and its support method, the deformation of surrounding rock during the excavation and mining of ZF4401 track roadway is monitored on site. The monitoring results are indicated in figure 13(a) and (b).



(a) Surrounding rock deformation during digging



(b) Surrounding rock deformation during recovery

Figure 13. *Deformation curve of roadway surrounding rock.*

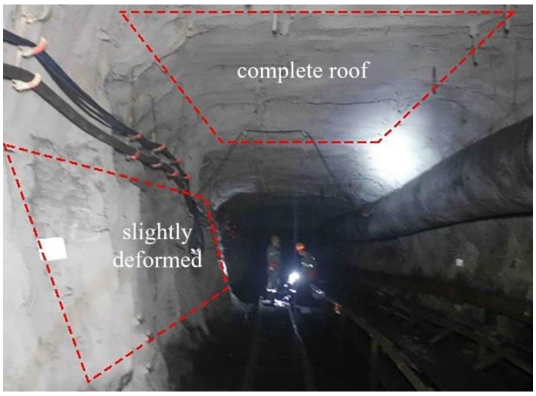


Figure 14. *Support effect of the roadway.*

The support practice of ZF4401 lower layered roadway shows that during the digging period, the change of roadway surrounding rock is large within 15 days after roadway support. Later on, the change progressively stabilized. The confluence of roadway roof and floor is less than 200 mm, and the confluence of two sides is less than 150 mm. During the mining period, the change rate of surrounding rock from near to far from the working face shows a gradual decrease. The abutment pressure's influence range is 0 ~ 200m. The greatest deformation of the floor and roof is 720mm, and the greatest deformation of the two sides is 515mm when it is near the working face. The change amount meets the production demand of coal mine, as indicated in figure 14. The roof and floor are relatively complete, the left side is slightly deformed, the bolt and anchor cable are not loose and damaged, the roof and floor and the side grouting are not damaged, and the roadway integrity is good, indicating that the roadway layout position, grouting and related support schemes have good application effect.

6. Conclusion

1. It is evident from the gathering and examination of the macroscopic and microscopic characteristic data of the section coal pillar and the upper slice mining highway that the high-intensity mining of Xiagou Mine is the reason behind the plastic failure of the wide coal pillar's edge. Through the borehole peep analysis, the surrounding rock failure and loosening depth is about 5.5m, and the fracture extension depth is about 8.2m. The disturbance to the lower layered coal seam and coal pillar is large, which makes the mining roadway undergo uncontrollable large deformation and failure. It is difficult to form effective support in overlapping and internal staggered roadways.
2. Through field, computer simulation and theoretical evaluation analysis, the reasonable offset distance of the roadway is determined. There are 6 ~ 7m plastic zones at the edge of the coal pillar with a width of 35m, which is basically consistent with the theoretical calculation and field detection results. From the perspective of avoiding high abutment stress and non-uniform stress distribution, it is determined that the outer stagger 6m roadway is the most reasonable position.
3. Based on the results of the computer simulation and theoretical analysis, combined with the field engineering geological conditions, the engineering analogy method is used to put forward the support scheme corresponding to the roadway layout. Through the computer simulation and the analysis of the monitoring points arranged on site, grouting and anchor cable support improve the mechanical strength of the surrounding rock of the roadway. The nearby rock of the roadway has some minor deformation and non-uniform deformation., and the layout and support of the roadway are reasonable.

Abbreviations

ZZ Stress	Stress in the ZZ Direction
FLAC3D	Fast Lagrangian Analysis of Continua
Shear-n	Shear-Now
Shear-p	Shear-Previous
Tension-n	Tension-Now
Tension-p	Tension-Previous

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Li Jing, He Jiang, Gong Siyuan, et al. Case study on prediction and warning of rock burst under overlying pillar [J]. Journal of China Coal Society, 2016, 41(S2): 305-310. https://doi.org/10.13225/j.cnki.jccs.2015.1835

[2] Chen Sushe, Zhu Weibing. Study on double-roadway layout under section coal pillar of ultra-close upper coal seams in Huojitu mine [J]. Journal of Mining and Safety Engineering, 2016, 33 (03): 467-474. https://doi.org/10.13545/j.cnki.jmse.2016.03.014

[3] LIU Guoxing, WANG Dong. Technology and practice of coal mining face support under the condition of caving loose regenerated roof in Xintaoyang Company [A]. China Coal Industry Association. National Coal Mining Technology for Complex and Difficult Coal Seams [C]. China Coal Industry Association: China Coal Industry Association, 2012: 4.

[4] He Ziming. Study on the re-mining technology of 3 # thick coal seam in Jushan Coal Mine [D]. China University of Mining and Technology, 2019.

[5] Lu Shiliang, Sun Yonglian, Jiang Yaodong. Selection of Horizontal Distance X Between Roadway and the Edge of its Upper pillar [J]. Journal of China University of Mining and Technology, 1993, 22 (2): 4-10.

[6] Jia Shangwei, Fan Zhigang, Song Zuguang, et al. Stress analysis of floor under residual coal pillar in close distance coal seam and reasonable layout of mining roadway [J]. Coal Engineering, 2020, 52 (10): 11-15.

[7] Zhang Wei, Zhang Dongsheng, Chen Jianben, et al. Selection of Horizontal Distance X Between Roadway and the Edge of its Upper pillar [J]. Journal of China University of Mining and Technology, 2012, 41 (02): 182-188.

[8] Zhang Baisheng, Yang Shuangsuo, Kang Lixun, etc. Selection of Horizontal Distance X Between Roadway and the Edge of its Upper pillar [J]. Journal of Rock Mechanics and Engineering, 2008 (01): 97-101.

[9] Suo Yonglu, Shang Tielin, Zheng Yong, et al. Numerical simulation on rational location of roadways at lower seam for ultra-close multiple seam mining [J]. Journal of China Coal Society, 2013, 38 (S2): 277-282. https://doi.org/10.13225/j.cnki.jccs.2013.s2.025

[10] Shi Jianjun, Ma Nianjie, Yan Dezhong, et al. Measure Technology for Loose Circle of Crush Roadway Surrounding Rock and lts Application [J]. Coal Engineering, 2008 (03): 32-34.

[11] He Manchao, Qi Gan, Cheng Cheng, etc. Deformation and Damage Mechanics and Coupling Support Design in Coal Roadway with Compound Roof [J]. Journal of Rock Mechanics and Engineering, 2007 (05): 987-993.

[12] Kang, Wang, Lin. Case Studies of Rock Bolting in Coal Mine Roadways [J]. Journal of Rock Mechanics and Engineering, 2010, 29 (04): 649-664.

[13] Liu Quansheng, Liu Xuewei, Huang Xing, et al. Research on the floor heave reasons and supporting measures of deep soft-fractured rock roadway [J]. Journal of China Coal Society, 2013, 38 (04): 566-571. https://doi.org/10.13225/j.cnki.jccs.2013.04.016

[14] Yuan Liang. Stability classification and engineering countermeasures of coal roadway in Huainan mining area [J]. Journal of Rock Mechanics and Engineering, 2004 (S2): 4790-4794.

[15] Liu Yonghong, Li Kang, Cao Minyuan, et al. Analysis of stress distribution under the coal pillar of open cut lane and its control countermeasures [J]. Coal Engineering, 2020, 52 (09): 47-51.

[16] Wang Yubo. Evolution mechanism of end structure and abutment pressure on fully-mechanized top coal caving face in extra thick coal seam [J]. Journal of China Coal Society, 2017, 42 (S1): 30-35. https://doi.org/10.13225/j.cnki.jccs.2016.1086

[17] Zhang Guangchao, He Fulian, Lai Yonghui, et al. Reasonable width and control technigue of seament coal pillar with high-intensity fully-mechanized caving mining [J]. Journal of China Coal Society, 2016, 41 (9): 2188-2194. https://doi.org/10.13225/j.cnki.jccs.2016.0145

[18] Wang Zhiqiang, Wu Chao, Luo Jianqiao, et al. Instability mechanism and control of section coal pillar in fully mechanized mining face with super thick roof and extra thick seam [J]. Journal of China Coal Society: 1-14. https://doi.org/10.13225/j.cnki.jccs.2021.0112

[19] Tu Hongsheng, Tu Shihao, Bai Qingsheng, et al. Instability mechanism and reasonable size of section coal pillar in steeply inclined coal seam working face [J]. Journal of China University of Mining and Technology, 2013, 42 (01): 6-11. https://doi.org/10.13247/j.cnki.jcumt.2013.01.003

[20] Wang Zhiqiang, Tian, Liu Yincang, et al. Study on surrounding rock instability mechanism and control technology of narrow coal pillar roadway in layered mining [J]. Coal Engineering, 2022, 54 (01): 94-100.

[21] Li Guodong, Liu Honglin, Wang Hongzhi. Surrounding rock control and reasonable layout of roadway in lower seam of extremely close coal seam [J]. Coal Engineering, 2021, 53 (07): 42-47.

[22] Yuan Bo, Zhang Zhaoqian, Zhang Baisheng, etc. Numerical Simulation of Grouting Reinforcement of Cracked Surrounding Rocks and it Application in Engineering [J]. Metal Mine, 2013 (07): 45-48 + 53.

[23] Qian Minggao, Shi Pingwu, Xu Jialin. Mine pressure and strata control [M]. Xuzhou: China University of Mining and Technology Press, 2010, 197-200.

[24] Zhou Lianchun, Li Wang, Wang Yan. Stress distribution law of mining face under coal pillar of overlying coal seam [J]. Coal Engineering, 2020, 52 (05): 121-125.

[25] Yuan Yong, Tu Shihao, Wu Qi, et al. Large mining height fully mechanized working face end of the bottom coal roadway in variable slope bottom recovery technology [J]. Coal Journal, 2010, 35 (10): 1594-1598. https://doi.org/10.13225/j.cnki.jccs.2010.10.007

[26] Wang K, Huang Y, Gao H, et al. Recovery Technology of Bottom Coal in the Gob-Side Entry of Thick Coal Seam Based on Floor Heave Induced by Narrow Coal Pillar [J]. Energies, 2020, 13(13).