Study on Pressure Relief Technology Using Hydraulic Fracturing in Hard Roof Strata at Guqiao Mine

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Abstract

During the mining of the adjacent working face at Guqiao Mine 1315(1), the hard roof proved difficult to collapse, leading to significant stress concentration in the coal pillars near the roadway. This study analyzes the causes of stress concentration in the coal pillars and proposes hydraulic fracturing and roof cutting as a mitigation method. Numerical simulations were conducted to determine the optimal roof-cutting angle and depth, followed by field trials. The results demonstrate that hydraulic fracturing effectively reduces stress on the coal pillar side and promotes roof caving in the goaf. A roof-cutting height of 28 m and an angle of 60° were found to be the most effective, shifting the stress concentration zone to 3.8 m from the 1315(1) track gateway, with a peak stress of 38.4 MPa-a reduction of 9.7 MPa or 20.1% compared to the scenario without roof cutting. The industrial application, guided by the simulated angle, yielded satisfactory outcomes.

Keywords

Hard Roof; Hydraulic Fracturing; Roof Cutting; Numerical Simulation.

1. Introduction

In the coal mining process, safety is a paramount concern that demands foremost attention. Ensuring safe production is an absolute priority. For instance, during the extraction of a working face, there may be one or more layers of hard roof strata above the immediate roof. The presence of such resistant layers can prevent the overlying strata from collapsing in a timely and predictable manner. To maintain mine safety and operational integrity, it is essential to apply specialized techniques such as roof cutting and pressure relief.

Regarding the roof-cutting and pressure-relief technology, domestic scholars have achieved a series of results through experimental research. Chen Zhen et al. [1] applied hydraulic fracturing in field practice to address the impact of secondary dynamic pressure on roadways. Xing Feifei et al. [2] conducted field tests and implemented hydraulic fracturing in reused roadways, achieving favorable outcomes. Pang Fengling and Xue Yanping [3] adopted the roof-cutting method to mitigate severe roadway deformation caused by dynamic pressure during coal mining. Cheng Lixing et al. [4] investigated the stress transfer mechanism of hydraulic fracturing using the numerical simulation software GDEM. Zhao Changxin et al. [5] studied the application of roof-cutting and pressure-relief technology under conditions of thick rock layers and wide coal pillars through numerical simulation. Zhang Kai [6] examined serious deformation at the tail of roadways and major deformations in main entries, resolving the issue of hard roof hanging through industrial trials. Lin Yukun et al. [7] effectively addressed significant deformation in development roadways adjacent to active working faces by employing hydraulic fracturing for roof cutting. Ge Shuaishuai [8] investigated severe

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surrounding rock deformation in roadways near working faces due to mining influence and used hydraulic fracturing to improve the rock pressure environment.

Current approaches focus on applying the roof-cutting and pressure-relief method to fracture thick and hard roof strata. For the 1315(1) working face in Guqiao Mine, numerical simulation and industrial practice have been employed to determine the optimal roof-cutting angle.

2. Project Overview

The 1315(1) working face at Guqiao Mine is situated in the North II Upper Panel, extracting coal seam 11-2. It is bounded by the North II panel system roadways to the west and the waterproof coal pillar of seam 11-2 to the east. To the north, it neighbours the 1314(1) working face, which completed retreat mining on June 10, 2020, with an 8m coal pillar left between the two faces. To the south, it adjoins the 1316(1) working face, which finished extraction on April 30, 2021, also separated by an 8m coal pillar, as shown in Fig. 1.

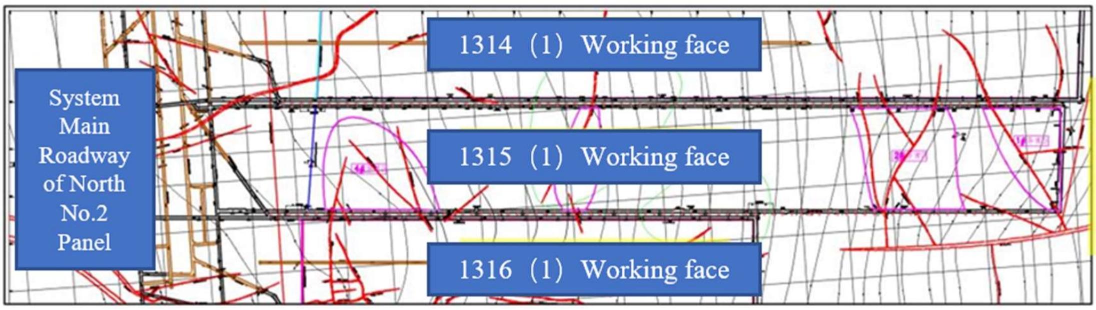

Fig. 1 Working face layout

The working face elevation ranges from -556.5m to -773.1m. The immediate roof consists of sandy mudstone, which is grey, blocky, and friable, with a thickness of approximately 4.6m. The immediate floor is also composed of sandy mudstone; its upper part has higher clay content while the lower part is more sandy, resulting in an overall relatively soft lithology. The floor thickness is about 2.2m.

Above the immediate roof are two layers of thick and hard strata. From bottom to top, these are medium-fine sandstone and fine sandstone. The medium-fine sandstone is greyish-white with interwoven bedding and contains dark minerals. It exhibits high mechanical strength and has a thickness of approximately 9.2 m. The overlying fine sandstone is also greyish-white but has a fine-grained structure, resulting in even higher mechanical strength, and is about 7.7 m thick.

Between these two hard layers lies a layer of mudstone, which contains visible plant fragments. This mudstone interlayer has low mechanical strength and a thickness of approximately 2.8 m.

During the mining of the adjacent working face, the presence of these hard roof strata led to difficulties in caving and caused excessive stress concentration in the coal pillars near the roadways. To mitigate this, pre-fracture roof cutting is necessary for the 1315(1) working face to manage strata behavior and alleviate the abutment pressure.

3. Numerical Simulation

Based on the geological conditions of the 1315(1) working face at Guqiao Mine, this study focuses on the 1315(1) track gateway as the subject for pre-fracture roof cutting. To better analyze the stress distribution, numerical simulation was conducted using FLAC3D 6.0 software. Fig. 2 illustrates the spatial relationships between the working face, roadways, and coal pillars. The model measures 306.8 m in length, 60 m in width, and 130 m in height, with a burial depth of approximately 600 m. A load of 15 MPa was applied in the simulation. The 1315(1) working face has a length of 216 m and a coal seam height of 2.9 m. It is flanked by the 1315(1) track gateway and the 1315(1) haulage gateway,

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each with dimensions of 5.4 m in width and 3.8 m in height. A 40 m isolation coal pillar was incorporated to mitigate boundary effects.

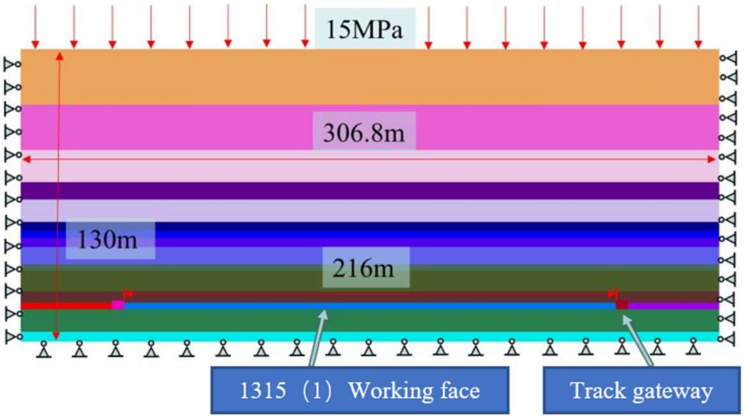


Fig. 2 Numerical simulation model diagram of 1315(1) working face

The focus of this simulation study is to evaluate various roof-cutting and pressure-relief schemes by selecting different cutting angles and heights, with the aim of identifying the most effective scenario for field application to address practical challenges. Accordingly, four distinct roof-cutting schemes were designed, all oriented toward the solid coal side. The schemes are as follows:

Scheme 1: 28 m height, 60° angle.

Scheme 2: 18 m height, 60° angle.

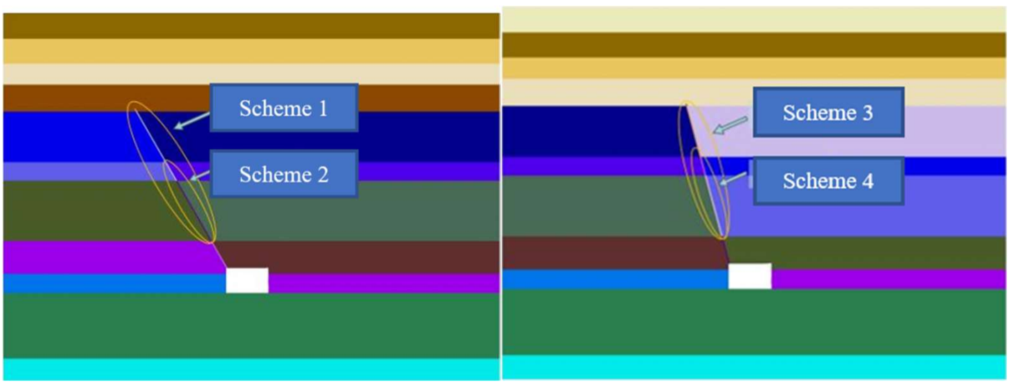
Scheme 3: 25 m height, 75° angle.

Scheme 4: 16 m height, 75° angle.

In the 60° angle group (Schemes 1 and 2), a height of 28 m penetrates both the medium-fine sandstone and the fine sandstone layers-the two hard roof strata-whereas a height of 18 m only cuts through the medium-fine sandstone layer.

Similarly, in the 75° angle group (Schemes 3 and 4), a height of 25 m severs both hard layers, while a height of 16 m only cuts the medium-fine sandstone.

The four designed roof-cutting schemes are illustrated in Fig. 3.



(a)Roof cutting of 60° (b) Roof cutting of 60°

Fig. 3 Roof cutting scheme design

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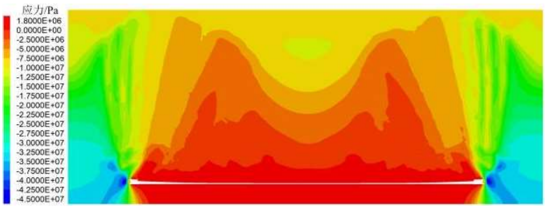
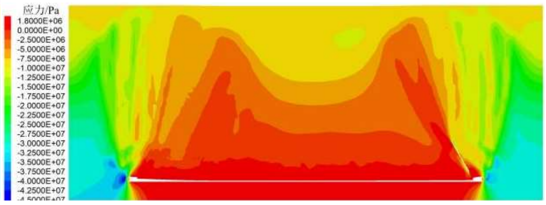
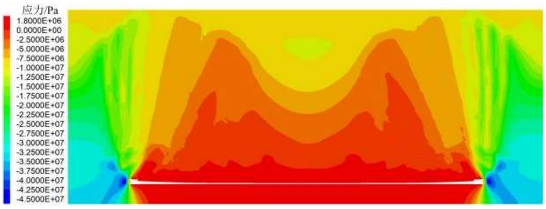


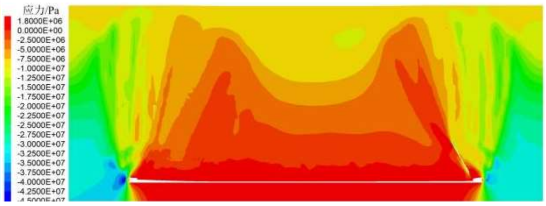
(a) non-roof cutting



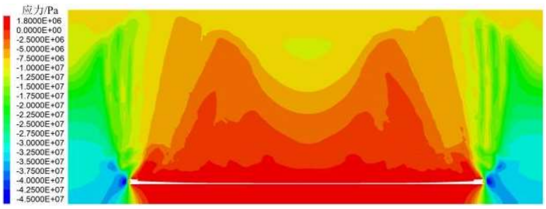
(b) Scheme 1



(c) Scheme 2



(d) Scheme 3

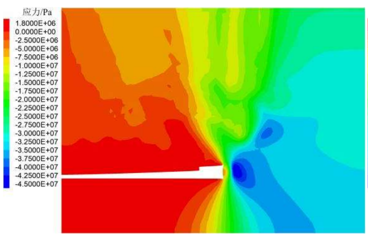


(e) Scheme 4

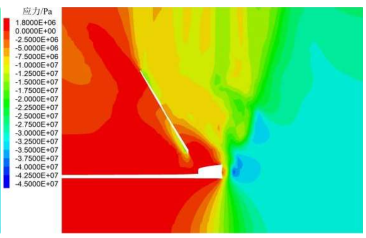
Fig. 4 Overall stress contour map

As shown in Fig. 4, the stress nephogram after roof cutting illustrates the results of applying four different techniques to the 1315(1) track gateway. From a stress perspective, it is evident that the stress concentration on the right side of the 1315(1) track gateway significantly decreased after roof cutting. In contrast, the stress concentration in the 1315(1) haulage gateway, which did not undergo roof cutting, remained unchanged. Among the four schemes, Scheme 1 demonstrated the best performance, while Schemes 2 and 3 showed similar effectiveness, and Scheme 4 was the least effective. Nevertheless, all pre-cutting schemes yielded better results compared to the scenario without roof cutting.

Overall, after the extraction of the 1315(1) working face, the overlying strata exhibited two interconnected triangular-shaped zones. The roof subsidence measured 2.23 m without pre-cutting, while the values for the schemes were as follows: Scheme 1~2.40 m, Scheme 2~2.35 m, Scheme 3~2.31 m, and Scheme 4~2.26 m. These results indicate that pre-cutting the hard roof strata accelerates the caving of the overburden and its contact with the goaf, thereby reducing stress concentration in the coal pillar area.



(a) non-roof cutting



(b) Scheme 1

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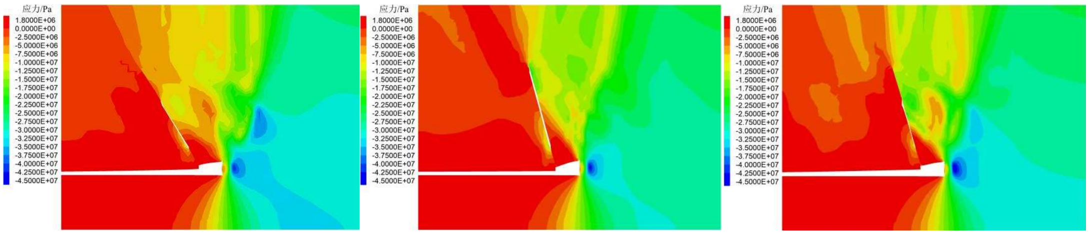


(c) Scheme 2 (d) Scheme 3 (e) Scheme 4

Fig. 5 Stress contour map of 1315(1) track gateway

An enlarged view of the nephogram near the 1315(1) track gateway is shown in Fig. 5. Fig. 5(a) displays the stress distribution without roof cutting, where the stress concentration reaches 48.1 MPa. The concentrated stress zone, located 4 m from the 1315(1) track gateway, exhibits a fan-shaped pattern with a high stress magnitude, indicating the necessity of implementing pre-fracture roof cutting.

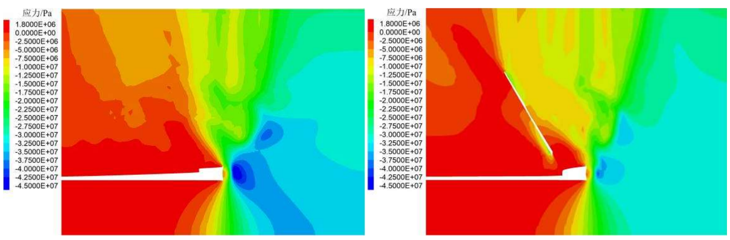
As illustrated in Fig. 5(b), Scheme 1, with a cutting height of 28 m and an angle of 60°, significantly reduces the fan-shaped stress area. The dark blue region in the figure lightens noticeably. The stress concentration zone is now 3.8 m from the gateway, with a peak stress of 38.4 Mpa-a reduction of 9.7 MPa or 20.1% compared to the uncut scenario.

Fig. 5(c) corresponds to Scheme 2 (18 m height, 60° angle), which also reduces the fan-shaped stress area to some extent, with a lightening of the dark blue region. The stress core remains 3.8 m away, registering 42.2 Mpa-a decrease of 5.9 MPa (12.2%).

For Scheme 3 (25 m height, 75° angle), shown in Fig. 5(d), the stress zone is slightly reduced in size and intensity. The stress center is 3.7 m from the gateway, measuring 43.5 MPa, which is 4.6 MPa (9.5%) lower than the baseline.

Scheme 4 (16 m height, 75° angle), depicted in Fig. 5(e), shows minimal change in the extent of the stress concentration zone, with only a slight lightening of the dark blue area. The stress core, located 3.7 m away, has a value of 46.5 MPa, reflecting a modest reduction of 1.6 MPa (3%).

Overall, the stress concentration zone on the pillar side of the 1315(1) track gateway is largest without any roof cutting. Comparing the effectiveness of the schemes: Scheme 1 outperforms Scheme 2, which in turn is better than Scheme 3, and Scheme 3 is superior to Scheme 4. This ranking is attributed to the fact that Scheme 1 successfully severed both the medium-fine sandstone and fine sandstone layers-the two hard roof strata-while Scheme 2 only cut through the medium-fine sandstone. In contrast, Schemes 3 and 4, due to their steeper cutting angles (75°), resulted in a hinged structure in the overlying strata. This inhibited significant caving and consequently limited the desired relief of stress concentration on the coal pillar side. Thus, the optimal outcome is achieved with a cutting height of 28 m and an angle of 60°.



(a) non-roof cutting (b) Scheme 1

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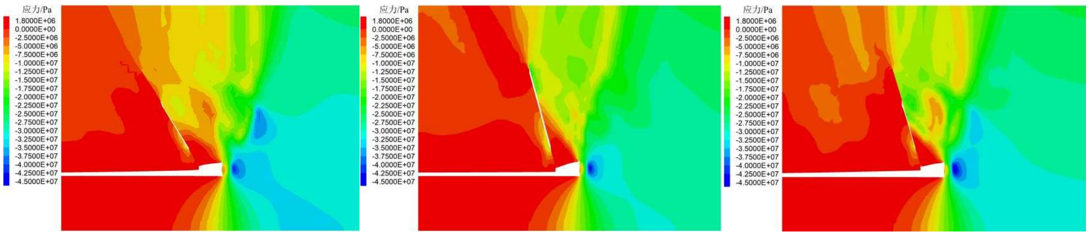

(c) Scheme 2 (d) Scheme 3 (e) Scheme 4

Fig. 6 Displacement contour map of 1315(1) track gateway

As shown in Fig. 6, it is the displacement contour map of 1315(1) track gateway. It can be seen that the roof displacement of 1315(1) track gateway before roof cutting is 0.78m; for Scheme 1, the roof displacement of 1315(1) track gateway is 0.85m; for Scheme 2, it is 0.88m; for Scheme 3, it is 0.88m; and for Scheme 4, it is 0.9m. Combining the stress and displacement data, it is concluded that Scheme 1, with a roof cutting height of 28m and a roof cutting angle of 60°, achieves the best effect.

4. Industrial Trial

Given the difficulty of hard roof caving during the mining of adjacent working faces and the resulting excessive stress concentration in the coal pillars near the roadways, pre-fracture roof cutting was implemented at the 1315(1) working face. Hydraulic fracturing was conducted from the 1315(1) track gateway over a trial length of 460 m. Boreholes were drilled at 10 m intervals, resulting in a total of 46 boreholes. Each borehole had a length of 28 m, amounting to a total drilling footage of 1288 m.

As illustrated in Fig. 7, the boreholes are perpendicular to the 1315(1) track gateway in the plan view, with a drilling angle of 90°. The projected horizontal length of each borehole is 14 m. the boreholes are inclined at 60° to the horizontal plane. The first 5 meters of each borehole were not subjected to hydraulic fracturing. After completion of drilling, fracturing operations were carried out targeting the 7.7 m thick fine sandstone layer and the 9.2 m thick medium-fine sandstone layer in the roof. Each borehole was fractured twice, with a pressure maintenance time of 30 minutes per stage.

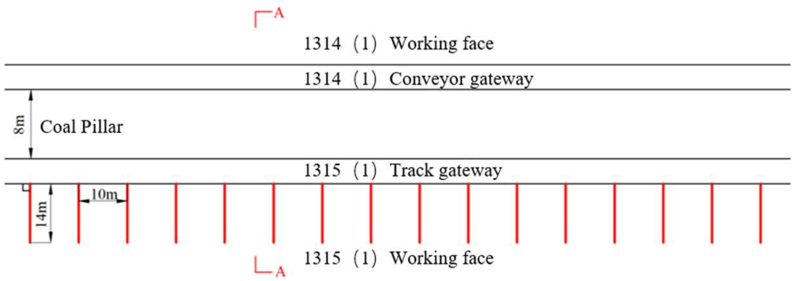

Fig. 7 Plan view of hydraulic fracturing in 1315(1) track gateway

During the hydraulic fracturing process, water seepage from adjacent boreholes was continuously monitored, and pressure gauge readings were recorded. Fracturing was immediately halted if a sudden pressure drop or significant water outflow from surrounding boreholes was observed.

During field operations, hydraulic fracturing was conducted following the drilling of each borehole. The pressure curve recorded during fracturing of the third borehole is presented in Fig. 8. The entire fracturing process for this borehole lasted approximately 30 minutes. Initiation of fracturing began around the 3-minute mark, and the process concluded at approximately the 27-minute mark. Throughout this period, continuous crack propagation was observed, accompanied by water infusion into the fractures. The injection pressure was maintained at around 28 MPa during the active fracturing phase.

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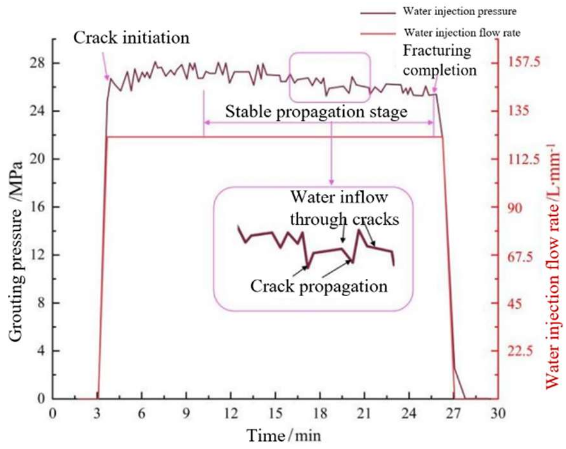
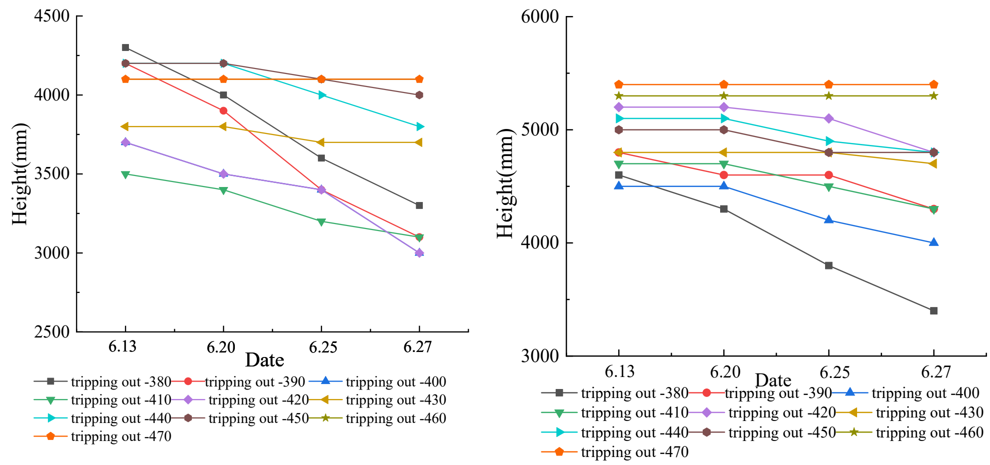


Fig. 8 Plan view of hydraulic fracturing in 1315(1) track gateway

To measure and analyze the deformation of the 1315(1) track gateway, the cross-point method was employed to monitor the height and width of the roadway after hydraulic fracturing and roof cutting. As shown in Fig. 9, data were collected from 10 monitoring points located between retreat chainages -380 m and -470 m.



(a) Measuring point height (b) Measuring point depth

Fig. 9 Roadway Deformation of 1315(1) track gateway

Fig. 9(a) illustrates the variation in roadway height, which ranged between 4.3 m and 3.0 m. Monitoring points closer to the working face-specifically at retreat chainages -380 m, -390 m, -400 m, -410 m, and -420 m-experienced significant changes in height due to the influence of advance abutment pressure. In contrast, the remaining points showed minimal height change, with no deformation observed at retreat chainage -470 m.

Fig. 9(b) shows the variation in roadway width, which values varied from 5.4 m to 3.5 m. Similarly, the four points nearest to the working face (-380 m, -390 m, -400 m, and -410 m) exhibited considerable width reduction under advance abutment pressure. The other points demonstrated minor to negligible changes in width.

5. Conclusion

During the mining process of adjacent working faces, there exists a phenomenon that the hard roof is difficult to collapse, and it causes excessive stress concentration on the coal pillars near the roadway. Therefore, it is necessary to carry out pre-splitting roof cutting on the Guqiao 1315(1) working face.

This paper draws the following conclusions through numerical simulation and on-site hydraulic fracturing tests on the 1315(1) working face of Guqiao Mine.

(1) When there is no roof cutting, the stress concentration is 48.1MPa, and the stress concentration area is 4m away from the 1315(1) track gateway. The effect is the best when the roof cutting height is 28m and the roof cutting angle is 60°. The stress center of this area is 3.8m away from the 1315(1) track gateway, and the stress in this area is 38.4MPa, which is 9.7MPa less than that without roof cutting, a decrease of 20.1%.

(2) In terms of displacement, with a roof cutting height of 28m and a roof cutting angle of 60°, the maximum displacement of the goaf roof is 2.4m, and the displacement of the roadway roof is 0.85m. The displacement of the goaf roof increases while the displacement of the roadway is small, so this roof cutting method is better.

(3) The industrial test is carried out in the 1315(1) track gateway, with a test length of 460m. Drilling is done every 10m. Hydraulic fracturing is not performed in the first 5m of each borehole, and only the two layers of hard roof are subjected to hydraulic fracturing. Each hole is fractured twice, with a pressure holding time of 30 minutes.

(4) After hydraulic fracturing roof cutting, the height of the 1315(1) track gateway ranges from 4.3m to 3m, and the width of the roadway ranges from 5.4m to 3.5m. The closer to the working face, the greater the roadway deformation; the farther from the working face, the less the roadway deformation.

Acknowledgments

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