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Research Article

Study of Combined Ground and Underground Hydraulic Fracturing for Multiple Hard Overlaying Strata Condition

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Abstract

In case of extra-thick Carboniferous coal seam mining, the hard rock strata of 50-100 m existing above the coal seam roof in upper layer, simple roof caving controlling technology can hardly achieve the engineering needs. To solve the strong abutment pressure in mining induced by multiple hard rocks overlying strata in coal mine, the structure and lithology of the overbeding hard rock strata were explored. Based on the engineering background of fully mechanized caving coal mine in Datong coalfield of China, a technical scheme of strata control of multiple hard roof fracturing was formulated. A ground and underground combined hydraulic fracturing technology was carried out. Results show that the deformational behavior of lower strata is closely related to the movements of the upper hard rock strata. The development and expansion of the cracks within upper hard rock strata is the dominant factor to the abutment pressure of the working face according to microseismic monitoring data. The working resistance of the hydraulic supports, deformation of the roadway and the pressure of the advanced support in tailgate were used to verify the effectiveness of the proposed controlling technology. The conclusions obtained in this study provide a novel method for the joint control of the multi-layer of rigid roof and provides a means of precise control of hard rock strata.

Keywords: Hard rock, Extra thick coal seam, Hydraulic fracturing, Microseismic monitoring, Support working resistance

1. Introduction

Currently, coal is high-intensity mined in China. The mining depth of most coal mines is now exceed underground 400 m. Due to the changes of the *in-situ* environment, the strata deformation becomes severe, and coal mine dynamic disasters have occurred frequently [1-3]. Especially, in case of hard surrounding rock, high abutment pressure can be induced by hard roof strata, which are commonly existed in the coalfields in the western region of China.

The hard rock strata are existance in most major coal mining countries in the world. However, the mining seams is deep in the western region of China, which is one important factor for the appearance of the high abutment pressure. Triditional measures of strata contral can hardly meet the requirements of mining safety. Especially, the controling measures of mutilple hard rock strata are highly demended technology for mining safety in the western region coalfields.

At present, the control methods of hard rock strata mainly adopts pressure relief mining, deep borehole blasting, underground hydraulic fracturing, and ground hydraulic fracturing [4-9]. Pressure relief technology includes protective layer mining [4-6], anthracitic column mining [7-8] and small coal pillar mining [9]. These measures can reduce the abutment pressure of hard roof so as to reduce the intensity of strata movements and induce the risk of dynamic disasters. It should be noted that the hydraulic fracturing control technology is one most commonly used manner for pressure relief, which directly improves the stress state of the coal pillar, working face and roadway. However, the hydraulic fracturing is often used either from ground or from underground, which is suitable for upper or lower hard roof respectively. This study implements combined ground and underground hydraulic fracturing technology under the engineering background of multiple hard rocks overlying strata.

2. State of the art

Deep borehole blasting technology is one technical measure for rock fracturing [10-13]. It uses the energy generated by the detonation wave to break hard rock strata and weaken the strength of surrounding rock. Scholars have carried out numerious achievements on this technology, such as blasting location, borehole parameters [10-12] and medium [12-13]. Compared with deep borehole blasting technology, underground hydraulic fracturing technology is one more safe operation in coal mines.

Underground hydraulic fracturing technology generates cracks which can reduce the integrity of the hard rock strata and decrease the mining induced stress. In this area, research mainly focuses on the crack initiation, development and propagation mechanisms [14-17]. It was found that the expansion plane of the crack is approximately parallel to the direction of maximum principal stress and perpendicular to the direction of minimum principal stress [18-20].

Ground hydraulic fracturing technology is widely used in petroleum and unconventional natural gas exploration. It can increase the permeability of surrounding rock which has a significant improvement on the flow conditions of oil and

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gas in the bottom borehole. In recent years, this technology has been introduced into projects such as coal mine gas drainage and hard rock strata control [21-22]. Compared with technologies such as underground deep borehole blasting and hydraulic fracturing, ground hydraulic fracturing is free from the constraints of underground construction space and the operation can be implemented in a large area by using high pressure [23-26].

Research results have been achieved on the control of hard rock strata. However, with the increase of mining depth, the control of complex hard rock strata becomes more complicated. It is difficult to achieve desire controlling effect using one single ground or underground technology.

Based on the engineering background of the fully mechanized caving coal mine in the Datong coalfield, this study formulated a technical scheme for the coordinated ground and underground hydraulic fracturing, and carried out engineering practice. The microseismic monitoring method was used to analyze the expansion of cracks in the hard rock strata after the fracturing operations. By analyzing the data of the working resistance of the hydraulic shields, roadway deformation and pressure of the advanced support, the applicability and effectiveness of the control technology of the combined ground and underground hydraulic fracturing were verified. The research results provide a reference for multiple hard rock strata control and rockburst prevention under similar conditions.

The rest of this study is organized as follows. Section 3 introduces the engineering background and the design of hydraulic fracturing. Section 4 analyzes the test results, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Engineering background

Tashan Coal Mine is one advanced modern demonstration coal mine in the Datong coalfield of China. The multiple hard rock strata are identified as an important causality for the severe strata behaviours in the Tashan Coal Mine. No. 8218 panel is in the middle of the second mining area of the Tashan Coal Mine. Its east boundary is the auxiliary transportation lane of the second mining area, the northeast adjacent to No. 8216 panel goaf, and a 38m coal pillar is left, the southwest is undisturbed territory, and the north is the Kouquan railway protection coal pillar.

No. 8218 panel is mainly mined 3-5# coal seam in Carboniferous strata. The average thickness of 3-5# coal seam is about 18 m, the average dip angle of 3-5# coal seam is 2° and the coal seam structure is complex. The length of working face is 230 m, and the length of No. 8218 panel is 3075 m. The layout plan of the working face is shown in Fig. 1. The immediate roof is carbonaceous mudstone, the main roof is dominated by sandy mudstone, and the strata above the main roof are dominated by sandstone, siltstone, sandy mudstone, which are relatively hard.

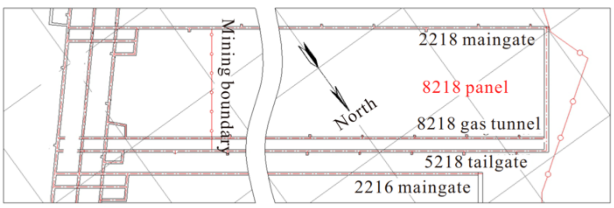

Fig. 1. No.8218 panel layout plan of Tashan Coal Mine.

3.2 Fracturing layers selection

According to the drilling column data of No. 8218 panel, the physical and mechanical properties of the overburden on 3-5# coal seam are listed in Table 1.

Table 1. Drilling column and parameters of No. 8218 panel.

Name	Lithology	Thick (m)	Density (kN/m^3)	Poisson's ratio	Elastic modulus (GPa)
Y35	Fine grained sandstone	8.7	26.0	0.21	25.42
Y34	Siltstone	7.3	25.3	0.24	23.40
Y33	Coarse grained sandstone	7.0	25.3	0.17	15.30
Y32	Kaolinite	7.7	26.0	0.18	17.60
Y31	K5 sandstone	15.9	26.0	0.22	18.31
Y30	Siltstone	5.4	25.3	0.24	23.42
Y29	Sandy mudstone	3.5	26.0	0.22	18.31
Y28	Fine grained sandstone	1.7	26.0	0.21	25.42
Y27	Siltstone	1.7	25.3	0.24	23.42
Y26	Coarse grained sandstone	4.1	25.3	0.17	15.30
Y25	K4 sandstone	14.2	26.0	0.21	25.42
Y24	Siltstone	3.0	25.3	0.24	23.42
Y23	Kaolinite	3.7	26.0	0.18	17.60
Y22	Siltstone	2.4	25.3	0.24	23.42
Y21	Kaolinite	4.1	26.0	0.18	17.60
Y20	Siltstone	14.4	25.3	0.24	23.42
Y19	Fine grained sandstone	1.4	26.0	0.21	25.42
Y18	Kaolinite	2.2	25.2	0.22	17.60
Y17	Coarse grained sandstone	2.4	25.3	0.17	15.30
Y16	Siltstone	2.7	25.3	0.24	23.42
Y15	Coarse grained sandstone	4.4	25.3	0.17	15.30
Y14	Siltstone	1.1	25.3	0.24	23.42
Y13	Kaolinite	0.9	26.0	0.18	17.60
Y12	Siltstone	2.9	25.3	0.24	23.42
Y11	Coarse grained sandstone	1.7	25.3	0.17	15.30
Y10	Siltstone	5.7	25.3	0.24	23.42
Y9	Kaolinite	1.1	26.0	0.18	23.60
Y8	Siltstone	1.0	25.3	0.24	23.42
Y7	Coarse grained sandstone	5.0	25.3	0.17	15.30
Y6	Kaolinite	4.0	26.0	0.18	23.60
Y5	Sandy mudstone	8.8	26.0	0.22	18.31
Y4	Shan 4# coal seam	4.4	14.3	0.32	2.80
Y3	Sandy mudstone	13.1	26.0	0.22	18.31
Y2	2# coal seam	3.2	14.3	0.23	2.80

Among the 170 m overlying rock strata, there are 4 hard strata with a thickness of more than 10m, namely the Y3, Y20, Y25 and the Y31 rock stratum. The lithology, thickness and distance from 3-5# coal seam of each rock stratum are shown in Table 2.

Table 2. Distribution of hard rock layers in the No. 8218 panel.

Name	Lithology	Thick (m)	Distance from 3-5# coal seam (m)
Y31	K5 sandstone	15.9	126.8
Y25	K4 sandstone	14.2	96.2
Y20	Siltstone	14.4	68.6
Y3	Sandy mudstone	13.1	5.8

All these 4 hard rock strata were selected for pre-mining fracturing either from ground or from underground.

3.3 Design of underground hydraulic fracturing

The lower level hard roof of No. 8218 panel is sandy mudstone with a thickness of 13.1 m. It is suitable for multi-point hydraulic fracturing using short boreholes. Multi-point fracturing boreholes can be arranged in one direction or in two directions. When the length of working face is less than 100 m, it is usually arranged in one direction, and when the length is greater than 100 m, it is usually arranged in two directions. The working face length of No. 8218 panel is 240 m. Therefore, a bidirectional arrangement is adopted in the roadway of No. 8218 panel. The plan view of underground hydraulic fracturing borehole arrangement is shown in Fig. 2.

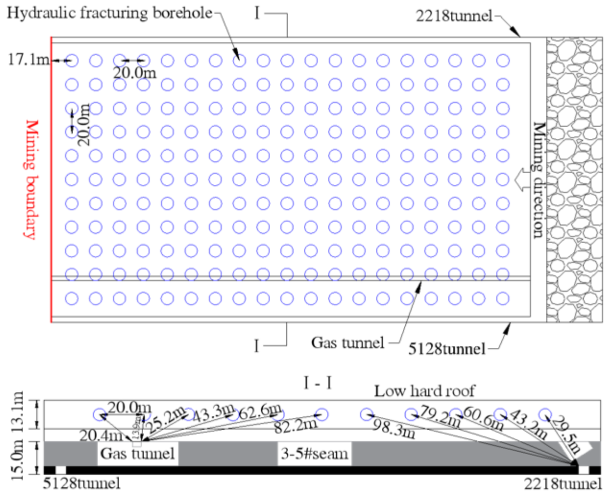

Fig. 2. Hydraulic pressure cracking borehole arrangement.

The hydraulic fracturing boreholes are 20 m apart along the strike and inclination of the working face. The construction is carried out within a range of about 400m from the mining stop line. There are 11 boreholes in each row, and the last row of drilling holes is 17.1 m away from the mining stop line. Among them, 6 boreholes are constructed in the top extraction tunnel of No. 8218 panel. The maximum borehole depth is 82.2 m, the minimum onr is 13.9 m, the maximum elevation angle is 89°, and the minimum one is 10°. Five boreholes were constructed in the No. 2218 maingate. The maximum borehole depth is 98.3 m, the minimum is 29.5 m, the maximum elevation angle is 59°, and the minimum is 15°. The diameter of the borehole is 44 mm, the diameter of the initial crack is 75 mm, and the initial pressure is 50 MPa.

3.4 Design of ground hydraulic fracturing

The medium-level and high-level hard rock strata of No. 8218 panel are located within the range of 70-140 m above 3-5# coal seam. There are 3 hard rock strata, and their vertical spacing is 20 m and 22 m, respectively. The measured maximum horizontal principal stress of Tashan Coal Mine is 15.95 MPa, and the vertical stress is 8.61 MPa. The in-situ stress is $\sigma_v < \sigma_H$.

Taking into account the characteristics of in-situ stress and the location of the target stratum, it was determined to use the horizontal fracturing well. According to the ground surface conditions of No. 8218 panel, it is determined that, in the east-west direction, the boreholes are between the tailgate of the second mining area and 42 m horizontal distance from the stop line. In the north-south direction, the boreholes are located in the middle of No. 8218 panel. The total length of the borehole is designed as 650 m, the first borehole has a diameter of 339 mm and a depth of 30 m, the second borehole has a diameter of 244 mm and a depth of 90 m, and the third borehole has a diameter of 216 mm and a depth of 210 m. The layout of ground fracturing plan at No. 8218 panel is shown as Fig. 3.

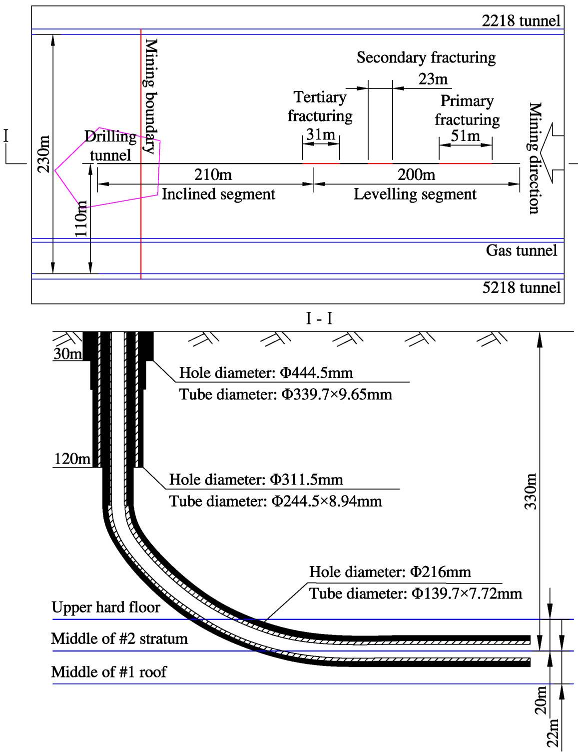

Fig. 3. Ground fracturing drilling scheme for No.8218 panel.

The horizontal fracturing well is designed to be divided into 3 stages for fracturing. Taking the ground borehole orifice as the origin, the fracturing tests were carried out at 573-623 m, 503-526 m, and 444-475 m, respectively. The hard strata are treated with sand blasting perforation + annulus sand adding staged fracturing technology and slick water + guar gum fracturing fluid system.

4. Results analysis and discussion

4.1 Microseismic monitoring of underground hydraulic fracturing

When No. 8218 working face is advanced to about 540 m from the stop line, that is, about 140 m ahead of the working face, the first row of boreholes will be fractured. There are 3 to 5 rows of fractures are generated everyday. The microseismic events during this period are shown in Fig. 4.

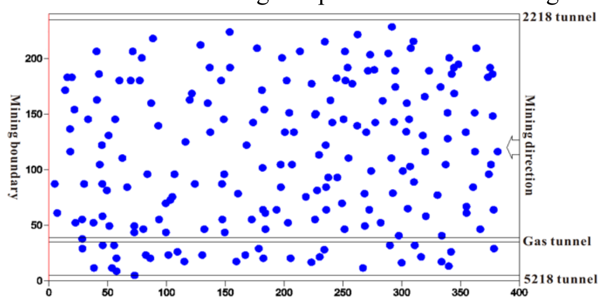

Fig. 4. Statistics of microseismic events in low-level hard rock stratum.

From the distribution of microseismic events shown in the figure, it can be seen that in the low-level hard rock stratum within the hydraulic fracturing range, the energy level of main microseismic events are less than 10^3 J. The microseismic events are intensive, indicating that after the implementation of underground hydraulic fracturing measures, a large number of fractures have been generated [27]. The integrity of low-level hard rock stratum is highly damaged.

4.2 Microseismic monitoring of ground hydraulic fracturing

To analyze the expansion of ground fracturing cracks, 3 sets of microseismic sensors were added on the ground. After the first stage of fracturing, the distribution of microseismic events is shown in Fig. 5.

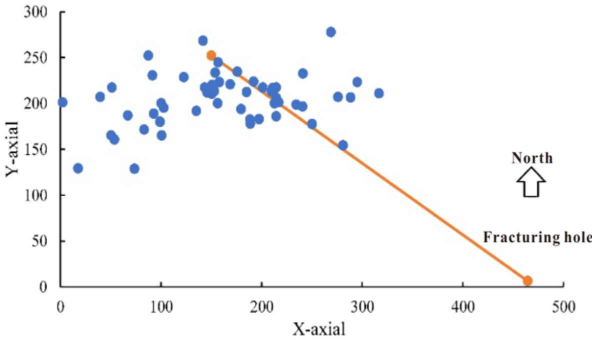

Fig. 5. First stage fracture crack propagation monitoring.

After the first stage of fracturing, the cracks extend along the NE90°. The cracks in the east are developed horizontally and the scale is small. The cracks in the west are developed horizontally at the proximal end, and the distal development orientation is NE80°. The cracks length in the west is about 120 m, the cracks length in the east is about 30 m, and the maximum height on one side of the crack is 38 m. After the second stage of fracturing, the distribution of microseismic events is shown in Fig. 6.

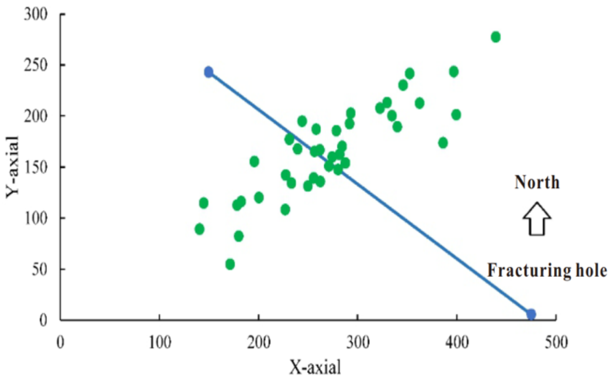

Fig. 6. Second stage fracture crack propagation monitoring.

After the second stage of fracturing, the cracks extend along the NE55°. The cracks in the west are well developed, while the cracks connectivity in the east is poor. The cracks length in the west is about 118m, the cracks length in the east is about 100 m, and the maximum height on one side of the crack is 48 m. After the third stage of fracturing, the distribution of microseismic events is shown in Fig. 7.

After the third stage of fracturing, the cracks expanded along the NE50°. The cracks in the east developed earlier, and there is a turning phenomenon at the end. The cracks length in the west is about 135 m, the cracks length in the east is about 100 m, and the maximum height on one side of the crack is 47 m.

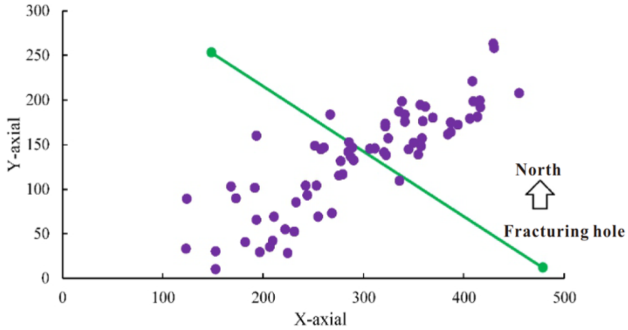

Fig. 7. Third stage fracture crack propagation monitoring.

4.3 Working resistance analysis of hydraulic supports

The working resistance is monitored by the KJ216 online system in No. 8218 panel. There are 114 supports, and 11 pressure sub-machines are installed. Starting from the 9# support, sensors were installed at 10 supports interval, as shown in Fig. 8.

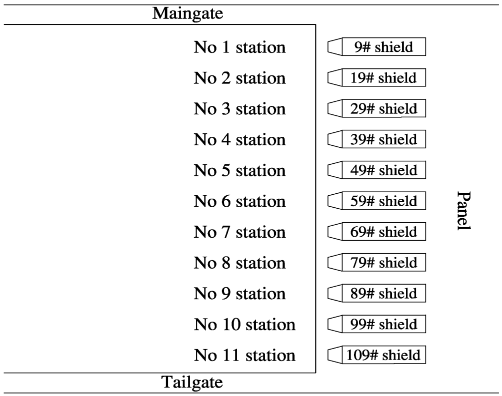

Fig. 8. Pressure observation station layout.

The average value of the working resistance of the three hydraulic supports 49#, 59# and 69# in the middle of the working face is analyzed. The working face is recovered to the mining position 2480 m to 2680 m. The working resistance curve of the hydraulic support is shown in Fig. 9.

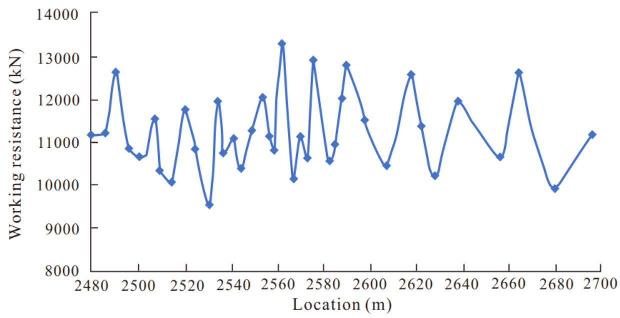

Fig. 9. Hydraulic support working resistance curve.

Whereas the combined hydraulic fracturing control technology has been implemented, the periodic weighting of the working face is not obvious. There is no opening of the safety valve of the hydraulic support. The average pressure step distance is 14.0 m. During the low-weighting period of the working face, the average working resistance of the hydraulic support increased slightly to 10835 kN. During the weighting period, the average working resistance of the hydraulic support was 12443 kN, and the dynamic load coefficient was 1.10-1.22. The overall average working resistance of the hydraulic support is improved by about

15%, and there is no strong strata deformational behaviors phenomenon nor dynamic events .

4.4 Deformation of No. 5218 tailgate

Three observation points are arranged in the tailgate at 2530 m, 2580 m and 2630 m away from the open-off cut. When the working face is advanced to about 100 m from the measuring point, the deformation of No. 5218 tailgate is recorded daily. The relationship between the working face position and No. 5218 tailgate height is shown in Fig. 10.

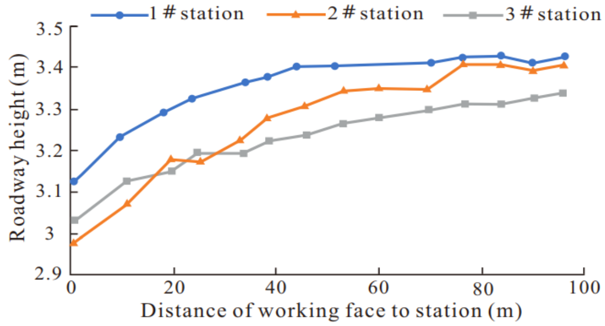

Fig. 10. No. 5218 roadway height variation curve.

Before entering the test area, the maximum deformation of No. 5218 tailgate can reach more than 1.0 m. In the area where the combined ground and underground hard rock strata control technology is adopted, the average rib convergence is about 0.65 m, and the average roof fall is about 0.45 m. The deformation of No. 5218 tailgate has been significantly limited.

Before the implementation of hard rock strata control technology, the deformation of No. 5218 tailgate was serious, and advance supports such as hydraulic prop and wooden stacks were erected. After the implementation of the technology, the deformation of No. 5218 tailgate was reduced by about 35.0%. No more wooden stacks are erected, and the hydraulic prop is in good state. The cost of advanced support is reduced, prop dumping and large compression do not occur, as shown in Fig. 11.

(a) Before implementation of control technology

(b) After implementation of control technology

Fig. 11. Deformation of No. 5218 roadway before and after implementation of control technology.

5. Conclusions

Based on the engineering background of top coal caving mining under multiple hard rocks overlying strata in Datong mining area, this study formulated a technical scheme of combined ground and underground hydraulic fracturing. Following conclusions can be drawn.

(1) There are 4 overlying strata that need to be pre-fractured, and a combined ground and underground hydraulic fracturing technical scheme has been formulated.

(2) Microseismic monitoring technology was used to analyze the effect of combined ground and underground hydraulic fracturing, the results show that the implementation of this technology induces cracks in the hard rock strata. The integrity of the hard rock strata is destroid.

(3) After the implementation of combined ground and underground hydraulic fracturing technology, No. 8218 panel cyclic weighting step is reduced by 34.6%. The working resistance of the hydraulic support is reduced by 15.1%, and the deformation of No.5218 tailgate is reduced by 35.0%. And the condition of the advance support is improved

The purpose of fracturing the hard rock strata in coal mine is to destroy their integrity. The control mechanism of the hard rock strata at different positions on the strata behaviors is not yet clear. The dynamic load effect when the hard rock strata is broken needs to be further studied.

Acknowledgements

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