

Research on Pressure Relief and Anti-impact Technology for Segmental Hydraulic Fracturing in Directional Long Borehole in Roof

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Abstract: After large-scale underground mining operations in coal mines, the stress of the overlying strata above the goaf is transferred to the surrounding support areas, creating support pressures. These pressures can easily trigger dynamic disasters such as gas outbursts and roof collapses, seriously threatening mine safety and production. To ensure the safety of underground mining operations, directional long borehole segment hydraulic fracturing technology was used in the roof strata of the 2305 comprehensive caving working face of Cuijiagou Coal Mine in Shaanxi Province to conduct experimental research on the technology of directional long borehole segment fracturing for pressure relief and anti-impact. The hydraulic fracturing of the roof's directional long borehole reduced the stress peak coefficient of the coal body in front of the working face ($K \approx 2.9$), blocked the propagation of mining stress and high stress in the goaf to the mining roadway, reduced the deformation of the mining roadway, and reduced the average working resistance of the working face support by 22% compared to the working face without any measures. The effective reduction of the length of the hanging roof, the improvement of the support resistance, and timely roof collapse during the working face mining period helped ensure the initial pressure did not form a strong impact. The initial pressure interval of the thick hard roof calculated theoretically was shortened by 53%, and the periodic pressure interval during normal mining was reduced by 27% compared with the 2303 working face under the same geological conditions. The experimental results show that the coverage of the directional long hole on the roof is extensive, with the utilization rate of segmented hydraulic fracturing wells reaching up to 80%. This technology effectively diminishes the strength of the roof above the coal seam on a large scale, thereby reducing the periodic pressure interval and intensity. As a result, it prevents the impact caused by the hanging roof during the mining period of the working face, ensuring a safe working environment for underground workers and facilitating the safe and efficient progress of mining operations.

Keywords: Hard roof disasters; directional long borehole segment hydraulic fracturing; pressure relief and anti-impact.

1. Introduction

Coal resources currently constitute the primary energy source in China. The demand for coal resources has steadily risen alongside the rapid development of technology and industrialization. China's raw coal production reached 4.66 billion tons in 2023. The sharp increase in demand for coal resources has caused a continuous rise in the depth of underground mining, leading to progressively challenging mining conditions [1]. After large-scale underground mining operations in coal mines, the stress from the overlying strata above the goaf is transferred to the surrounding support areas, creating support pressure belts around the goaf. Additionally, there is mobile support pressure in front of the working face and residual support pressure on the inclined upper and lower sides and behind the working face. These pressures can easily trigger dynamic disasters, such as gas outbursts and roof collapses, which seriously threaten mine safety and production [2-6]. To address this safety concern, scholars have conducted on-site experimental research on underground dynamic pressure issues. Existing pressure relief and anti-impact technologies mainly include slot cutting, drilling, loosening blasting, and pressure-relief coal pillars. These methods can release or transfer high stress in the surrounding rock mass near the roadway or working face to varying degrees. They help achieve control of surrounding rock stability and prevent dynamic disasters. However, the scale of construction for these techniques is significant, the

economic costs are substantial, the safety factor is low, and controlling the pressure relief effect artificially to achieve the intended prevention and control outcomes is challenging. As a result, a technology that efficiently and widely alleviates roof pressure has yet to be developed. The hydraulic fracturing technology for coal-rock masses originates from surface fracturing technology used in oil and gas field development. It involves injecting high-pressure water into the coal-rock mass, fracturing it, and driving the cracks to expand, forming a network of cracks. This process alters the overall mechanical properties of the coal-rock mass [3,4].

Hydraulic fracturing induces fractures within the coal-rock mass, establishes pressure relief zones around the fracture openings, diminishes the strength of the coal roof, modifies stress distribution within the surrounding rock mass, and redistributes or diminishes stress. Directional hydraulic fracturing technology can also achieve directional stress transfer in the surrounding rock and directional initiation and expansion of cracks [7]. By utilizing hydraulic fracturing technology, it is possible to promptly reduce and weaken the surrounding rock pressure on the roof. This action shortens the cantilever length of the triangular plates on both sides of the working face, disrupts the transmission of mining stress, and induces timely and effective collapse of the roof of the goaf. This method aims to limit the rotation and sinking of the overlying rock structure of the roof, mitigate the impact of the rotation and deformation of the large structure of the working face on the mining operation space, reduce dynamic pressure on the coal pillar, and alleviate stress concentration to achieve

pressure relief and erosion resistance. Since the introduction of hydraulic fracturing pressure relief and anti-impact technology, significant technical advancements have been observed. This technology features simple construction procedures, high safety coefficients, and wide applicability in preventing and controlling underground dynamic pressure, as well as improving roof coal caving [8-10]. This article discusses the application of hydraulic fracturing pressure relief and anti-impact technology on the 2305 comprehensive caving working face of Cuijiagou Energy Co., Ltd. in Shanxi Province. This application aims to address issues such as delayed collapse of hard roof strata leading to dynamic and gas disasters, providing technical support for safe and efficient mining operations.

2. The On-site Experimental Scheme

2.1. Stratigraphic conditions and optimal layer selection in the experimental area

The 2305 comprehensive caving working face is the third working face in the second level three-panel area of Cuijiagou Energy Co., Ltd. The structure starts at the security coal pillar of three centralized alleys in the western wing, extends to the minefield boundary in the north, encompasses the goaf of the 2303 working face in the west, and remains unmined in the east. It has a strike length of 1550 meters and a dip length of 200 meters. The coal seam extracted in the working face belongs to the Yan'an Formation of the Lower Jurassic, which comprises four coal formations numbered 1 through 4 from top to bottom. The 4-2 coal seam, located within this formation, is considered mineable and exhibits relatively stable occurrence characteristics. It is characterized by its hardness, with a firmness coefficient ranging from 0.8 to 2.1, surpassing the threshold of 0.5, indicating robust resistance to external damage. Structural integrity remains intact even in proximity to folds and faults, with no observable damage to the coal. The overall trend of the coal seam is a northwest-oriented monocline structure. This section is situated on the west wing of the syncline and displays a relatively wide and gentle monocline structure. The dip angle of the coal seam ranges from 0 to 12 degrees, with an average of 6 degrees,

and an average thickness of 13.4 meters. The immediate roof of coal seam 4-2 is primarily composed of siltstone, with a thickness ranging from 2.16 to 2.6 meters. This roof is moderately stable but weak and susceptible to collapse. The main roof consists mainly of gray and grayish-white fine siltstone, which is relatively hard and less prone to collapse. The floor is primarily composed of gray and grayish-black mudstone, with a thickness varying from 2.8 to 6.08 meters, including some sandy mudstone and sporadic fine sandstone.

Based on the comprehensive histogram of the 2305 working face and combining it with the parameters determined in the "Cuijiagou Mine 4-2 Coal Seam Impact Direction Identification," there is a layer of silt-middle sandstone with a thickness of 10-20 meters at the upper part of the roof of the 4-2 coal seam, ranging from 5 to 25 meters. This layer possesses significant thickness and relatively high strength, making it the key stratum for subsequent hydraulic fracturing treatment.

2.2. The arrangement of drilling holes for hydraulic pre-fracturing weakening process

A horizontal directional drilling rig is set up at the 7# drilling site within the return air groove at the 2305 working face. The directional drilling rig drills boreholes in a specific direction from the drilling site towards the critical layer of the roof above the working face. The termination point of the borehole is 15 meters away from the coal seam roof. As shown in Figure 1, a total of three fracturing holes were constructed with a spacing of 40 meters. The drilling holes were located 40 meters away from the high-level drilling of the roof, 40 meters away from the transportation channel of 2305, and more than 100 meters away from the old empty water area of the 2303 working face. The positioning ensured that the construction area for fracturing was within a safe range. Multiple-stage fracturing is conducted within the boreholes, with a design consisting of 10-12 stages of segmented fracturing. Each stage has a fracturing length of 10 meters and an interval of 30 meters. The construction parameters and fracturing design of the directional long boreholes are shown in Table 1.

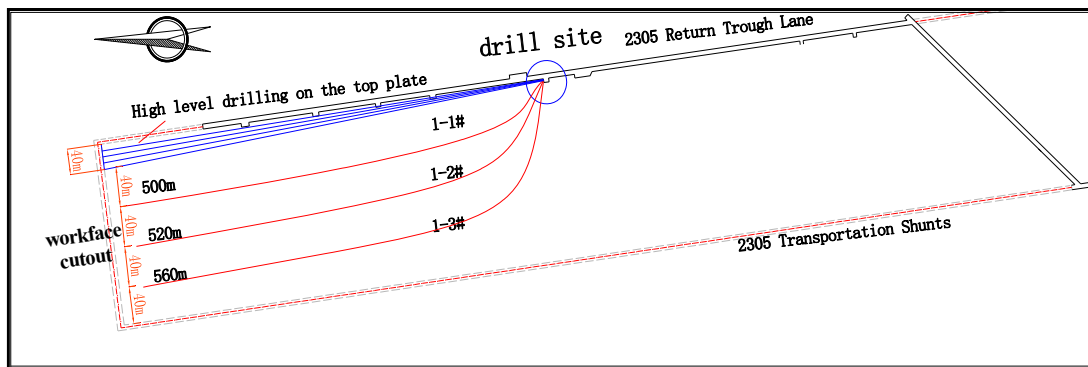


Figure 1. Directional long borehole design plan

Table 1. Directional long borehole construction parameters

Borehole site	Borehole number	Diameter of hole /mm	Projected length of long borehole /m	Number of fractured sections
1#	1-1#	120	564	10
	1-2#	120	579	11
	1-3#	120	600	12

2.3. Hydraulic fracturing equipment and tools

The BZW250/50 coal mine underground fracturing pump group was selected for this hydraulic fracturing construction project. This model of coal mine underground fracturing pump group (hereinafter referred to as the fracturing pump group) is specifically designed for coal mine underground fracturing conditions. It has a rated pressure of 50 MPa and a maximum discharge flow rate of 13.2 m³/h. The fracturing pipeline utilizes the YLGH70 fracturing pipe manifold system, capable of withstanding a maximum pressure of 70 MPa. Segmented fracturing tools are used to isolate and seal fractures in boreholes. These tools feature dual packers to seal off the fracturing sections. The tool combination is simple for construction and easy to maneuver. The packers are expandable, utilizing high-pressure water for expansion. The capsule makes full contact and seals with the hole wall. This packer is designed for visual sealing, and the method for unsealing is pressure relief unsealing. This tool string offers rapid hole sealing and continuous fracturing capabilities. The hydraulic fracturing equipment and tools are depicted in Figure 2.

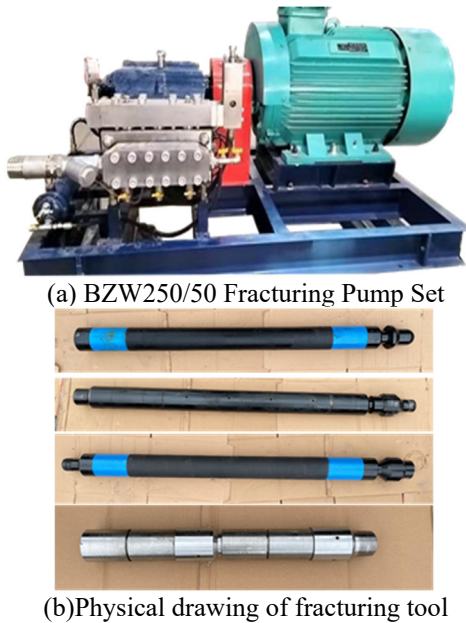


Figure 2. Hydraulic fracturing equipment and tools

3. Analysis of the Hydraulic Fracturing Test Process and Results

3.1. The hydraulic fracturing construction process.

After completing the drilling process, the fracturing tool

string is connected and installed. Static water pressure is utilized for both inflating and pressure testing the packers. Once installation, connection, and debugging work are completed, the water injection pipeline is connected, and the tool string is inserted into the target fracturing section of the borehole. The staged reverse fracturing method is used to seal holes and inject water during fracturing operations. A caution zone is designated within the area where the high-pressure pipeline is laid and extends 20 meters around the hydraulic fracturing borehole. Warning lines and signs are posted, and access is restricted to personnel involved in the operation during fracturing. The high-pressure pump is initially used to seal the packer with low pressure, followed by increasing the pressure and water discharge from the sieve tube to initiate fracturing. Pressure gauge and flow meter data are recorded during fracturing, while also observing any abnormal conditions in the surrounding coal walls and roof. The pump is stopped when the fracturing requirements are met or based on the actual conditions at the site. After the hydraulic fracturing operation is completed, the hole mouth pressure relief device is opened to release pressure and drain water. Following the completion of pressure relief, a 30-minute waiting period ensues for the packer's expansion rubber cylinder to return to its original size. Subsequently, the fracturing tool string (for directional long boreholes, the reverse drilling method is used) is shifted to the next target fracturing section to continue the fracturing operation.

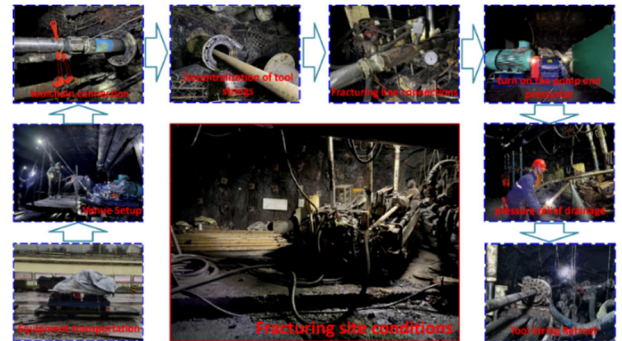


Figure 3. Directional long borehole segmental fracturing construction procedure

3.2. The result of hydraulic fracturing construction.

The directional long borehole segmented hydraulic fracturing was conducted in boreholes 1-1#, 1-2#, and 1-3#, with a total fracturing length of 1743 meters. There were 39 fracturing stages in total, and the fracturing process took a total of 5,231 minutes. The total volume of water injected during fracturing was 983.1 cubic meters.

Table 2. Summary of overall fracturing data for directional long boreholes

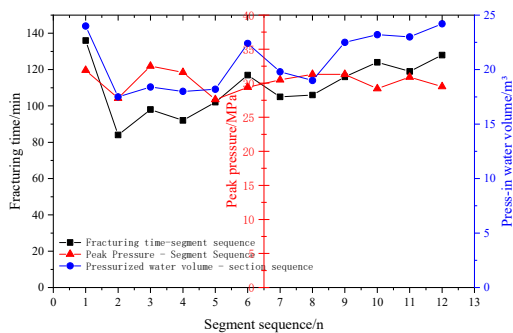
Borehole number	length of borehole /m	Number of fracturd sections	Total fracturing time /min	Total pressurised water volume /m ³	Fracturing timeframe /min	Peak pressure range/MPa	Water injection volume range/m ³
1-1#	564	12	1372	250.2	84-136	27.6-32.5	17.5-24.2
1-2#	579	13	1762	333.6	104-168	31.4-37.5	19-33.5
1-3#	600	14	2097	399.3	124-196	28.1-35.3	23.2-36.8

For borehole 1-1#, fracturing was completed in 12 stages, with a total duration of 1372 minutes. The fracturing duration ranged from 84 to 136 minutes, with peak pressures ranging from 27.6 to 32.5 MPa. The average peak pressure was 30.3 MPa, and the injected water volume ranged from 17.5 to 24.2 m³, with a total injected water volume of 250.2 m³. For borehole 1-2#, fracturing was completed in 13 stages, with a total duration of 1762 minutes. The fracturing duration ranged from 104 to 168 minutes, with peak pressures ranging from 31.4 to 37.5 MPa. The average peak pressure was 33.8 MPa,

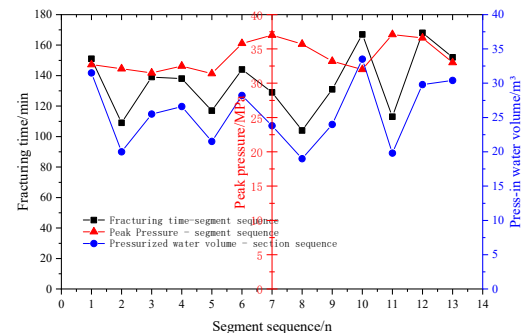
and the injected water volume ranged from 19 to 33.5 m³, with a total injected water volume of 333.6 m³. For borehole 1-3#, fracturing was completed in 14 stages, with a total duration of 2097 minutes. The fracturing duration ranged from 124 to 196 minutes, with peak pressures ranging from 28.1 to 35.3 MPa. The average peak pressure was 31.7 MPa, and the injected water volume ranged from 23.2 to 36.8 m³, with a total injected water volume of 399.3 m³. A summary of the fracturing construction for each stage of boreholes 1-1#, 1-2#, and 1-3# is provided in Table 3 and Figure 4.

Table 3. Summary of fracturing data for each hole in the directional long borehole

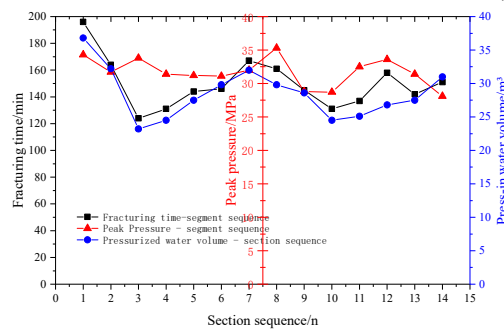
Borehole number	1-1#			1-2#			1-3#		
	Fracturing time /min	Peak pressure /MPa	Press-in water volume /m ³	Fracturing time /min	Peak pressure /MPa	Press-in water volume /m ³	Fracturing time /min	Peak pressure /MPa	Press-in water volume /m ³
1	136	31.9	24	151	32.7	31.5	196	34.3	36.8
2	84	27.8	17.5	109	32.1	20	164	31.7	32.2
3	98	32.5	18.4	139	31.5	25.5	124	33.8	23.2
4	92	31.6	18	138	32.5	26.6	131	31.4	24.5
5	102	27.6	18.2	117	31.4	21.5	144	31.2	27.5
6	117	29.4	22.4	144	35.8	28.2	146	31.1	29.8
7	105	30.5	19.8	129	37	23.8	167	32	32
8	106	31.3	19	104	35.7	19	161	35.3	29.8
9	116	31.3	22.5	131	33.2	24	145	28.8	28.6
10	124	29.2	23.2	167	32	33.5	131	28.7	24.5
11	119	30.9	23	113	37.1	19.8	137	32.5	25.1
12	128	29.5	24.2	168	36.6	29.8	158	33.6	26.8
13				152	33	30.4	142	31.4	27.5
14							151	28.1	31



(a) 1-1# borehole



(b) 1-2# borehole



(c) 1-3# borehole

Figure 4. Fracturing of each hole in a directional long borehole

3.3. Analysis of hydraulic fracturing construction data.

Hydraulic fracturing technology involves drilling, pressurizing, and creating fractures in coal rock formations using high-pressure fluids to disrupt the overall mechanical properties of the rock, thereby improving the conditions of

hard roofs to achieve the purpose of pressure relief and prevention of roof collapse [11,12]. Consequently, in the entire engineering application, the expansion results of hydraulic fractures determine the final effectiveness of hydraulic fracturing construction [13]. According to the principles of hydraulic fracturing technology, continuous pressurization and water injection by the high-pressure pump

during the fracturing process cause deformation and softening of the coal rock formations around the boreholes under the action of high-pressure water, resulting in cohesive fractures. Subsequently, high-pressure fluid further promotes the development and expansion of these cohesive fractures, forming real fracture spaces. The formation of hydraulic fractures is evidenced by the jumping behavior of the water pressure curve, defining this phenomenon as a pressure drop. Analyzing the data from this fracturing operation, the pressure drop parameter is used to summarize and characterize the effectiveness of hydraulic fracturing construction.

Table 4. Summary of pressure drops above 3MPa in directional long boreholes

Sequence Segments Borehole number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	total
1-1#	1	2	2	4	2	3	3	2	4	2	3	2			30
1-2#	2	2	1	1	2	3	4	2	3	2	5	4	4		35
1-3#	5	2	1	1	1	2	1	0	1	3	1	2	0	3	23

In the directional long borehole hydraulic fracturing construction, there were 30 occurrences of significant pressure drops exceeding 3 MPa in borehole 1-1#, 35 occurrences in borehole 1-2#, and 23 occurrences in borehole 1-3#. In total, there were 88 occurrences of significant pressure drops exceeding 3 MPa across the three boreholes. There is a trend from borehole 1-1# to borehole 1-3# of initially increasing and then decreasing occurrences of significant pressure drops exceeding 3 MPa. This trend is attributed to the conditions at the onset of fracturing construction, where the overall mechanical properties of the roof are relatively intact, and natural fractures within the coal rock formation are scarce. However, upon completion of fracturing construction in borehole 1-1#, a substantial number of hydraulic fractures are generated within the coal rock formation, thus weakening the mechanical integrity of the roof. Despite this, due to the limited extent of fracturing, the roof retains a certain degree of strength. Consequently, during fracturing construction in boreholes 1-2#, the development and expansion of hydraulic fractures become more pronounced, leading to their continued growth and eventual convergence into a network of hydraulic fractures. After the completion of fracturing construction in boreholes 1-1# and 1-2#, the overall integrity of the roof is effectively reduced, and the structure of the coal rock formation is transformed, leading to a significant reduction in its mechanical properties. Consequently, during the fracturing construction process in borehole 1-3#, the occurrences of significant pressure drops are diminished compared to previous stages.

4. Evaluation of Pressure Relief and Impact Prevention Effects

4.1. Analysis of stress relief in the coal body

On the west side of the 2305 working face lies the 2303 goaf, with a 52-60m waterproof coal pillar reserved between them. Utilizing the monitoring data from stress gauges placed on the waterproof coal pillar side and solid coal side in the transportation roadway of the 2305 working face, plot the variation curve of stress gauge data as mining time progresses (i.e., the stress value variation curve during the gradual

The expansion of hydraulic fractures includes the extension of the main hydraulic fracture and the development of micro-fracture networks based on this. In the analysis of the hydraulic fracturing effect of directional long boreholes, the expansion of the main hydraulic fracture is regarded as the main object of investigation for this pressure relief and prevention of roof collapse effect analysis. Therefore, by analyzing and statistically summarizing the hydraulic fracturing construction data, the occurrences of significant pressure drops exceeding 3MPa are compiled, as shown in Table 4.

reduction of distance from the working face to the stress gauge), as illustrated in Figure 5. As depicted in the figure, during the early stages of mining activities, the coal body situated farther away from the working face resides within the original rock stress zone. As the mining distance decreases, the support pressure exerted on the coal body steadily increases. Once the support pressure reaches its peak stress level, it begins to decline. By substituting relevant numerical values, the stress peak coefficient K is calculated using $K=P3/P1$, yielding approximately $K \approx 2.9$. This value indicates a relatively small stress peak coefficient, which will not lead to impact phenomena.

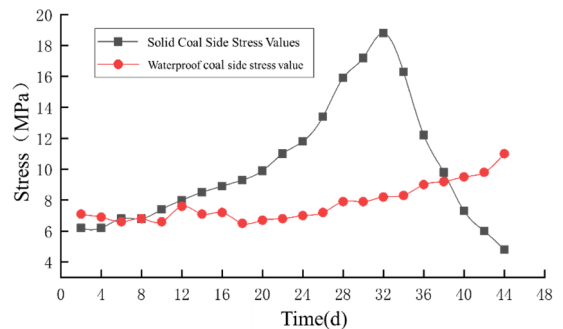


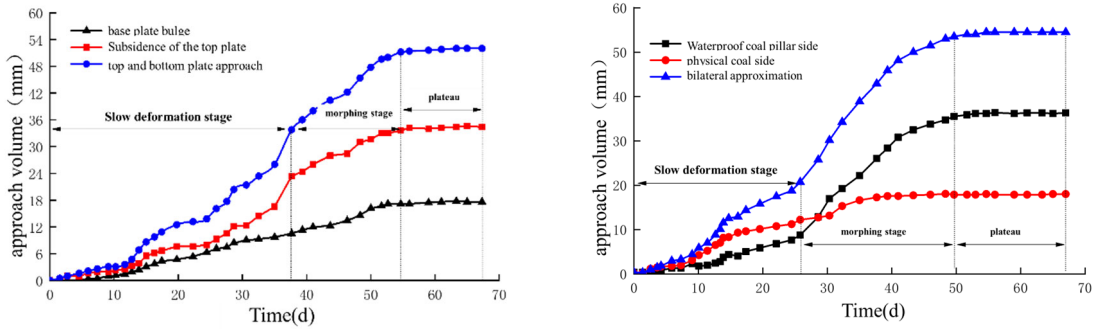
Figure 5. Coal body stress gauge variation curve with push mining

4.2. Analysis of coal body deformation

The cross-measuring point method was employed to monitor the movement of both the top and bottom of the roadway and the movement of the two sides in the transportation roadway of the 2305 working face. The monitoring results are depicted in Figure 6. According to the monitoring results, it is evident that after implementing hydraulic fracturing pressure relief and erosion prevention measures, the final displacement of the top and bottom of the roadway affected by mining is 55mm, and the final deformation displacement of the two sides is 58mm. Both the displacement of the top and bottom of the roadway and the displacement of the two sides tend to stabilize over time

without secondary impact deformation, thereby reducing the overall deformation of the roadway and lowering the

maintenance cost associated with it.



(a) top and bottom plate approach (b) bilateral approximation
Figure 6. Variation curve of lane approaching volume

4.3. Analysis of Support Resistance

The roof pressure of the working face and the support strength of the hydraulic support interact with each other. During the mining period of the 2305 working face, the resistance of the mining support is measured using mining pressure monitoring equipment. Based on the increased resistance characteristics of the support, the caving characteristics of the top coal are assessed, and the pressure step of the roof is determined according to the change in the support resistance. By comparing the mining pressure monitoring data before and after fracturing in the 2305 working face, the effects of pressure relief and impact mitigation are analyzed. Based on the analysis of the monitoring results of the support's working resistance on the working face, it was observed that the resistance of the support significantly decreased during the initial mining and release period. The average support resistance of the 2303 working face without fracturing measures was 5840kN, while the support resistance of the 2305 working face after implementing fracturing measures to relieve pressure and prevent impact was approximately 4100kN under normal pressure conditions. During the initial pressure phase, the support resistance was around 4550kN, increasing by only 11% under pressure. The average working resistance during pressure reduction was 22% lower compared to the average working resistance of the 2303 working face. This indicates that the hydraulic fracturing measures implemented by the working face to relieve pressure and prevent erosion have reduced the length of the roof overhang and improved the support resistance.

4.4. Analysis of the Subsidence during Mining Operations

Analyzing the roof collapse situation during the mining period of the 2305 working face, after implementing fracturing measures, the first collapse occurred when the working face had advanced only 6 meters. The collapse range was behind the supports numbered 42-58, and after advancing 10 meters, the collapse occurred behind the supports 20-60. Subsequently, at 16 meters of advancement, a large-scale collapse occurred behind supports numbered 16 to 119. By the time the workforce advanced 22 meters, almost all areas had collapsed. At 26 meters of advancement, the entire old roof behind the goaf collapsed, marking the completion of the initial pressure relief. Throughout the entire mining process, the roof collapse occurred promptly without forming strong impacts, reducing the initial pressure step distance by 53% compared to the theoretically calculated 60-meter thick and hard roof. The periodic weighting step distance during normal mining is reduced by 27% compared to the 2303 working face with the same geological conditions.

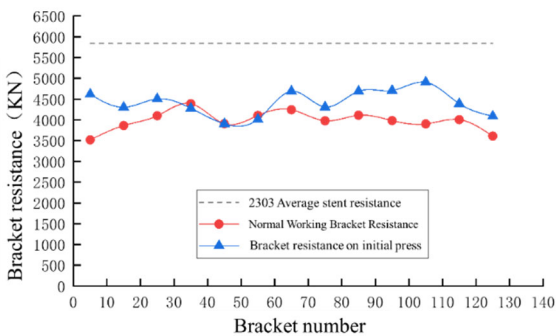


Figure 7. Comparison of brace resistance during normal and first incoming pressure

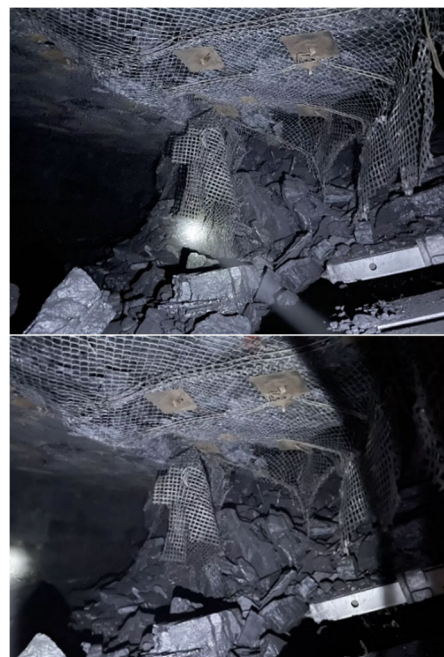


Figure 8. Collapse of 20 to 60 frames behind at 10m thrust

5. Conclusion

(1) The 2305 comprehensive mining workface underwent a highly efficient and successful drilling and hydraulic fracturing construction utilizing the top plate directional long-hole segmented hydraulic fracturing technology. A total of 1743 meters of directional long holes were fractured, with 39 segments fractured, totaling 5231 minutes of fracturing time and a total injected water volume of 983.1 cubic meters. Notably, there were 88 occurrences of significant pressure drops exceeding 3 MPa, which were effectively managed and resolved.

(2) The implementation of directional long drilling and fracturing on the roof has significantly reduced the peak stress coefficient of the coal body in front of the working face ($K \approx 2.9$). This has effectively blocked the propagation of mining stress and high stress in the goaf to the mining roadway, resulting in a stable roadway without the occurrence of secondary impact large deformation. The movement of the top and bottom plates of the transportation roadway has been reduced by 55mm and the deformation of the two sides by 58mm. These results demonstrate the effectiveness and reliability of this technique in stabilizing roadways and reducing deformation.

(3) The measures implemented to relieve hydraulic fracturing pressure and prevent erosion resulted in a significant improvement in the support resistance of the working face. During the initial pressure, the average support resistance increased by 11%, while the average working resistance decreased by 22% compared to the working face without measures. As a result, the length of the roof overhang was effectively reduced and the support resistance was improved. The roof collapsed in a timely manner during the mining process of the working face, resulting in a 53% reduction in the initial pressure step distance compared to the theoretically calculated 60m thick and hard roof. Moreover, the cyclic weighting step distance during normal mining decreased by 27% compared to the 2303 working face with the same geological conditions.

(4) The directional long drilling technique achieves an impressive 80% utilization rate of segmented hydraulic fracturing drilling, with a wide coverage range on the roof. This method significantly weakens the strength of the roof above the coal seam across a large area, effectively shortening the cycle to compress the step distance and strength. As a result, it successfully prevents the impact caused by the suspended roof during the mining process of the working face.

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