Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 15, No. 2, 2025

Study on Stress-Strain Response Characteristics of Hydraulic Fracturing in Deep Coal Mines

Yuming Zhao[1, 2]

[1]China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing 400039, China
[2]State Key Laboratory of Coal Mine Disaster Prevention and Control, Chongqing 400039, China

Abstract: To investigate the evolution law of stress and strain during hydraulic fracturing, hollow inclusion stress-strain gauges were used to monitor the variations in stress and strain before and after hydraulic fracturing. The results show that two hours after hydraulic fracturing, the influence range of high-pressure water extended to the monitoring borehole at 32 m, exerting the maximum impact on the stress-strain monitoring points, after which the strain tended to stabilize. Six days after hydraulic fracturing, the strain returned to a stable state with no further changes, though it remained higher than the pre-fracturing state. During hydraulic fracturing, the principal stress increments increased but with varying magnitudes. Hydraulic fracturing primarily affected the increase in vertical stress, which is related to the spatial positions of the stress-strain monitoring points and the hydraulic fracturing borehole. After fracturing, due to the gradual pressure release of the fracturing fluid, the stress increment gradually decreased and tended to recover to the original stable state, though it still remained higher than the pre-fracturing state. Hydraulic fracturing had little influence on the azimuth and dip angle of the coal-rock mass. The stress-strain behavior can provide a reference for exploring the mechanism of permeability enhancement in coal seams through hydraulic fracturing.

Keywords: Hydraulic fracturing; coal seam permeability enhancement; stress-strain monitoring; principal stress.

1. Introduction

Hydraulic fracturing technology utilizes high-pressure dynamic water injected by fracturing pump units at pressures exceeding the initiation threshold to create and propagate fractures within coal seams. By continuously injecting high-pressure water, the fractures are extended and enlarged, thereby enhancing coal seam permeability and improving gas drainage efficiency [1-2]. Since its introduction in China, most studies on stress-strain evolution during hydraulic fracturing have relied on theoretical mechanical models, with limited field experimentation. Various methods exist for monitoring stress-strain in underground coal mine rock masses, among which hollow inclusion stress gauges are widely applied [3-4]. Li Jinkui et al. [5] conducted in-situ stress measurements at four locations, including the track decline and auxiliary cross-cut in the first mining district of Yuncheng Coal Mine, Shandong. Guo Shupeng et al. [6] performed stress tests at three sites, such as the conveyor roadway in the 1111 mining district, with depths ranging from -855 to -885 m. Using borehole stress relief testing, they identified horizontal stress as the maximum and intermediate principal stresses, while vertical stress was the minimum principal stress. Several domestic scholars have conducted stress-strain monitoring experiments on coal seam roof hydraulic fracturing. Kang Hongpu et al. [7] employed hollow inclusion stress gauges to monitor stress variations near boreholes before and after hydraulic fracturing in Wangtaibao Coal Mine, Jincheng, revealing stress evolution patterns and influencing factors during fracturing. Huang Fei et al. [8] monitored stress-strain evolution in the roof during hydraulic fracturing at Tonghua Coal Mine, Songzao mining area, concluding that hydraulic fracturing alters the stress state of the coal seam roof. They demonstrated that directional hydraulic fracturing can effectively weaken the roof. While the aforementioned field tests focused on monitoring roof fracturing, few studies have reported on stress-strain monitoring during coal seam hydraulic fracturing. Therefore, based on the above analysis, this study conducts in-situ stress-strain monitoring during coal seam hydraulic fracturing to explore its stress evolution patterns, providing a reference for understanding the permeability enhancement mechanism of hydraulic fracturing.

2. On-site Implementation of Stress and Strain Monitoring

The test site is selected in a coal mine gas extraction lane, hydraulic fracturing K_2 coal seam, the inclination is 30°, the average thickness is 1.5m. The roof of coal seam is dark gray mudstone (0.25m) and argillaceous limestone (4.57m). The floor of the coal seam is sandy mudstone (3.2m). The buried depth of the test area is between 800 and 810m. In this test, one perforation hydraulic fracturing borehole and two stress and strain monitoring boreholes were designed. The design parameters are shown in Table 1. KX-81 hollow inclusions strain gauge (precision 0.1μs) and KJ327-F mine pressure monitoring system sub-station (precision measurement value ±0.1% word) were used to monitor the stress and strain in the process of hydraulic fracturing.

Table 1. Borehole parameters of hydraulic fracturing and stress-strain monitoring

Borehole type	Aperture/mm	Dip angle/°	Angle with cross-entry/°	Length/m	End borehole location
1# monitor borehole	130mm	10	45	38m	Siliceous limestone
2# monitor borehole	130mm	33	0	17m	Siliceous limestone
Hydraulic fracturing borehole	108mm	22	0	69m	K_2 coal seam

3. Analysis of Stress-strain Monitoring Results

3.1. Analysis of strain monitoring results

Strain is closely related to the pressure borne by the borehole wall and the formation and expansion of cracks, which is the manifestation of the formation and expansion of cracks in the borehole wall under the action of water pressure. Field strain data collection is set to take 20 minutes for each collection, and the collection frequency is once per minute. Before fracturing, the strain gauge is connected, and the fracturing pump is activated and the fracturing is monitored in real time. After fracturing, data collection will be carried out every day, and stress-strain data will be analyzed every day. Monitoring will be stopped when it is found that data tend to be stable. Due to the large amount of stress-strain data collected in the field, it was found through analysis that the stress-strain variation rules of the two stress gauges were similar. In this paper, only the representative strain monitoring data of the monitoring 1# borehole was listed for analysis. The monitoring data were plotted into the strain curve of the whole hydraulic fracturing process, as shown in Fig. 1.

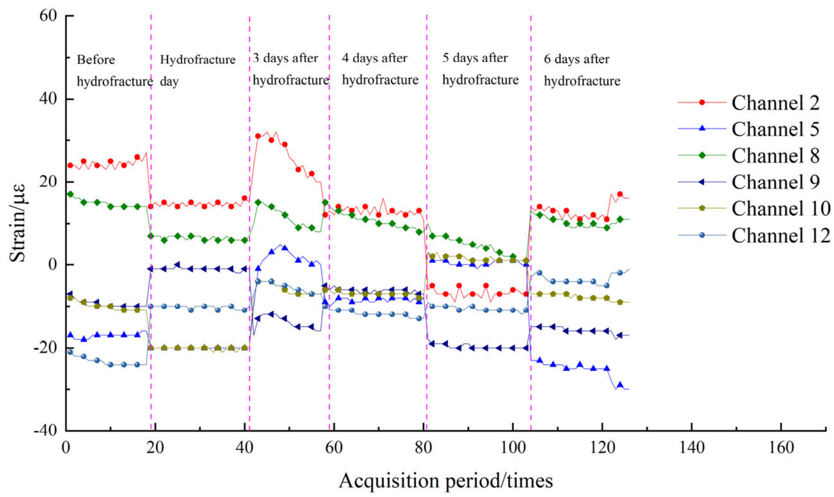

Figure 1. Strain curve in the whole process of hydraulic fracturing

From Fig. 1, two hours after hydraulic fracturing, fracturing water has affected the stress monitoring point, and has reached the maximum, up to 32m. At the later stage of fracturing, the strain tends to remain stable without large changes. It can be inferred from the coal seam geological histogram that there is no pressure through the coal seam floor during the whole fracturing process. After fracturing, the strain gradually recovered. At 6 days after fracturing, the strain returned to a stable state without any change, but it was still slightly larger than that before fracturing, indicating that hydraulic fracturing had changed the stress state of coal and rock mass.

3.2. Analysis of stress monitoring results

Stress monitoring can indirectly describe the stress change of coal seam roof by monitoring the strain of surrounding rock. In general, the increment of stress can be more convenient to show the change rule of stress, and the increment of principal stress can be calculated by inputting the monitoring data into the program. In this paper, the principal stress increment is used to represent the change of principal stress. The maximum, intermediate and minimum principal stress increments are Δσ1, Δσ2 and Δσ3 respectively when the stress meter is just embedded and the reading is stable.

(1) Principal stress increment analysis of 1# borehole

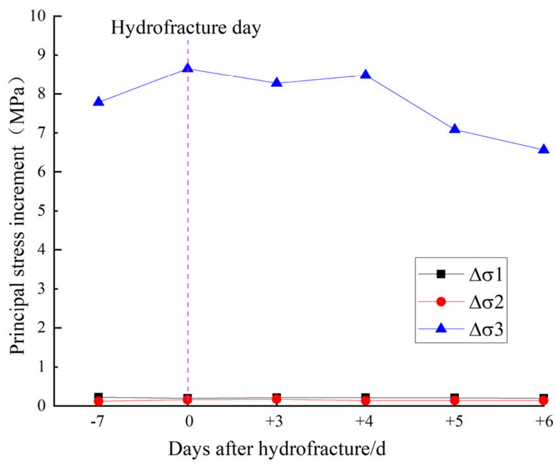

Figure 2. Principal stress increment change curve of 1# borehole

From Fig.2, on the day of fracturing, high-pressure water cracks in the relatively soft coal seam first, and the stress (principal stress increment Δσ3) changes most obviously in the vertical direction of fracturing in the No.1 stress monitoring borehole. Day 3 after fracturing: principal stress increment began to decrease, Δσ3 drops to about 8 MPa, coal and rock and borehole wall in some areas appear the phenomenon of elastic compression, the stress monitoring borehole storage energy, when after fracturing has stopped, in the coal and rock stress decreases, the elastic deformation of the borehole wall gradually restored, the deformation has a tendency to gradually return to the initial state, show is the principal stress increment decreases. Day 4 after fracturing, the increment of the principal stress increased, and the azimuth angle and inclination angle changed greatly. Because the fracturing borehole kept the pressure, the high-pressure water continued to act on the coal and rock mass, infiltrated into the coal and rock mass and changed the mechanical properties of the coal and rock mass, thus affecting the increment of the principal stress and the change of the direction. Day 5 after fracturing, the fracturing borehole was relieved, and the increment of principal stress continued to decrease, and the decreasing rate increased, the fracturing fluid loss rate in the coal and rock masses accelerated, and the pressure gradually returned to the original state. Day 6 after fracturing: the increment of principal stress continues to decrease, the rate slows down, and the stress level in coal and rock gradually tends to be stable, but it is still larger than the state before fracturing. Hydraulic fracturing affects the 1# monitoring borehole, which reaches 32m, and changes the stress state of coal seam roof. During the fracturing process, the pressure of the high-pressure pump was about 22MPa, but the principal stress increment of the stress monitoring borehole was about 8.5MPa at most. Because in the fracturing process, there is inevitably pressure loss as the high-pressure water flows to the stress monitoring borehole.

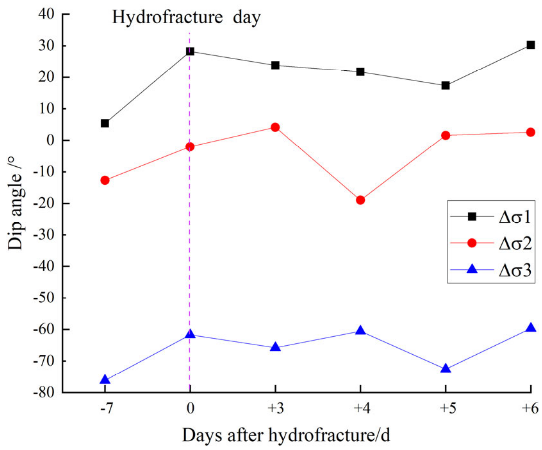

Figure 3. Variation curve of dip Angle of principal stress in 1#borehole

From Fig. 3, the azimuth Angle and inclination Angle of the stress on coal and rock mass changed with time. On the day of fracturing, hydraulic fracturing affected the 1 # stress monitoring borehole, leading to a sharp change in the stress state of surrounding rock. In general, in the monitoring period, hydraulic fracturing has a great influence on the azimuth of the principal stress increment Δσ2, and has little influence on the azimuth and dip angles of other principal stresses, and each stress state gradually returns to the initial state.

(2) Principal stress increment analysis of 2# borehole

The change curve of principal stress increment in monitoring borehole 2# is shown in Fig. 4. On the day of fracturing, the principal stress increment in monitoring borehole 2# increases in all three directions, but mainly in the vertical direction, while the stress increment in other directions is small. Because the 2# monitoring borehole is far from the pressure cracking borehole (47m away) and is subject to the resistance of coal and rock mass, when the fracturing fluid is transferred from the pressure cracking borehole to the 2# monitoring borehole, the pressure loss is large, the principal stress increase of the 2# monitoring borehole is small, and the fracturing fluid is spread to the 2# monitoring borehole, and the influence range is not less than 47m. After hydraulic fracturing, the decrease rate of stress increment in monitoring borehole 2# is faster than that in monitoring borehole 1#, because the location of monitoring borehole 2# is far away, the stress recovery rate is faster, and the stress increment basically returns to the original state on the 6th day after fracturing.

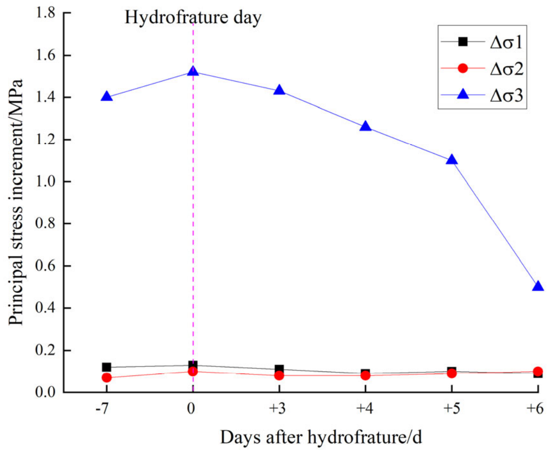

Figure 4. Change curve of principal stress increment in 2#borehole

The change curve of azimuth and dip angle of the principal stress of coal and rock mass around the 2# monitoring borehole as shown in Fig.5. On the fracturing day, 2# monitoring borehole three-way azimuth angle and dip angle of principal stress influenced by fracturing has some changes, but quickly recovered after fracturing, gradually stabilized, because 2# borehole in place far away from the pressure, compared with 1# borehole, change smaller, faster recovery.

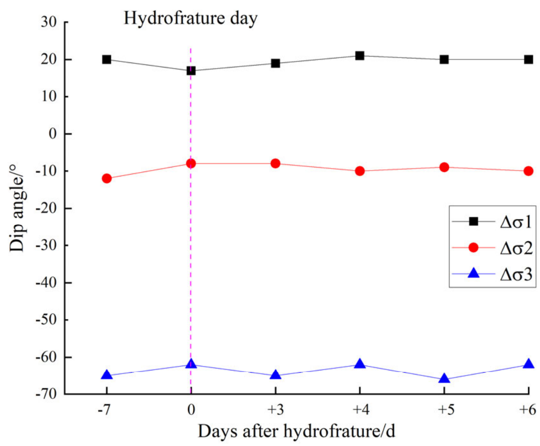

Figure 5. Variation curve of dip Angle of principal stress in 2# borehole

4. Conclusion

The stress-strain changes before and after hydraulic fracturing were monitored using a hollow package stress-strain gauge.

(1) On the day of fracturing, 2 hours after the start of fracturing, the fracturing water spread to the top of the 1 # stress monitoring hole, with an impact range of not less than 29m. After 2 hours of fracturing, the impact on the stress monitoring point had reached its maximum, and the strain tended to stabilize in the later stage of fracturing. In the later stage of fracturing, the strain remained almost stable without significant changes, and the entire fracturing process did not penetrate the coal seam floor. After the fracturing is completed, the strain gradually recovers. By 6 days after fracturing, the strain returns to a stable state and no longer changes, but it is still slightly higher than the pre fracturing state, indicating that hydraulic fracturing has changed the stress state of the coal rock mass.

(2) The hydraulic fracturing process changes the stress state of the coal rock mass, affecting the stress monitoring drilling area, and the fracturing range is not less than 44m. The increment of principal stress increases during hydraulic fracturing, but the magnitude of the increase varies. Fracturing mainly affects the vertical stress increment, which is related to the spatial position of stress monitoring points and fracturing holes. After fracturing, due to the filtration of fracturing fluid, the pressure gradually decreases, and the stress increment no longer undergoes a large sudden change, gradually decreasing and showing a trend of returning to the original stable state, but still greater than the state before hydraulic fracturing. Hydraulic fracturing has little effect on the azimuth and dip angle of coal rock mass.

References

[1] Ge Xi. Application Analysis of Permeability Enhancement Technology by Hydraulic Fracturing in Low-Permeability Coal Seams[J]. Energy and Energy Conservation, 2025, (04): 266-268.

[2] Li Quangui, Wang Mingjie, Yu Xu, et al. Experimental Study on Fracture Propagation Characteristics of Flow-Controlled Pulsed Hydraulic Fracturing[J]. Coal Science and Technology, 2025, 53(02): 178-189.

[3] Si Linpo. Selection Method of Stratum for In-Situ Stress Measurement by Hollow Inclusion Stress Relief Method in Underground Coal Mines[J]. Coal Mining Technology, 2015, 20(04): 18-22.

[4] Li Tianyu, Li Yuan, Qin Zhixuan, et al. Construction of Disturbed Stress Cloud Monitoring System Based on Hollow Inclusion Strain Gauges[J]. China Mining Magazine, 2021, 30(10): 96-105.

[5] Li Jinkui, Li Guang, Tian Zhaojun. Application of Hollow Inclusion in In-Situ Stress Measurement at Yuncheng Coal Mine[J]. Industrial Safety and Environmental Protection, 2019, 45(04): 15-19.

[6] Guo Shupeng, Li Yingfu. In-Situ Stress Measurement at Kouzidong Mine Based on Hollow Inclusion Strain Method[J]. Shanxi Coking Coal Science & Technology, 2024, 48(08): 18-21.

[7] Kang Hongpu, Feng Yanjun. Stress Monitoring and Evolution Law of Coal Body in Working Face During Directional Hydraulic Fracturing[J]. Journal of China Coal Society, 2012, 37(12): 1953-1959.

[8] Huang Fei, Li Shuqing, Zuo Weiqin. Stress Monitoring and Evolution Law of Coal Seam Roof During Underground Hydraulic Fracturing[J]. Mineral Engineering Research, 2018, 33(3): 23-27.