Application of hydraulic fracturing for destressing mining-induced stresses in underground coal mines

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ABSTRACT: Hydraulic fracturing (HF) has emerged as a widely used ground control strategy in Chinese coal mining practice, often employed in combination with ground support techniques. HF campaigns can be broadly categorized into two types based on the size of the targeted region: local campaigns, which are applied to smaller areas such as the roof above a coal pillar, and large-scale campaigns, which encompass a broader area, such as the entire width of a longwall panel. This paper presents two case studies that examine the use of both local and regional HF as a ground support strategy in Chinese coal mines. The field studies demonstrate that HF is effective in reducing or redistributing mining-induced stresses, preconditioning hard rock strata, and, in some cases, decreasing mining-induced microseismicity.

Keywords: hydraulic fracturing, underground coal mine, destressing, case study

1 INTRODUCTION

In contrast to civil tunnels, underground coal mine roadways possess a distinctive characteristic: they are unavoidably subjected to mining-induced stresses, particularly in the entries of longwall panels. As the longwall extraction proceeds, abutment stresses form around the periphery of the mined-out area. The presence of high abutment stresses can result in a range of problems concerning the stability of longwall entries and pillars, such as roof fall, rib failure, floor heave, and even coal burst. At greater mining depths, these challenges become more pronounced owing to the high overburden stresses associated with the relatively brittle response of coal measures. Thus, the development of protective measures to counteract the damaging effects of excessive stresses is necessary.

Destress blasting is a long-established stress relief technique utilized in underground coal mining. Its primary objective is to shift stress concentration zones to the interior rock mass and establish a protective barrier surrounding the excavation (Konicek et al., 2011). In China, destress blasting was successfully implemented to control floor heave in deep coal mines (Kexin, 1995; Xia et al., 2007), as well as to mitigate coal burst issues in Poland, the Czech Republic, China, and Germany (Konicek et al., 2011; Dvorsky et al., 2005; Gu et al., 2016; van As et al., 2004; Catalan et al., 2012). The technique is believed to release stored strain energy and reduce modulus values, thereby ensuring that the rock mass does not bear a critical stress level (Sedlak, 1997).

Hydraulic fracturing (HF) is another commonly employed measure for reducing excessive stresses in Chinese coal mining. It is often used in combination with ground support techniques for ground control (Katsaga et al., 2015; Jeffrey et al., 2013; Juncal et al., 2014; Board et al., 1992; Araneda et al., 2007). In contrast to destress blasting, hydraulic fracturing offers better control of fracture geometry through directional fracturing (Konicek et al., 2011) and shadow stress effect

(He et al., 2017; He et al., 2016), while generally being less destructive. HF campaigns can be classified into two types according to the size of the targeted region: local HF campaigns, which are applied to smaller areas such as the roof above a coal pillar, and large-scale HF campaigns, which encompass a broader area such as the entire width of a longwall panel. In this paper, two case studies are presented to illustrate the two typical applications of HF: the use of local HF campaigns as a stress relief measure for a coal pillar between two adjacent longwall panels, and the use of large-scale HF campaigns to promote regularity of the main roof as the longwall panel advances and thereby alleviate mining-induced stresses.

2 APPLICATION OF LOCAL HF FOR DESTRESSING ABUTMENT PRESSURES

2.1 *Geological conditions and local HF campaign*

2.1.1 *Geological conditions*

The study was conducted at the Hongqinghe Coal Mine, located in Inner Mongolia Province, Northwest China. The study site was the 101 longwall panel, which was the first mining panel of the mine, measuring approximately 3,200 m in length and 245 m in width. The sub-horizontal coal seam, with an average thickness of 6.9 m, was mined using the longwall retreat mining method, while the depth of the overburden was approximately 700 m. The tailgate and main gate both had a rectangular cross-section profile, measuring 4.0 m in height and 5.9 m in width. The pillar between the 101 tailgate and 103 main gate was 30 m in width. The layout plan of the study site is presented in Figure 1.

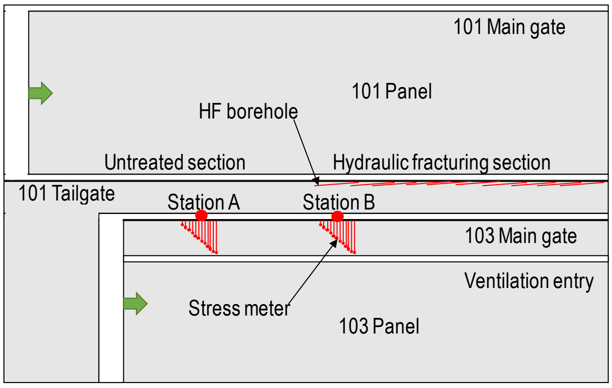


Figure 1. Layout of panel and entries in the study site of local HF campaign, not scaled.

The geological characteristics of the immediate roof of the coal seam were determined through underground borehole televiewing. The immediate roof was composed of a 9.2-meter thick layer of siltstone, overlain by a 14.6-meter thick layer of moderately competent fine-grained sandstone. Above this sandstone layer was a massive, competent conglomerate with an approximate thickness of 5.7 meters. The nature of the sandstone and conglomerate was confirmed to be massive and non-laminated through underground borehole televiewing. In-situ stress measurements obtained through the use of hydraulic fracturing (HF) demonstrated a regional thrust-fault stress regime at a depth greater than 200 meters, where the minimum principal stress was the vertical stress.

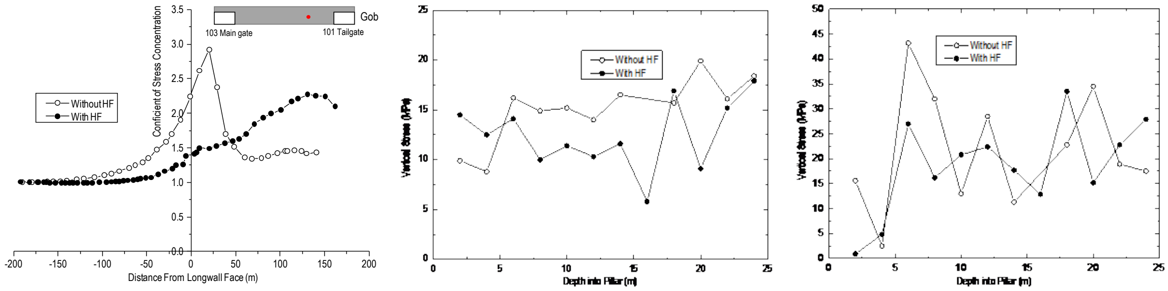
2.1.2 *HF operations*

HF operations were conducted in a 1,000 m long section of the 101 tailgate, as shown in Figure 1. A total of 110 fracturing holes were drilled along the main roof with a spacing of 10 m. The holes, which had a diameter of 56 mm and were 50 m long, were drilled in a dip direction of 5° measured from the pillar rib and a dip angle of 50° into the roof. To enable independent HF operations in each section of the borehole, 14 sections were separately sealed along the borehole axial direction for each fracturing hole. The aim was to create a series of horizontal fractures above the pillar. It was anticipated that the fractures would be initiated at regular intervals along the borehole and extended as essentially parallel fractures, with a spacing of 2.6 m to a radius of at least 10 m, which was estimated from field observation during HF operation, wherein water leaking was observed in adjacent boreholes.

The hydraulic pressure and flow rate were designed to be 62 MPa and 80 L/min, respectively. Typically, the hydraulic pressure used for HF operations in the field falls between 30 to 40 MPa. Fracturing operations were halted upon observation of water leakage on the surface of the roof or ribs of the tailgate. Injection durations at each section varied from 20 to 30 minutes. All HF operations were performed prior to the extraction of the 101 longwall panel.

2.2 *Effect of local HF campaign on destressing abutment pressures*

Figure 2(a) presents a comparison of the vertical stress changes with longwall face advances, as monitored at two distinct stations. At station A, where HF was not performed, the vertical stress began to increase when the longwall face was approximately 150 m away, and experienced a dramatic increase as the longwall face approached within 60 m. The vertical stress reached its peak value when the longwall face passed by the monitoring station at around 36 m, and then quickly decreased as the longwall face progressed. The greatest coefficient of stress concentration, which represents the ratio of the abutment stress to the pre-mining vertical stress, was 2.9. It is important to note that the monitored vertical stress was not the front abutment stress, but rather the aside abutment stress caused by the mining of the 101 longwall panel. Therefore, the peak value was not observed before the longwall face passed by the monitoring station but after it passed by the monitoring station at a certain distance. This delay can be attributed to the progressive fracturing and caving of the roof strata above the mined-out area in the proximity of the monitoring station. The decrease in the vertical stress after the peak value can be attributed to the failure of the rib of the 101 tailgate under high abutment stress, rendering it incapable of withstanding extensive stress. At station B, where HF was performed, the vertical stress began to increase when the longwall face was approximately 70 m away, and gradually increased to reach its peak value when the longwall face passed by the monitoring station at around 130 m. The greatest coefficient of stress concentration was 2.3, which is significantly less than that at station A.



(a) (b) (c)

Figure 2. Effect of local HF on destressing abutment pressures. (a) Vertical stress changes with longwall extraction monitored within the pillar, (b) Abutment stress distribution within the pillar when the longwall face passed by 10m, and (c) When the longwall panel passed by 50m.

Figure 2(b) and 2(c) depict a comparison of the vertical stress distribution within the pillar at the two monitoring stations. Although there appears to be an irregular trend in the distribution of the vertical stress at some points within the pillar, potentially caused by localized stress concentration, the results indicate a substantial impact of the HF operation on destressing the abutment stresses.

3 APPLICATION OF RIGIONGAL HF FOR DESTRESSING ABUTMENT PRESSURES

3.1 Geological conditions and regional HF campaign

3.1.1 Geological conditions

The present case study was carried out at the Caojiatan coal mine, situated in the Yushen mining area in the northeast of Yulin city, Shaanxi Province, China. This mine is a typical example of a thick coal seam mine that features thick hard roof strata. The ongoing mining operation is focused on the 2-2 coal seam, which lies at a burial depth ranging from 255 to 338 m and has an average recoverable thickness of 11.22 m. The seam is characterized by a slight dip angle of up to 5°. The immediate roof consists of fine-grained sandstone with an average thickness of 7.61 m, overlain by medium-grained sandstone with an average thickness of 22.8 m, and further topped by fine-grained sandstone with an average thickness of 12.7 m. The sandstone layers generally lack preexisting discontinuities and are massive. The uniaxial compressive strength of the medium- and fine-grained sandstone is 20-30 and 50-60 MPa, respectively.

As illustrated in Figure 4(a), the longwall panels at Caojiatan coal mine have a specific layout, and the 122106 panel has already been extracted. The 122108 panel, which spans a width of 280 m and a length of 5966 m, was subjected to large-scale HF operations in the final 1000-m-long section. The 122108 panel can be accessed through one tailgate and two headgates, namely a main haulage gate and an auxiliary haulage gate. The pillar located between these two headgates is 20-m wide and has crosscuts. The in-situ stress field prevailing at the mine is a reverse fault stress regime.

3.1.2 Regional HF campaign

To conduct the regional HF operations at the Caojiatan coal mine, a series of small-scale HF tests were initially performed to identify favorable rock layers. Based on a comprehensive evaluation of the test results of borehole televiewing, in-situ rock strength, and small-scale fracturing, three rock horizons at 10, 23, and 38 m were selected for the LHF trial.

The regional HF operations were carried out in two phases, covering the entire area of the final 1000 m of the 122108 longwall, as depicted in Figures 4(b) and (c). In the first phase, drilling site H1 was established in the 122108 tailgate, while two sites, F1 and F2, were established in the auxiliary haulage gate. At each site, 5-7 extra-long boreholes, 400-600 m in length, were drilled into the three target rock layers using a high-power directional drilling rig with a torque greater than 15,000 N•m. Initially, the boreholes were drilled with a diameter of 193 mm and reinforced with a 150-mm-diameter casing upon reaching the target rock horizon. Subsequently, the boreholes were drilled horizontally within the rock layer with a diameter of 120 mm. In total, 17 boreholes were drilled during the first stage, with a total length of 8598 m.

After the completion of drilling a borehole, an inflatable packer was deployed to the bottom of the borehole using a directional drilling rig, and connected to the pumping equipment to initiate fracturing. The packer was then moved to the subsequent fracturing position using the same rig for further fracturing, until all positions were fractured. The flow rate used in each fracturing stage was greater than 1.5 m3/min. The average fracturing period for the 17 boreholes was 476 min, with an average water injection of 367 m3 and HF pressure ranging from 15.1 to 35.1 MPa.

During the second phase, four HF drilling sites (R1–R4) were established in the recovery roadway of the longwall panel. A total of 20 extra-long boreholes were drilled to reach the three target rock horizons. The lengths of the boreholes were 510–576 m at sites R1–R3, and 300–348 m at site R4, totaling 10,056 m in length. The average fracturing period for the 20 boreholes was 574 min, with an average water injection of 609 m^3 and HF pressure ranging from 12.5 to 28.0 MPa.

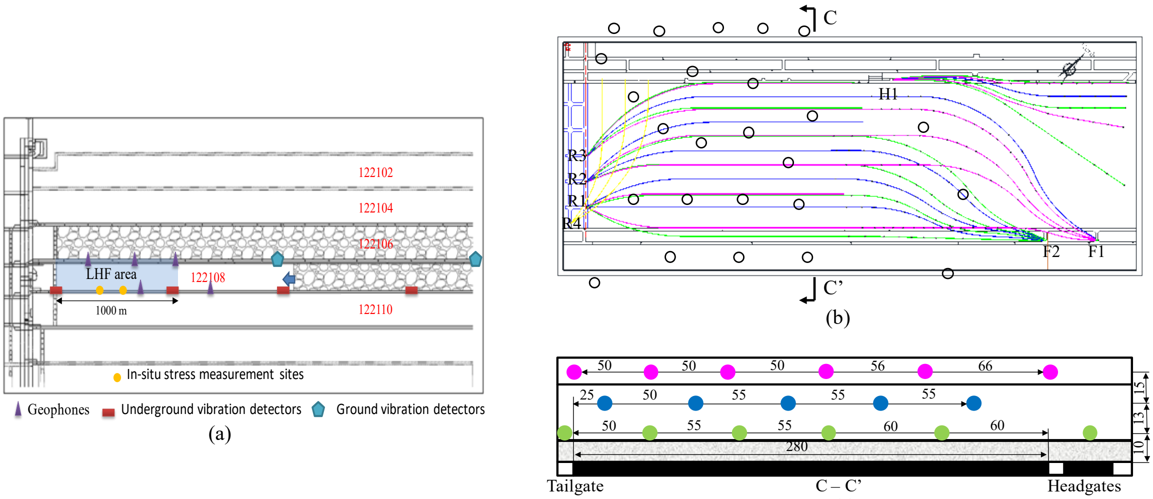
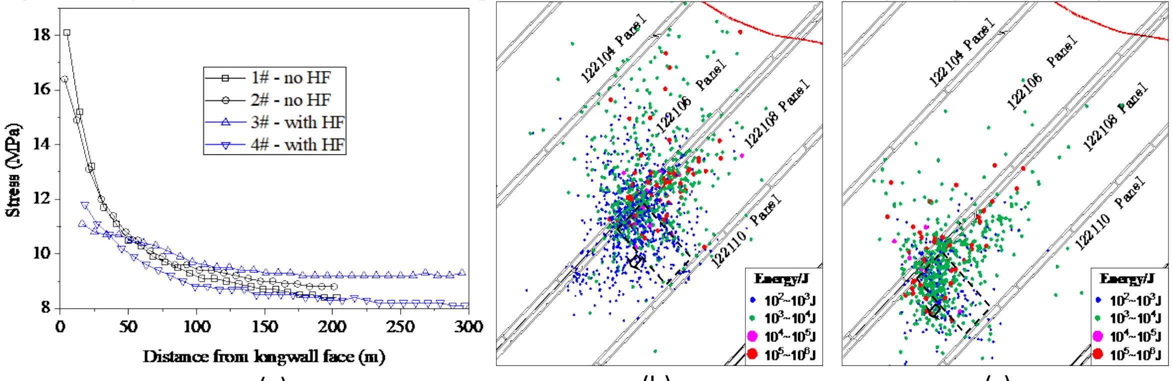


Figure 4. (a) Layout of panel and entries in the study site of regional HF campaign. (b) Layout of long directional boreholes used for HF. The black circles indicate the location of microseismometers placed on the ground. (c) Cross-sectional view showing the borehole locations in the three rock horizons. Not to scale.

3.2 *Effect of regional HF campaign on destressing abutment pressures*

Figure 5(a) illustrates the changes in monitored stress as the longwall face approached. Notably, the effects of front abutment pressure became evident when the face was approximately 200 m away, and gradually increased until the face was approximately 100 m away. Beyond this point, the pressure dramatically increased in all four stress meters. This phenomenon was particularly pronounced for stress meters 1 and 2, which were located in the non-HF area. When the longwall face was only a few meters away, the vertical stress change reached its maximum value of 16.5 MPa and 18.1 MPa at stress meters 1 and 2, respectively, corresponding to a coefficient of stress concentration of 3.0 and 3.2, respectively. Stress meters 3 and 4, which were installed in the HF area, recorded a maximum vertical stress change of 11.0 and 11.8 MPa, respectively, corresponding to a coefficient of stress concentration of 2.3 and 2.4, respectively. It is noteworthy that LHF significantly reduced the front-abutment pressure that resulted from the longwall panel mining.



(a) (b) (c)

Figure 5. Effect of HF on reducing the front abutment pressure and mitigating microseismicity. (a) Changes of the vertical stresses as the longwall face approaches, (b) and (c) Location of microseismic events that occurred during a 124-m advancement of the longwall panel in the non-HF and HF section, respectively.

3.3 Effect of regional HF campaign on mitigating microseismicity

Figures 5(b) and (c) depict the distribution of microseismic events prior to and following fracturing during the same longwall face advance distance. Over the course of the 124-meter advancement of the longwall face in the non-HF area, from 4832 to 4956 m, a total of 1234 microseismic events were captured in the roof of the longwall panel. These microseismic events were concentrated within a range of 200 meters ahead and 750 meters behind the longwall face, indicating that mining-induced seismic events occurred up to 200 meters ahead of the longwall face and that roof rupture occurred as far back as 750 meters. Notably, a significant number of microseismic events occurred in the roof of the 122106 gob, despite the fact that it had been mined out two years prior and was considered to be largely stable. This observation suggests that mining activity in the 122108 panel significantly disturbed the rock strata above the 122106 gob.

4 CONCLUSION

The results of this study indicate that both local and regional HF campaigns can effectively reduce the front abutment and side abutment pressures generated by the mining of a longwall panel, making them a promising approach for ground control in areas where high mining-induced stresses are present. Furthermore, regional HF has been shown to significantly reduce the occurrence of microseismic events resulting from the fracturing of thick, strong rock strata above the gob area of a longwall panel, which can lead to dynamic loading and coal bursts. Therefore, regional HF represents a promising solution for the prevention of coal bursts.

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