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Interpretation of the extent of hydraulic fracturing for rockburst prevention using microseismic monitoring data

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ABSTRACT

As the mining depths increase, an increasing number of deep coal mines in China encounter frequent intense rockburst problems. Conventional destress measures, employed effectively in shallow mines to reduce rockburst risk, are not suitable to deep coal mines because they are labor-intensive and time-consuming and hence are costly. Hydraulic fracturing in coal seams before mining a particular area has been considered as an effective destressing method for rockburst prevention. This paper focuses on using microseismic data to evaluate the extent of hydraulic fracturing in coal seams. To that purpose, innovative methods are proposed to process and interpret microseismic monitoring data. The proposed methods consist of an improved HHT method for signal filtering, an improved time-window energy eigenvalue method for first arrival picking, and a four-channel combined algorithm for seismic source location determination. Using the elaborate signal processing and interpretation methods, high-precision source locations of microseismic events recorded in a field hydraulic fracturing test at Huafeng Coal Mine are obtained. Microseismic event frequency and energy contours are plotted to characterize the fracture development and propagation process. The interpretation method was successfully applied in the coal seam hydraulic fracturing tests. Direct field observation and stress monitoring were also conducted to verify the results by the microseismic data interpretation method. Compared with conventional monitoring techniques such as stress monitoring and direct field observation, microseismic monitoring can cover a large monitoring volume with a high response sensitivity and it can capture the spatial-temporal fracture evolution process easily. It provides a practical approach to quantify the extent of hydraulic fracturing in coal seams for rockburst prevention.

1. Introduction

Rockburst is one of the most dangerous dynamic hazards in deep mines (Cai, 2013; Li et al., 2013; Hou et al., 2013; Kaiser and Cai, 2012). In recent years, an increasing number of coal mines in China have encountered intense rockburst problems as the mining depth reached one kilometer (Jiang et al., 2013, 2014). Frequent rockbursts present serious threats to mine safety and production, and various measures have been taken to prevent and mitigate rockburst damage. Conventional rockburst prevention techniques focus on a small volume using destress drilling and blasting. These measures, although effective, are labor-intensive and time-consuming, which make them less suitable for deep mines with frequent rockburst problems. Cost-effective technique for rockburst prevention is urgently needed to enhance safety in deep mining.

Hydraulic fracturing has successfully applied to the prevention of coal and gas outbursts and control of roof stability in coal mines (Altounyan and Taljaard, 2001; Feng et al., 2015; Huang et al., 2012; Jiang et al., 2015). The hydraulic fracturing technique was first proposed in 1947 for oil and gas stimulation (Montgomery and Smith, 2010). Coal and rock can be weakened using hydraulic fracturing through the creation of a large number of fractures,

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which is helpful to reduce and redistribute stress. Coal permeability can be greatly enhanced due to fracture development; as a result, gas can be extracted more easily from the coal seams. Hydraulic fracturing is also used to condition rock masses in block caving and for in-situ stress measurement (Zhao et al., 2013).

Few literatures exist on applying hydraulic fracturing for rockburst prevention in underground mines and evaluating the results of hydraulic fracturing for that purpose. Current methods for evaluating the effect of hydraulic fracturing include laboratory testing, numerical modeling, and field monitoring of water pressure and stress (Kim and Moridis, 2015; Li et al., 2013; Shapiro et al., 2006). Conventional field evaluation methods are restricted to their monitoring volume and accuracy. In the oil and gas industry, microseismic monitoring is typically used to evaluate the effect of hydraulic fracturing, which includes recording induced microseismic events, inversing the source locations, onset time and seismic magnitude (Clarkson and Beierle, 2011). Then the fractures can be characterized quantitatively by identifying their spatial form and distribution (Murdoch and Slack, 2002; Power et al., 1976; Sasaki and Kaieda, 2002; Sun et al., 2016). In coal mines, microseismic monitoring has been employed to predict rockburst, coal and gas outburst, and water inrush (Jiang et al., 2007). Because the volume, medium, mechanism and goal of hydraulic fracturing in coal mines and, oil and gas industry are totally different, the microseismic evaluation method used in the oil and gas industry cannot be directly introduced to evaluate the effect of hydraulic fracturing for rockburst prevention in coal mines. Hence, a specific microseismic data processing and interpretation approach for coal mining is needed to be investigated.

Hydraulic fracturing tests were conducted at Huafeng Coal Mine in Shandong Province, China, for mine-wide rockburst prevention (Feng et al., 2015; Jiang et al., 2015; Huang et al., 2015). Coal seams and roofs were hydro-fractured to promote strength weakening, energy release, and stress reduction and transfer. This paper focuses on developing innovative methods for microseismic data processing and interpretation. Using the processed high quality microseismic data, the extent of hydraulic fracturing at the test site is evaluated quantitatively.

2. Field test of hydraulic fracturing in coal seams

2.1. Site description

Huafeng Coal Mine in Shandong Province in China has a history of rockburst and a total of 108 intense rockbursts have occurred in the No.1 mining district since 1992, causing casualties and economic losses. Conventional destress measures such as destress drilling and blasting cannot prevent and control rockbursts in the mining district effectively. As the gob areas in the No.1 mining district increase constantly, rockburst risk increases in the remaining longwall panels.

A project using staged hydraulic fracturing in coal seam LW1412 before mining was initiated for testing the hydraulic fracturing technique for mine-wide rockburst prevention. Because this first step of the project was to evaluate the extent of hydraulic fracturing using microseismic monitoring, only a small test area was considered. The hydraulic fracturing test location is shown in Fig. 1. LW1412 is a longwall panel in the No.1 mining district with a dimension of 2200 m $\times$ 157 m and an average overburden depth of 1100 m and an average coal seam thickness of 6.2 m. Fully mechanized top coal caving mining method is adopted to mine LW1412. The coal seam's uniaxial compressive strengths (UCS) range from 10.8 to 25.5 MPa, and the laboratory test results indicated that the coal is burst-prone.

2.2. Process and monitoring of hydraulic fracturing in coal seam

The hydraulic fracturing test was carried out in the tailgate of LW1412. Three 94-mm diameter hydraulic fracturing boreholes were drilled in the coal seam at a spacing of 8 m and the hole depths ranged from 38.9 to 60 m (Fig. 2). Based on the success of hydraulic fracturing monitoring and evaluation in the oil and gas industry (Warpinski et al., 2012; Abdulaziz, 2014), we adopted the microseismic monitoring technique to evaluate the extent of hydraulic fracturing in the coal seams. A high-precision microseismic monitoring system, developed at the University of Science and Technology Beijing (USTB), was used. The system had 12 channels (12 geophones) per substation with a geophone frequency range of 40–320 Hz and a sampling frequency range of 0.2–10 K. The source location accuracy was 4 m.

Four 94-mm diameter microseismic monitoring boreholes were drilled in the coal seam. The spacing between two adjacent holes was 2 m (Fig. 2). M1 to M6 (blue dots) in Fig. 2 denote the installation locations of the geophones and two geophones as a group were placed in each location. The geophones were sent into the boreholes by a wire rope and a pulley, and were fixed in the boreholes by spring clamps shown in Fig. 3b. An underground monitoring station (Fig. 3a) was placed near the hydraulic fracturing site. In order to better understand and verify the extent of hydraulic fracturing, stress monitoring sensors were also installed in the field test. Six 42-mm diameter boreholes were drilled in the coal seam at a spacing of 4 m in which six stress meters (S1 to S6) were installed with a measuring range of 0–30 MPa and a sensitivity of 0.01 MPa (Fig. 2).

The hole packer of the hydraulic fracturing system consists of two single 2-m-long packers on both sides of a 1-m-long fracturing segment (Fig. 4). The hole packer works when filled with high pressure water through a rubber hose and it can work under a maximum pressure of 40 MPa. The fracturing pump and hole packers used in the test are shown in Fig. 5.

In the subsequent discussion, the mechanism of microseismic events and their response characteristics are studied first, followed by the evaluation of the hydraulic fracturing extent using the obtained data.

3. Microseismic event characteristics in coal seam hydraulic fracturing

3.1. Characteristics of microseismic event signals in hydraulic fracturing

The occurrence mechanisms of fracturing-induced, natural, and mining-induced microseismic events are different. In hydraulic fracturing, the generation of microseismic activities is mainly caused by tensile failure occurring around hydraulic fractures. Many small tensile fractures initiate and propagate around the tips of high pressure water paths until major fractures are formed in the coal seam. During the formation of the major fractures, microseismic events are generated and seismic waves propagate in the form of elastic waves. By monitoring the wave signals, seismic source locations and the event occurrence time can be determined. These seismic sources indicate the fracture locations and the dynamic fracture development process.

Most large microseismic events in mining are generated by shear failure of coals and rocks. The microseismic signals of shear failure are characterized by low frequency components and a broad frequency band. In hydraulic fracturing, microseismic events are generated once the effective tensile-stress-induced by high pressure water reaches the coal's tensile strength. As a result, the coal seam experiences brittle failure and energy release. In this case, the