Applications of Microseismic Monitoring in China's Underground Coal Mines

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ABSTRACT

Longwall and continuous mining are prevalent methods employed by Chinese underground coal operations. The main ground control challenges include roof skin deformation, roof collapse, and outbursts of coal, gas, and water. Microseismic monitoring provides valuable information on rockmass behavior and fracture propagation caused by stress redistribution, active geological structures, or gas build up within the coal strata and the surrounding rockmass. Collecting and assessing seismic data has proven to be an instructive tool for engineers to better assess ground conditions and mitigate seismic hazards associated with mining. The development of intrinsically safe and explosion proof certified seismic monitoring equipment has revolutionized China's underground coal mines. The use of this technology allows for the optimization of gas drainage at an increased rate of two at a 50% higher purity without any increase in drilling costs. Microseismic monitoring can also be used in identifying seismically active faults and shear zones. This information can be used to assess and revise mining strategies to improve safety and ground stability.

INTRODUCTION

Microseismic monitoring has been employed routinely in hard rock mines for more than 40 years (Alexander and Trifu, 2005). The technology has also been applied in research studies carried out in coal mines (e.g., Luo et al., 1998; Gale et al., 2001; Westman et al., 2001). However, the difficulties associated with the maintenance of seismic sensor arrays in a rapidly advancing longwall mining environment have delayed its implementation in this environment.

In the United States, rock mechanics is called upon to improve safety by addressing any potential design deficiencies (Heasley, 2011). While microseismic monitoring has been part of the ongoing research, the transfer of this technology to the industry remains largely undeveloped. In China, on the other hand, the need for enhanced work safety through a better understanding of the rockmass conditions under a fast mining extraction rate has led the Chinese mining industry to fast track the use of microseismic monitoring over the past few years. This study reports on the use of this technology in China's deep coal mines, outlining some applications as well as the results obtained.

INTRINSICALLY SAFE AND EXPLOSION PROOF SEISMIC SYSTEM CONFIGURATION

The general configuration of a microseismic monitoring system operating in a coal mine is similar to that of a system employed by any hard rock mine. The principal system components are as follows:

- Seismic sensors, which record the ground motions generated by the stress released during the fracturing process. Seismic sensors can be geophones, which record ground velocity, or accelerometers, which record acceleration. The 2D layout of the coal operations makes it very difficult to install seismic sensors in a 3D array configuration.
- Recorders, which convert the seismic signal from analog to digital.
- Time synchronization equipment, including a central or master time server and time receivers that provide time stamping of the acquired data.
- Data communication equipment, consisting of twisted copper cables from sensors to the recorders, and fiber optics from recorders to the central acquisition workstation.
- Seismic acquisition and processing workstation, which acquires and processes the seismic data in continuous and/ or triggered mode. Seismic processing software can provide automatic and manual results, subsequently allowing for their interpretation, visualization, and reporting.

Deep coal mines require a sensor array that can effectively record and determine small fracturing corresponding to moment magnitude below zero ($M_w < 0$). The potential presence of methane imposes major restrictions on the installation and operation of underground systems. Most of the coal mines in the United States can deploy recording and acquisition equipment in ventilated areas containing fresh air, leaving only the sensors placed in methane exposed areas. Sensors, therefore, must be Intrinsically Safe (IS) and connected to the recorders through IS barriers.

In China, however, there are often no certified fresh air areas in deep coal mines. This is why recorders must also satisfy explosion proof requirements. As such, in addition to the IS barriers, the junction boxes containing seismic recorders are also explosion
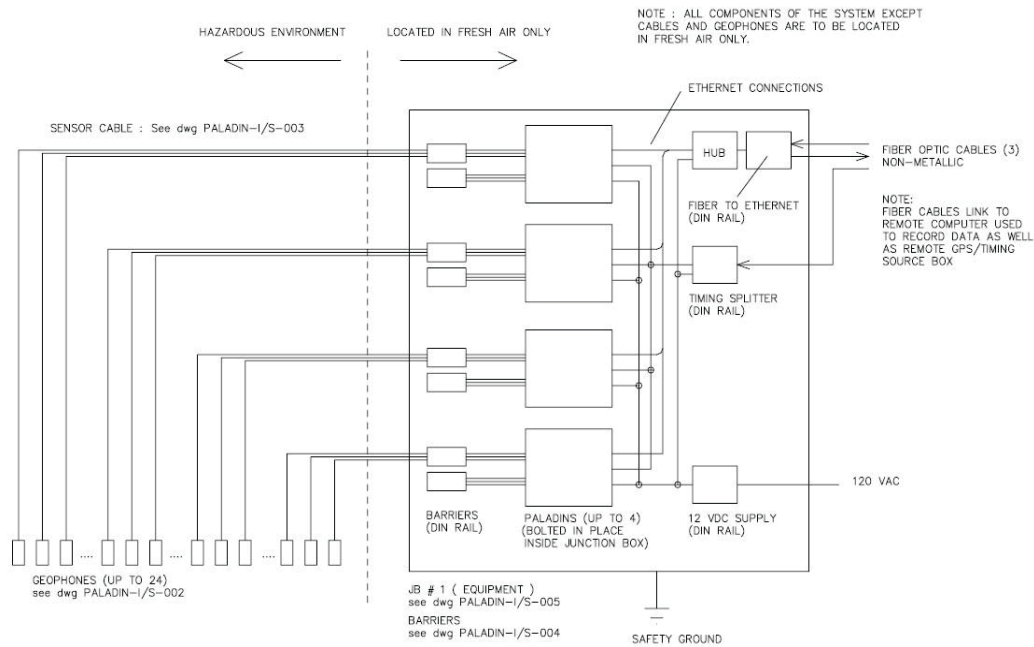
Figure 1. Intrinsically safe MSHA-certified seismic system configuration; seismic recorders must be located in ventilated, fresh air areas.
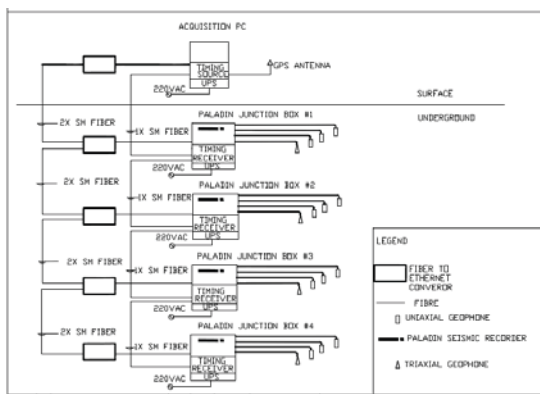

Figure 2. Intrinsically safe and explosion proof MA-certified seismic system configuration; the IS barriers are installed inside explosion proof junction boxes, which allow seismic recorders to be located in non-ventilated areas.

proof and specially designed to withstand the accidental release of energy stored inside these recorders.

Figure 1 shows a system configuration provided by ESG Solutions with IS sensors, as certified by the U.S. Mine Safety and Health Administration (MSHA). Figure 2 presents a configuration also offered by ESG Solutions, with IS sensors and explosion proof recording hardware certified by China's Mining Products Safety Approval and Certification Center (MA). Worth noting, the MSHA certification is not directly transferable to China. Regardless of the similarity between some of the technical specifications, the MA certification demands independent testing carried out at one of the MA Centers.

While the MSHA certification does not require expensive explosion proof junction boxes for the underground equipment, the MA certification offers the possibility of installing this equipment closer to the sensor array. This has the direct effect of reducing the cable cost, electrical interference, signal attenuation, and various maintenance problems associated with running long twisted copper cables, thus allowing an improved signal quality.

SEISMIC ARRAY DESIGN IN UNDERGROUND COAL ENVIRONMENTS

The type and sensitivity of seismic sensors as well as the array configuration are essential in the performance of a microseismic system in coal mines. One issue to consider when designing a microseismic monitoring system in coal is the rockmass characteristics. Coal is a soft rockmass characterized by a relatively lower quality factor (Q) and slower P- and S-wave velocities compared to the hard rockmass encountered in metal mines. These characteristics lead to a significantly higher attenuation of the high frequency waveform in coal strata, even when recorded at a short distance from the seismic source. Accelerometers are generally more sensitive for detecting higher frequencies, characteristic to weak, lower magnitude seismic events, while geophones are more suitable for the recording of the lower frequency range, appropriate for relatively stronger, higher magnitude seismicity (Alexander and Trifu, 2005). In soft rockmass environments, however, high sensitivity geophones are preferred over accelerometers in underground sensor arrays because of the significantly higher attenuation of the acceleration with distance.

Figure 3 presents an example of the geophone array installed by ESG Solutions at Wudong coal mine, a longwall coal mine in Xinjiang Province, China. Geophones are installed in the south roadway of the 620#43 longwall panel (20 m width) and north roadway of 655#45 longwall panel (25 m width). The inter-sensor distance along both roadways is about 150 m. These sensors provide a frequency bandwidth from 6 to 1,000 Hz, with
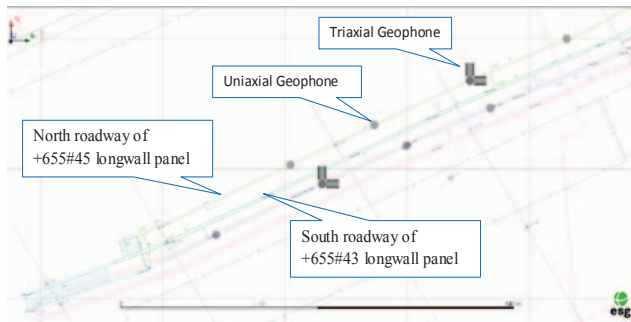
Figure 3. Geophone array at Wudong coal mine.

a sensitivity of 51 V/m/s (undamped). Such an array can monitor seismic events between M_w -1.5 to 2.

Another challenge in the installation of seismic sensors in underground coal mines is that most of these mines have only one working level that follows the quasi-horizontal coal seam. Consequently, underground sensors can be installed only in accessible areas around the coal panels, which results in a planar sensor array. In case of a planar sensor array, event location errors in the depth coordinate will be higher than those in the horizontal coordinates. Moreover, event locations based on first P- and S-wave arrivals at uniaxial sensors cannot resolve the intrinsic symmetry that comes with a planar array. Figure 4 shows the expected event location errors at Wudong coal mine for a uniaxial geophone array. As seen in the right hand side of this figure, such an array will not be able to resolve whether seismic events occur above or below the array. It is strongly recommended to add triaxial geophones, because they can provide additional information through wave polarization analysis, which can resolve the above uncertainty. Alternatively, a three-dimensional array can be installed but this will increase the drilling costs. A preliminary array design will evaluate the array performance in terms of sensitivity and event location accuracy, based on the number and type of sensors, as well as their position with respect to the monitoring area. The results depend on the quality of the geological and rockmass information available.
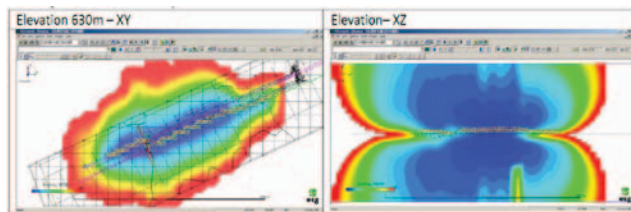

Figure 4. Simulation results estimate seismic event location errors at Wudong coal mine between 15 m (blue) and 200 m (red).

SEISMIC DATA PROCESSING AND INTERPRETATION

Data processing includes seismic event identification and location, along with the evaluation of its magnitude and other source parameters. A seismic waveform analyzer (WaveVis™)

allows the users to view the seismic waveforms, pick the P-and S-wave arrival times, perform event location, spectral analysis, etc. Typical waveforms and amplitude spectra are shown in Figure 5 using the WaveVis™ software for a seismic event with M_w -0.3 that occurred at Wudong coal mine on September, 19, 2011, at 13:45:20 local time. Amplitude spectra indicate that frequencies above 100 Hz are heavily attenuated.
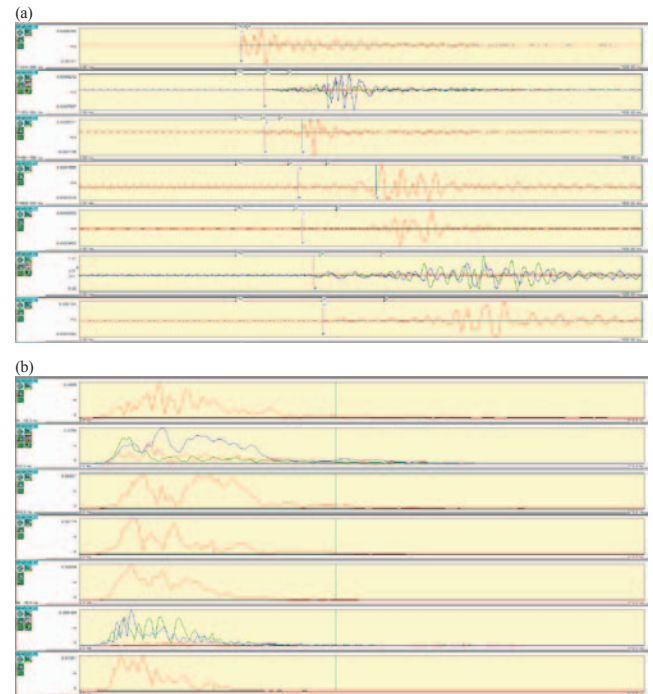

Figure 5. (a) Typical waveforms and (b) amplitude spectra for a M_w -0.3 seismic event that occurred at Wudong coal mine. The vertical line on the amplitude spectra marks 100 Hz.
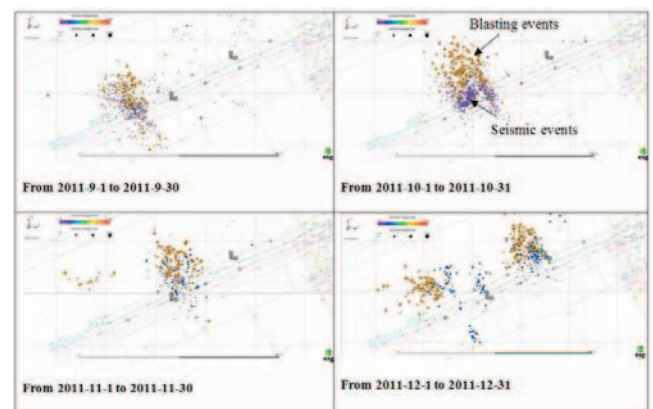

Figure 6. Plan view of monthly seismic (blue) and blasting (yellow) activity at Wudong coal mine from September to December 2011.

The seismic visualizer (SeisVis™) provides an interactive, three-dimensional display of event locations, magnitudes, and other source parameters with respect to the site geometry. Figure 6 presents an example of the SeisVis™ plan view option, which illustrates the monthly seismic and blasting events at Wudong coal mine from September to December 2011. This function can assist the ground control engineer to record blasting and create images of the roof subsidence process following the support retreat sequence. Unexpected clusters of microseismicity and the occurrences of large seismic events indicate potential ground hazards in certain areas.

CASE STUDY #1—GAS DRAINAGE OPTIMIZATION

Xinzhuangzi is a gassy, longwall coal mine in central China. In order to prevent coal and gas outbursts, and control gas emissions during mining, it is required to partially drain the gas from the coal seam. The main challenge of gas drainage is to first identify the areas of high gas concentration in order to improve gas extraction efficiency. Based on research work carried out at Huainan coal mine, Yuan and Liu (2003) proposed a model in which gas accumulates in a cavity above the roof. A microseismic monitoring system was installed at Xinzhuangzi mine to monitor the facture development in the roof strata.

Following a three-month monitoring period, from April to July 2009, the clustering of microseismicity allowed the identification of a circular shaped fracture region in the mine roof, as shown in Figure 7a (Chao, 2011). This result closely matches the cylindrical circular model (Figure 7b) that characterizes the roof cavity collecting gas that has migrated from the coal seam through the surrounding fractures. Subsequently, an optimized coal gas drainage procedure was designed to extract coal gas from the respective cavity.

Figure 8 plots the gas extraction rate and purity after the optimization of the gas drainage scheme. Compared to the previously used conventional gas drainage procedure, the optimized scheme improved the gas extraction rate from 3-8 m^3/min to 5-15 m^3/min. Also, the optimized procedure raised the gas purity by approximately 50%, all without any increase in drilling costs (Chao, 2011).

CASE STUDY #2 —FAULT IDENTIFICATION AT XINZHUANGZI COAL MINE

Seismic monitoring is a very reliable tool in identifying seismically active, indefinite geological features within the mining zone or a better characterization of already mapped structures. A seismically active shear zone or fault can result in a cluster of microseismicity and occasional large magnitude events. Any seismic event associated with a geological structure can be further analyzed and used in conjunction with other available geological data to identify and characterize seismically active structures, aiming to improve mining strategies around these zones of potential instability and hazardous conditions.
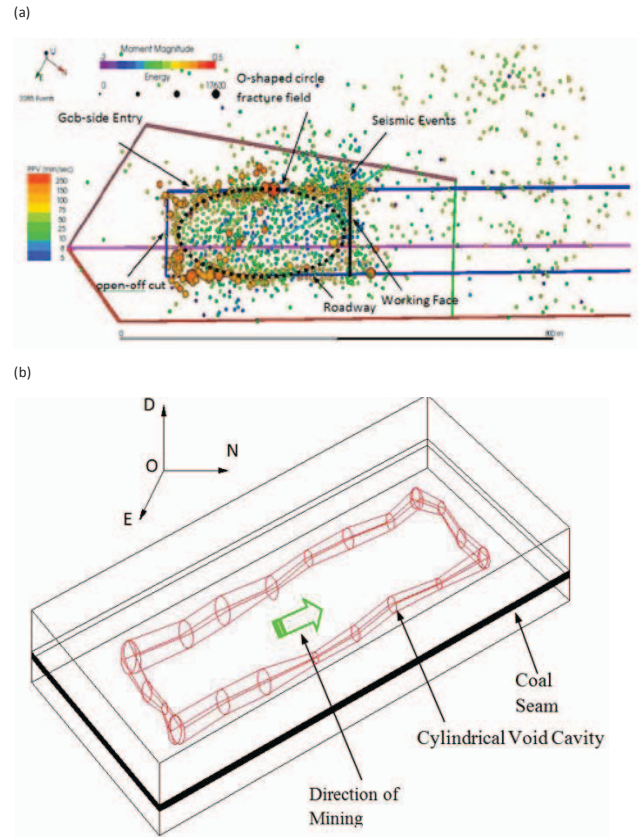
(a)

(b)

Figure 7. (a) A seismic clustering pattern identifies a circular shaped fracture zone in the roof of Xinzhuangzi coal mine, matching the (b) model of a gas cavity.
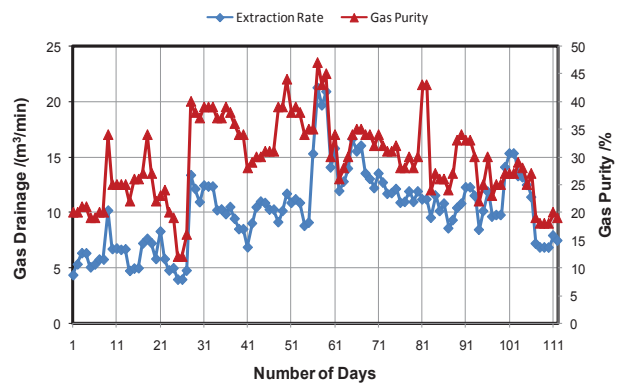
Figure 8. Gas drainage rate and purity after optimization.

Figure 9 presents the result of a two-dimensional active seismic study carried out by Anhui University of Science and Technology, in which two faults were explored: F10-5(10) and Fa. The seismic moment density, calculated from passive microseismic source parameters is shown in Figure 10, underlining the areas of the Fa and F10-5(10) faults (Chao, 2011).

The comparison of Figures 9 and 10 proves that passive and active seismic monitoring results are consistent with each other. It is worth noting, however, that only passive monitoring can identify active faulting through the presence of induced seismicity on pre-existing geological features. Additionally, passive monitoring provides continuous, real-time imaging of active fault zones, while active seismic monitoring offers static results, only from time to time. As such, the objective of passive monitoring is the identification of new, unknown faults and the characterization of active faulting. This allows an evaluation of the impact of faulting onto mining, thus enabling ground control personnel to suggest more effective support solutions.
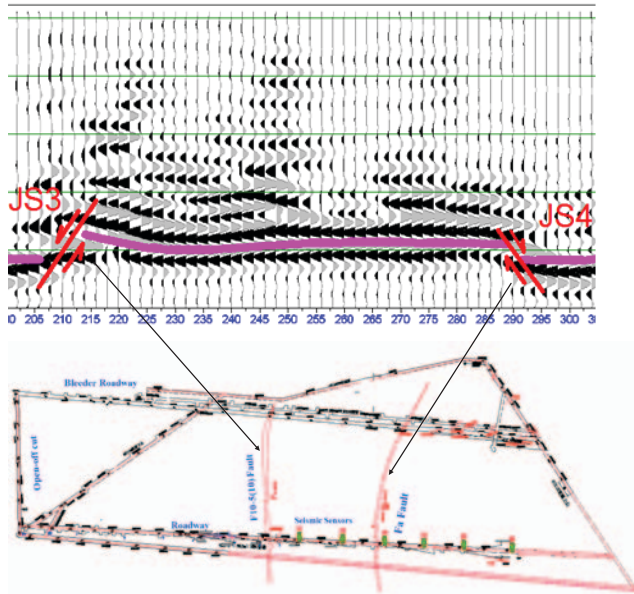

Figure 9. A two-dimensional active seismic survey indicates the presence of two faults at Wudong coal mine, JS3, or F10-5(10), (bottom left), and JS4, or Fa, (bottom right).
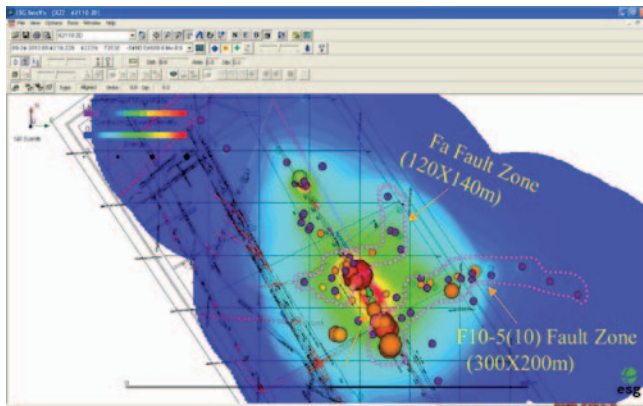

Figure 10. Seismic moment density evaluated from microseismic source parameters for events in the areas of the Fa and F10-5(10) faults at Wudong coal mine. (a) (b) (a) (b).

CONCLUSIONS

This overview documents several applications of microseismic monitoring technology in underground coal mines. The presence of methane and unventilated areas require IS and explosion proof equipment. Ideally, the sensors are installed in close proximity to the advancing coal face. However, the relocation of seismic monitoring hardware is not trivial, reason for which the redeployment of the sensor array needs to be carefully planned. Geophone arrays are recommended due to reduced attenuation of ground velocities compared to accelerations, even for small source-sensor distances. While uniaxial geophones offer the best return on cost vs. performance, the planar layout, due to the presence of only one mining level, requires the use of at least a few triaxial geophones in order to eliminate the intrinsic symmetry in seismic event location. The use of microseismic monitoring allows the identification of the effects of stress redistribution within the coal seam. In particular, the technology is presently used in Chinese coal mines for the optimization of gas drainage, identification of new faults and shear zones, as well as characterization of active faulting. Simplex ray tracing and migration algorithms are currently under development to improve the depth accuracy of event locations carried out using planar sensor array geometry.

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