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Seismic monitoring and analysis of excessive gas emissions in heterogeneous coal seams

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ABSTRACT

Uncontrolled and excessive gas emissions pose a serious threat to safety in underground coal mining. In a recently completed research project, a suite of monitoring techniques were employed to assess the dynamic response of the coal seam being mined to longwall face advance at Coal Mine Velenje in Slovenia. Together with continuous monitoring of gas emissions, two seismic tomography measurement campaigns and a microseismic monitoring programme were implemented at one longwall top coal caving panel. Over 2000 microseismic events were recorded during a period of four months. Over the same period, there also was a recorded episode of relatively high gas emission in the same longwall district. In this paper, a detailed analysis of the processed microseismic data collected during the same monitoring period is presented. Specifically, the analysis includes the spatial distribution of the microseismic events with respect to the longwall face advance, the magnitude of the energy released per week and its temporal evolution. Examination of the spatial distribution of the recorded microseismic events has shown that most of the microseismic activity occurred ahead of the advancing face. Furthermore, the analysis of the gas emission and microseismic monitoring data has suggested that there is a direct correlation between microseismicity and gas emission rate, and that gas emission rate tends to reach a peak when seismic energy increases dramatically. It is believed that localised stress concentration over a relatively strong xylite-rich zone and its eventual failure, which was also identified by the seismic tomography measurements, may have triggered the heightened microseismic activity and the excessive gas emission episode experienced at the longwall panel monitored.

1. Introduction

Gas outbursts, which are also referred to as uncontrolled gas emissions, pose a serious threat to the safety of underground coal mining throughout the world. Since the first documented coal and gas outburst occurred in the Issac Colliery in France (1843), as many as 30,000 outbursts have occurred in the world coal mining industry (Lama and Bodziony, 1998). As the understanding of the structural conditions and mechanisms leading to gas outbursts improve, more effective preventative measures are being developed and implemented. However, gas outbursts in coal mining still occur, especially in China, where 288 miners died from these events in 2011 alone.

An outburst can be defined as spontaneous and violent ejection of gas from a solid coal surface. Depending on the seam gas composition, the ejected gas can sometimes be a mixture of methane and carbon dioxide, and normally one component predominates (Beamish and Crosdale, 1998). For some powerful outbursts, the ejection of gas is normally accompanied by a considerable volume of failed coal. During the process of an outburst, a sudden state change of the rock–coal–gas system from static to dynamic occurs along with the release of a significant volume of gas over the duration (Choi and Wold, 2004). It has been reported that the ejected coal and released gas can be as much as several hundred tonnes and thousand cubic metres in some catastrophic outbursts (Lama and Bodziony, 1998).

Farmer and Pooley (1967) suggested that outbursts only occur in districts subject to severe tectonic movement, hence their association in many places with depositional structures such as folds, faults, rolls and slips and in particular with rapid fluctuations in the seam thickness. Hargraves and Upfold (1985) have also concluded that microstructurally altered coal will lead to higher outburst tendency. Thresholds of 9 m^3/tonne for CH_4 and 6 m^3/tonne for CO_2 have been used in the Sydney Basin, Australia, to indicate outburst prone conditions (Beamish and Crosdale, 1998). In China, 10 m^3/tonne methane is used as the outburst threshold and the gas contents in the mines

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experiencing outbursts are higher than 10 m^3/tonne, and generally range from 15 to 25 m^3/tonne coal (Cao et al., 2001).

It is suggested that outburst-prone coal exhibits low permeability. Lama and Bodziony (1998) found that coal seams with in situ permeability >5 mD are not liable to outburst. Other studies (Hargraves, 1993; Shepherd, 1995) have concluded that stress is an additional contributing factor to outbursts. Kidybinski (1980) took into consideration the gas content and flow, stress, and coal failure to explain his theory of gas outbursts. Williams and Weissman (1995) referred to the outbursts frequently encountered under Australian conditions and stated that "the most important parameter is gas desorption rate, in conjunction with the gas pressure gradient ahead of the face". Wold and Choi (1999) developed a coupled geomechanical-flow model and applied to field conditions at a number of Australian coal mines. They concluded that pore fluid pressure and its gradient, which is a function of the reservoir pressure, desorption pressure/isotherm, absolute permeability and relative permeabilities rather than gas content is a key determinant of outburst initiation risk. They further concluded that, contrary to expectations, coal seams rich in CO_2 were not more outburst prone than seams rich in CH_4. It was suggested that, because of the higher adsorption capacity of coal to CO_2 relative to CH_4 at the same partial pressure, outbursts tend to be initiated at higher gas contents for CO_2 compared to CH_4 (Choi and Wold, 2002).

Although less often, the European coal industry still experiences gas outburst events, which lead to loss of production, and even loss of life. For example, the Santa Lucia mine, which exploits the steeply dipping thick seams of the Ciñera–Matallana coal basin in the North of León Province in Spain, experienced its last major outburst recently in October 2013, where six miners lost their lives. In 2009, 40 metres length of a development heading in the virgin section of the coal seam was subjected to a coal and gas outburst in the same coalfield. In Slovenia, Coal Mine Velenje experienced its last major coal and gas outburst in 2003, when two miners were killed, and the longwall district in question lost one month's worth of production, which was worth nearly US$4.5 million and 4% of the total income of the mine in that year. Besides such major incidents, the Velenje mine experiences at least one excessive gas emission event and a resulting stoppage each year, losing 5 days' worth of production (35,000 tonnes of coal) per event on average. High gas emission rates at the production faces require high rate of ventilation and energy consumption.

A recently completed research project funded by the European Commission Research Fund for Coal and Steel (RFCS) aimed at developing techniques to identify gas outburst conditions and mitigate against them in thick/ultra-thick seam coal mining. A suite of techniques, including borehole gas pressure, concentration and time-lapse seismic tomography, as well as microseismic monitoring and ventilation measurements have been employed to monitor the dynamic response of the coal seam being mined to longwall face advance at Coal Mine Velenje. Fortunately, there were no outburst events during the three year research period, however, the mine experienced the occasional excessive gas emission at its production levels, and one of these events was observed at the experimental Longwall Top Coal Caving (LTCC) district where the above mentioned monitoring programme was implemented. This paper presents a detailed analysis of the processed seismic tomography and microseismic monitoring data leading to and post this excessive gas emission incident. Specifically, the analysis includes the spatial distribution of the microseismic events with respect to the LTCC face advance, the magnitude of the energy released per week and its temporal evolution. An explanation for this excessive gas emission episode is proposed and also confirmed by the results of active seismic tomography campaigns conducted in the same study area.

2. Background

Early studies have shown that seismic measurements can be promising tools for defining stress redistribution around an area of active mining. Anomalous seismic wave velocity distributions may be an indicator for potential hazards and successful velocity imaging could help identify the conditions leading to such hazards in underground mines. The laboratory measurements of seismic wave velocity and its relationship with CO_2 content (Xue, 2005) suggests that time-lapse seismic tomography can be useful to image gas content and pressure changes in coal seams. Furthermore, passive seismic monitoring, which is continuous, can identify and assess hazardous conditions in real time.

Seismic velocity tomography is an established non-invasive technology used to investigate geological formations. By transmission of acoustic waves through the rock, lithological parameters and structural information can be gained. With active seismic tomography, the transmitters and the receivers of the seismic waves are placed on different sides of a block of rock or coal in the field. The result of the measurement is the distribution of the seismic velocity in a plane and tomograms are created by mapping this velocity distribution. Active sources have also been implemented repeatedly to image individual pillars in underground mines (Scott and Williams, 2004; Watanabe and Sassa, 1996). Tunnels have also been imaged to determine stress distribution around an excavation, implementing both passive (Maxwell and Young, 1996) and active sources.

In the early days, seismic tomography measurements have been used in coal mines mainly to detect voids, to image structures and/or old workings well ahead of planned developments (Hanson et al., 2002). This reduced the need to drill probe-holes. An earlier study was able to image velocity on a longwall panel and has shown that high velocity areas advanced with the longwall face (Kormendi et al., 1986). There are fewer large scale mine studies in the literature. Roof bolt mounted receivers have been used with a longwall shearer as the seismic source to image a section of a longwall panel mine in the western United states (Westman, 2001). This study has shown a correlation between averaged tomogram values and seismically active areas and demonstrated that the tomography system is capable of imaging heavy shield-leg loading and outburst-prone conditions prior to them disrupting the face operation. Recognising that outbursts are often associated with geological anomalies, active seismic tomography may be useful in detecting these anomalies and providing early warnings.

Underground coal extraction activities lead to continuous stress and pressure redistributions around mine openings. It has been well documented that dynamic failure of rocks is associated with detectable geophysical signals such as microseismic events (Cook, 1976; Sato and Fujii, 1988; Tang, 1997). The energy released in an outburst is from accumulated strain energy in the coal, roof or floor. Numerous factors have been stated to influence the occurrence of bumps, including properties of coal, geology (joints, folds, faults, etc.), mining induced stresses, strong sandstone beds in the roof, pillar size and shape, mining technique and mining rate (Westman, 2001). Therefore, microseismic monitoring has also been suggested as a potential approach to provide early warning and even prediction for rock bursts and gas outbursts (Flores, 1998; Shepherd et al., 1981).

Microseismic monitoring first gained wide application for rock burst prediction in hard rock mines. In a pioneering study of applying microseismic monitoring at gold mines in South Africa, Cook (1976) noted that mining-induced microseismic events tended to concentrate in the afternoon of a working day and on Thursday and Friday of a working week. Based on the observation of anomalous seismic behaviour, miners were successfully evacuated prior to a moderate rock burst at a zinc-mine in the US (Brady and Leighton, 1977). High-frequency seismic waveform was monitored prior to a rock burst event, which was believed to be a valid precursor (Archibald et al., 1990).

In recent years, and with the improvement of monitoring and interpretation techniques, microseismic monitoring has been accepted as a standard approach to understand and predict rock bursts in coal mines (Cai et al., 2014; Fujii et al., 1997; Kabiesz and Makówka, 2009; Lu et al., 2013). Li et al. (2007) suggested that rock bursts might induce high gas emission in underground coal mining. In Laohuitai coal mine, China, a few incidences of unusual