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STRESS CHANGE NEAR A MAJOR GEOLOGICAL STRUCTURE DURING LONGWALL MINING

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ABSTRACT: Stress state and geotechnical conditions often change significantly near major geological structures (e.g. faults, shear zones, dykes) in underground coal mines, which is the cause of most major mine instability and/or safety hazards including coal burst, roof falls, water inrush and gas outburst. In order to understand and quantify the stress state near major geological structures, an integrated study had been conducted in the vicinity of a dyke in an Australian underground coal mine. The field monitoring program included installing microseismic geophones, stressmeters and extensometers in the roadway roofs and coal pillars, aiming to obtain seismic and stress change data during longwall mining. The monitoring results indicate that the stress regime was clearly different on the inbye and outbye sides of the dyke. The inbye side had a much higher stress than the outbye side before and during the longwall mining. This study provided quantified field evidence that the stress concentration occurs near major geological structures. This stress concentration could lead to high strain energy concentration in the rib of a roadway, and hence increase the risk of coal burst.

INTRODUCTION

Coal burst (also called coal bump) is a violent collapse of coal walls and/or roofs occurring in underground coal mines. It may happen in development roadways, at the longwall face or at the chain pillars. Because it occurs suddenly with no or very little early warning, coal burst is particularly dangerous to mine personnel and mining equipment. Coal burst is a long-standing issue for underground coal mines in many countries all over the world. The first reported coal burst was recorded in the UK in 1783. Since then many countries including Germany, USA, Canada, Poland, Russia, India, China and Australia have experienced coal burst events, some sadly with the loss of lives. In Poland, 60% of coal mines have experienced coal burst with about 20 coal burst events per year (Kleczek and Zorychta, 1993). In China, the largest coal producer in the world, over 140 underground coal mines currently are coal burst prone. During 2011-2013, over 60 fatalities occurred in 17 coal burst related accidents in China (Pan, et al., 2013)

The occurrence of coal burst is relatively rare in Australia as the majority of underground mines are still relatively shallow. However, as mines in Australia are going deeper and moving into more challenging geotechnical conditions, the risk of coal burst is certainly on the rise. Some mines have experienced several apparent coal burst events where the mining depth has reached between 500 m - 600 m. Mines with strong massive roof conditions have also experienced pressure bumps and major weighting on the longwall support system.

Many coal burst events in both Australian and overseas mines have occurred near faults, dykes and other geological structures. Dynamic roadway instability events have occurred in several underground mines in New South Wales near dykes, thrust faults, and normal faults. Fatal coal burst incidents were reported overseas due to geological structures. For instance, the Qianqiu coal burst incident with 11 fatalities in China in 2011 was a direct result of the stress elevation by a thrust fault during mining. Faults, dykes and other geological structures are considered to be some of the key contributing factors to coal bursts.

The study of stress anomalies and geotechnical conditions near major geological structures is one of the key research areas for hazard identification and management in underground mining, not only for coal burst risk but also for broader applications in risk assessment and management (such as gas outburst, roadway stability).

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This paper presents a summary of the recent systematic study on monitoring the stress state near a major geological structure in an Australian underground coal mine. The work is part of a research project sponsored by the Australian Coal Association Research Program (ACARP) and the CSIRO. More details of the study can be found in Shen, et al., (2019) and Shen, et al., (2020).

FIELD MONITORING DESIGN AND INSTALLATION

Monitoring site

A comprehensive field monitoring program was designed to collect stress and seismic data in the vicinity of an identified major geological structure during actual mining. It is ideal that the monitoring site may be coal burst prone so that the monitoring data represents possible conditions found prior to coal burst. An Australian underground coal mine (referred to as “Mine A” hereafter) had been selected for the field monitoring.

Mine A uses the longwall extraction method to mine a 9 m thick coal seam where only the bottom 3.5 m – 4.0 m of coal is extracted. The current longwall panels are typically 400 m wide and 3 km long. The overburden depth ranges from 160 m to 380 m. The roadways are typically 5.5 m wide and 3.5 m high. Mine A was identified as a suitable site for a case study due to its unique geological and geotechnical conditions. The following key geological and geotechnical conditions exist in Mine A:

- A normal fault with a displacement between 1 m and 5 m and a dyke with a thickness ranging between 0.5 m and 3 m exist.
- Pressure bumps of various magnitudes have been recorded in the underground workings.
- A massive 15 m-20 m thick conglomerate exists in the immediate roof which influences the loading (stress) behaviour and periodic weighting is present in the main roof.

Monitoring plan

The selected monitoring site is located in Longwall (LW) 107 at Maingate B heading between cut-through (CT) No.9 and No.10 in an area of the panel intersected by the dyke. A vertical borehole was drilled from the surface to lower the instrumentation cables. Two logging stations were setup at the surface, one for microseismic data and the other for stress/displacement data. The stress/displacement data were remotely collected from the CSIRO’s office in Brisbane in real-time through an optical fibre network, while the microseismic data were recorded in real time and collected manually on site on a weekly basis. Underground, two monitoring stations were established on either side of the dyke (inbye and outbye) as shown in Figure 1. Figure 2 shows the sensor arrangement in a vertical cross-section at the inbye location, and those at the outbye location are very similar.

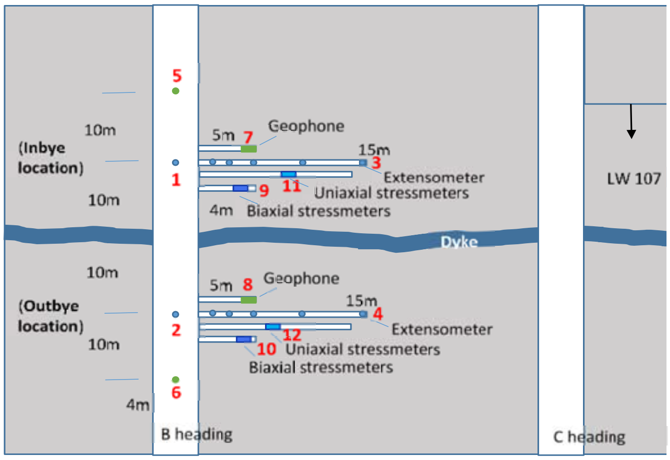

Figure 1: Plan view of inbye and outbye monitoring locations. Sensors are numbered in red

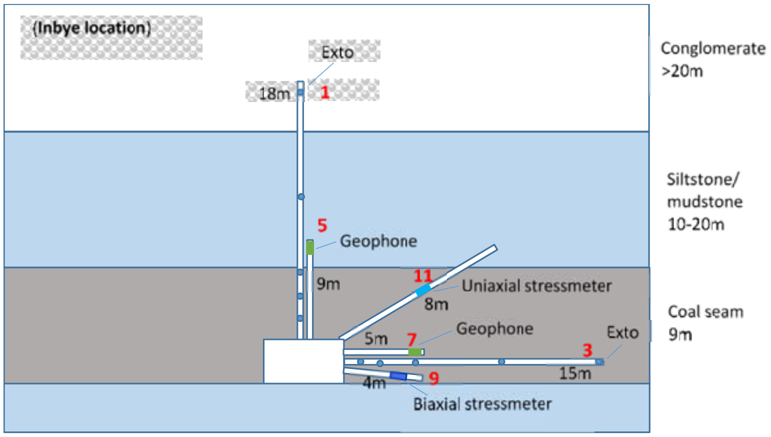

Figure 2: Vertical section inbye monitoring location

At the inbye monitoring station, two extensometers were installed, one in the roof, and one in the rib. Similarly, two geophones were also installed, one in the roof and one in the rib. To monitor the stress change, one uniaxial and one biaxial stressmeter were installed in the rib. The outbye monitoring station mirrored the inbye monitoring configuration. A total of 4 tri-axial geophones, 4 stressmeters and 4 extensometers were installed at the two monitoring stations. The discussion in this paper will be focused only on the stress and microseismic monitoring results due to page limitations associated with this paper. The displacement monitoring results are consistent with results reported in Shen, et al., (2019).

MONITORING RESULTS

One of the key objectives of the field monitoring program was to obtain quantitative evidence of the stress change around a major geological structure since the stress concentration is considered to be a key contributor to coal burst. In Mine A the targeted major geological structure was a sub-vertical dyke, dipping to the south at an approximate dip angle of 75° - 80°. It had a width of approximately 1.5 m at the monitoring location. Two identical sets of monitoring sensors (stressmeters, extensometers and geophones) were installed both sides of the dyke at a distance of 10-20 m. The aim was to directly compare the stresses and geotechnical conditions at the two sides during longwall mining, and hence quantify the influence of the dyke on the risk of coal burst.

Stress change

Uniaxial stressmeters

Two uniaxial stressmeters were installed in the pillar between roadway headings B and C, in two inclined boreholes drilled from the B heading. Stressmeter #11 was located inbye of the dyke at a distance of 10 m, whereas the Stressmeter #12 was outbye at a similar distance. Both stressmeters were installed at the borehole depth of about 6-8 m from the B heading. The uniaxial stressmeters only measure one-dimensional stress change. Because the stressmeters were inclined at an angle of 30° upwards, they actually measured the equivalent stress change in the direction of 60° from the horizon.

Figure 3 shows the measured stress change in the pillar in the period from the 25th November 2017 to the 23rd April 2018. This period covers the critical period when the longwall face travelled from 422m in front of the dyke through to when it was 226m past the dyke. The black curve in Figure 3 shows the longwall distance to the dyke, and the blue and red curves are the measured stress at the inbye and outbye locations.

Stress changes in the pillar could be observed starting from the 19th January 2018 when the longwall face was about 150m from the dyke. As the longwall mining approached the dyke, the stress change at both monitoring locations increased exponentially until the 14th February 2018 when the face passed by the dyke at a distance of 30m. The mining was then stopped for 12 days, and consequently no significant stress changes were recorded during this period. This demonstrates a close correlation between the mining progress and the pillar stress change.

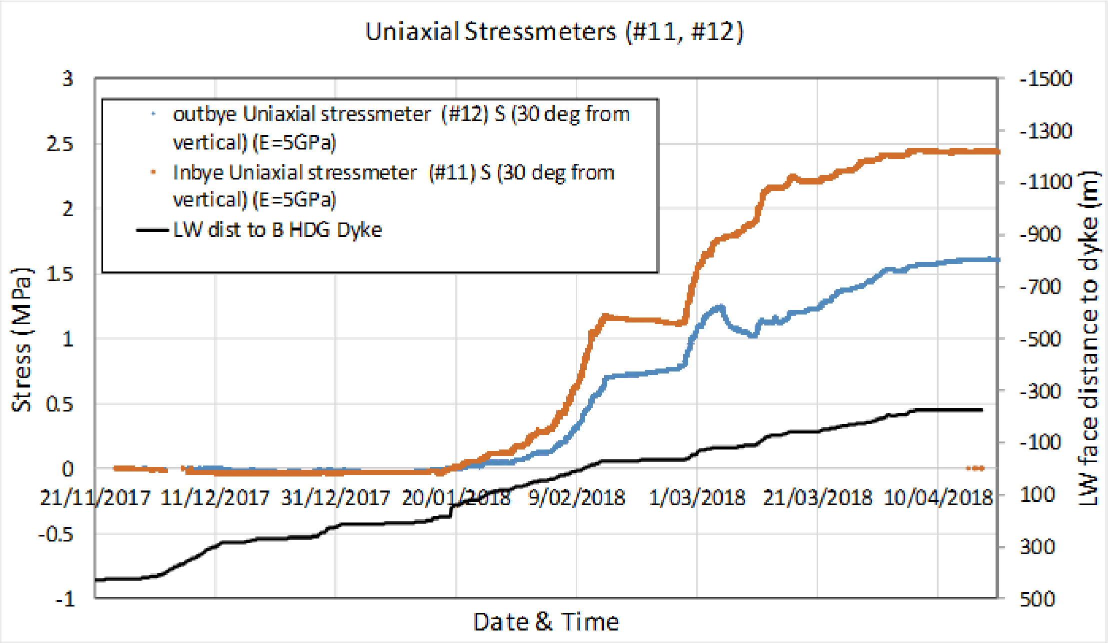

Figure 3: Measured sub-vertical stress change in the pillar at both sides of the dyke using uniaxial stressmeters.

When longwall mining was resumed on the 26th February 2018, the measured stress change continued to increase. It is interesting to note that, during the period from the 5thto the 15th March 2018 when the longwall face was some 80-90 m past the dyke, the outbye stress change dropped by 0.2 MPa while the inbye stress change continued to increase. This could have been caused by the shearing along the dyke during the caving process, which could have released the vertical stress outbye and increased the load inbye. The stress change rate slowed down gradually as the longwall face passed beyond the dyke by some 130 m.

An important observation is that the measured pillar stress increase at the inbye location is significantly higher than that at the outbye location. When the longwall face was 30 m past the dyke, the stress increases at the two locations were 1.2 MPa and 0.7 MPa, respectively. When the longwall was 200 m passed the dyke, these values were 2.4 MPa and 1.6 MPa. The overall difference in the stress magnitude at the inbye and outbye sides of the dyke was 30-40%. This highlights the significant influence of the dyke on stress re-distribution in its vicinity. During longwall mining, the dyke could have acted as a barrier for stress transfer due to the shear movement along the dyke. The dip direction of the dyke had a major influence on the stress concentration pattern around the dyke. The “hanging wall” of the dyke would take more stress than the “footwall”.

Biaxial stressmeters

Two biaxial stressmeters were installed, one at each of the two sides of the dyke. They were installed in two sub-horizontal boreholes at a depth of 4 m into rib, hence measuring the two-dimensional stresses in the pillar in a vertical cross section parallel to the roadway axis. Figure 4 shows the measured major principal stress change (P) and minor principal stress change (Q) in the rib from the outbye location. In this case, P was approximately in the vertical direction and Q in the horizontal direction. Unfortunately, the biaxial stressmeter at the inbye location appears to have malfunctioned and did not return any valid reading.

The measured stress changes from the outbye biaxial stressmeter in Figure 4 showed a similar trend to those in Figure 3 from the uniaxial stressmeters, but the magnitude of the stress changes was much higher. The measured vertical stress change was 8.5 MPa from the biaxial stressmeter, compared with the 1.6 MPa from the uniaxial stressmeter when the longwall face was beyond the dyke by some 226 m, both at the outbye side of the dyke. This huge difference could be partially caused by two factors: (1) The biaxial stressmeter was located in the roadway rib where a high stress concentration existed due to roadway excavation. The uniaxial stressmeter was installed in the roof coal above the rib, where the stress concentration should be much less. (2) The biaxial stressmeter measured the vertical stress whereas the uniaxial stressmeter only measured the stress at a 30° angle from the vertical direction.

Based on this comparison, the magnitude of vertical stress change in the rib could be about five times the magnitude of measured stress changes in the roof coal using the uniaxial stressmeters. If the same proportion holds for the inbye location as for the outbye location, the total stress increase at the inbye location could be as high as 12 MPa. This would be on top of the existing rib stress at an overburden depth of 280 m at the monitoring location, which is greater than the in situ vertical stress of 7 MPa. The resultant total stress of >19 MPa in the rib is close to or exceeds the uniaxial compressive strength of the coal, and hence may cause localised failures.

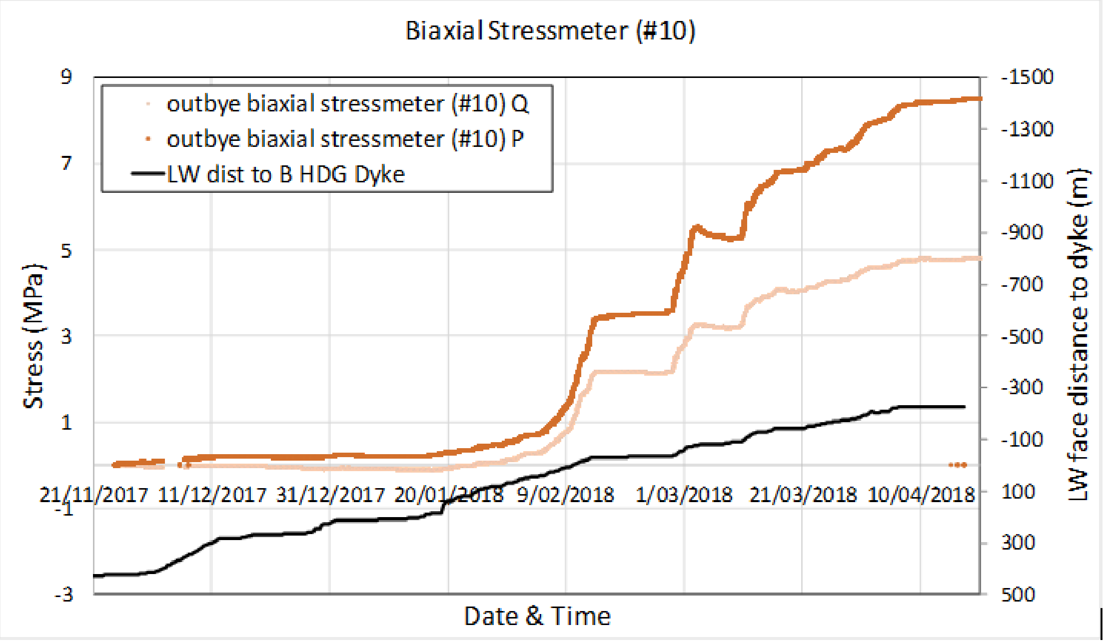

Figure 4: Measured stress changes in the pillar at the outbye of the dyke using a biaxial stressmeter. P – Major principal stress change (vertical), Q – Minor principal stress change (horizontal)

Seismicity

During the monitoring period, two major groups of seismic events were identified. The first group was associated with the longwall caving and they were located near the longwall face. This group of events triggered both geophone arrays underground and additional geophones located on the surface. Event location results have shown that the majority of these events occurred near the longwall face and a clear decrease in the time difference between the Longitudinal Wave (P) and Shear Wave (S) arrivals could be observed as the longwall face approached the monitoring network. The dominant frequency domain for this type of events was from 25 Hz to 75 Hz. The magnitude of this type of event was estimated to be from -3.5 to -3.0 Richter Scale.

The second group was close to the dyke. This group of events triggered four underground geophones installed close to the dyke. Event location results have shown that most of these events occurred around the dyke area. These events also showed clear arrivals of P and S waves, which indicates that they were associated with the shear fractures in the rock mass around the dyke. The dominant frequency domain was from 150 Hz to 300 Hz. The magnitudes of these types of events were estimated to be from -4.0 to -3.5 Richter Scale.

The seismic event location was applied to events with clear P wave and S wave arrival-times and recorded by four underground geophones. In total, there were 528 events selected for location. The locations of the selected events are shown in Figure 5 in plan view. The majority of the events occurred in the immediate roof and coal seam.

Because the underground geophones were closely deployed around the dyke, to avoid significant bias in the locations, the location for the seismic events related to the longwall was only applied to the data recorded from the 15th January to the 31st March 2018, when the longwall face was within 200 m of the dyke.

It can be seen from Figure 5, that most of the significant seismic events located (larger red dots) were related to the longwall and the moderate seismic events (smaller red dots) were mainly clustered around the dyke. Among the seismic events near the dyke, there were rock fracturing events both inbye and outbye.

Interestingly, the seismic events around the dyke were observed even when the longwall face was 400 m ahead of the dyke. While the longwall face was approaching the dyke, the fracturing events in the rock mass continued to propagate. Stronger seismic events were detected when the longwall was mining through the dyke. Also, the rock fracturing events near the dyke were constantly captured until the longwall production was completed in July 2018.

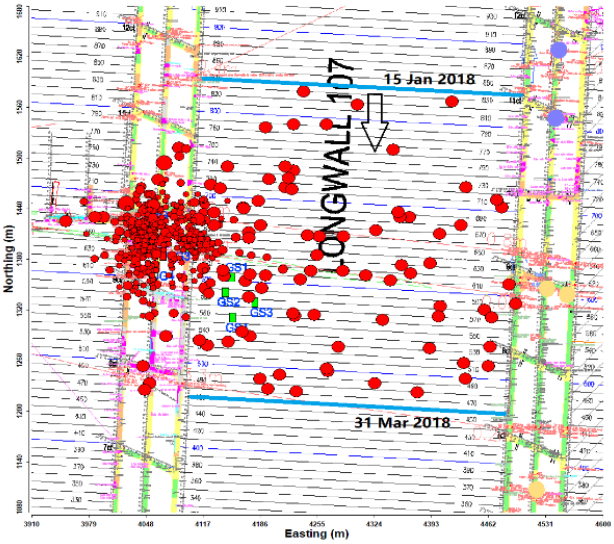

Figure 5: Plan view of the mine plan and locations of the 528 selected events.

Figure 6 shows the accumulative amplitude of seismic events received by each underground geophone for the duration from the 27th November 2017 to the 8th April 2018. Geophones 7 and 8 were located 5 m into the roadway rib at a location of 10 m inbye and outbye the dyke, respectively. They were at approximately the same locations as the biaxial stressmeters, making the comparison with the stressmeters more relevant. Geophones 5 and 6 were located 9 m into the roadway roof at a location of 20 m inbye and outbye the dyke respectively.

The accumulative amplitude curves shown in Figure 6 represent the total energy from all the seismic events received by each geophone without considering their locations. Stronger events from a far distance away may have received similar amplitude to a weaker event at a close point. In reality, these curves are more likely to capture the weak seismic events occurred in close vicinity to each geophone but in a great number.

The results in Figure 6 clearly show that the two rib geophones recorded many more seismic events than the two roof geophones. The accumulative seismic amplitude from the rib geophones was above 4 times that of the roof geophones. It was also noted that the geophones at the inbye locations received more seismicity than the outbye locations, although with respect to the locations from the dyke they were not very different.

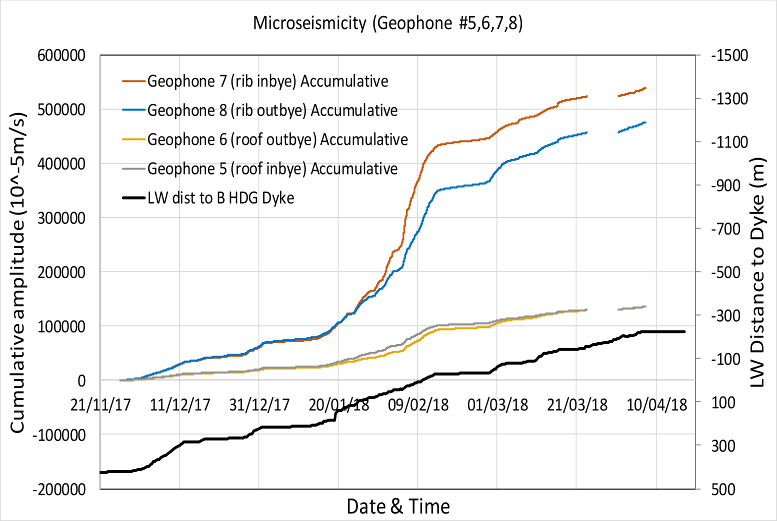

Figure 6: Seismic event cumulative amplitude from each of the underground geophone.

The seismic monitoring results are consistent with the stress monitoring results. All these results showed that, at the inbye location of the dyke, the measured stress change and seismicity were significantly higher than that at the outbye location. At the same roadway location, the measured seismicity in the rib was greater than that in the roof.

From the monitored data, it can be concluded that the inbye and outbye sides of the dyke had different stress regimes. The inbye side experienced much higher stresses than the outbye side. At the same location, the rib experienced higher stresses than the roof. This is clear evidence that the dyke had changed the stresses and hence the mining conditions. The risk of coal burst could have been increased at the inbye side of the dyke.

Correlation between stress change and seismicity

The vibrating wire type stressmeters used in the field monitoring have a resolution as high as 0.002 MPa. Previous experience (Shen, et al., 2013) indicated that, the rate of stress change can reflect the longwall caving events with a success rate of more than 80%. Here the rate of stress change and the accumulative seismic amplitude are used to investigate the precursor of pressure bumps or coal burst.

The rate of stress change is defined as:

$$S' = \frac{\Delta S}{\Delta t} = \frac{\mathrm{S - Average\ (S)}}{\Delta t} \tag{1}$$

where: S' Rate of the stress change (MPa/min),

S Stress magnitude at any given time from the stressmeter readings (MPa),

Average (S) Average stress magnitude over the previous 10 readings (MPa),

Δt Time interval between two data readings (= one minute).

Using the rate of stress change, any small sudden stress variation can be picked up and plotted clearly. Figure 7 shows the comparison between the rate of measured stress change and the maximum seismic amplitude. At the inbye location, the stress change in the rib measured by the uniaxial stressmeter and the maximum seismic amplitude per minute recorded by the rib geophone are plotted (top figure). At the outbye location, the stress changes from both the uniaxial and biaxial stressmeters (vertical stress only) are plotted against the maximum seismic amplitude by the correspondent geophone (bottom two figures).

In general, both the rate of stress change and the seismic amplitude increased rapidly when the longwall face approached to the monitoring location and shortly passed it. There were many spikes in the stress rate plots and the seismic amplitude plots, many of them were closely correlated. For instance, on the 31 December 2017, all the curves showed a series of sudden stress changes and seismic events, albeit their magnitude were small. The most obvious one was on the 9 April 2018 when nearly all the curves showed maximum spikes. The longwall face reached the dyke on this day.

Additional analysis was also conducted for much short time windows to examine the correlation between stress and microseismic results. Overall, there was a very close correlation between the stress change rates and the seismic amplitude. For every stress spike, there was a corresponding seismicity spike. It is also interesting to note that the stress spikes from all three stressmeters occurred at the same time although they were located at different locations. This indicated that they all responded to the same stress event very accurately.

The cause of these stress and seismicity spikes are of great interest, as they could present geotechnical events or pressure bump events. The relationship between the stress and seismic events was examined with respect to the longwall shearer position when the longwall face was close to the dyke location. It was found that an excellent correlation exists between the shearer position and the measured stress rate and seismicity amplitude. When the shearer was moving from the tailgate to the maingate, both the stress rate and seismicity amplitude were increasing and they reached their maximum values when the shearer reached the maingate. When the mining stopped and the shearer stayed still, there were only very limited stress changes and seismicity events.

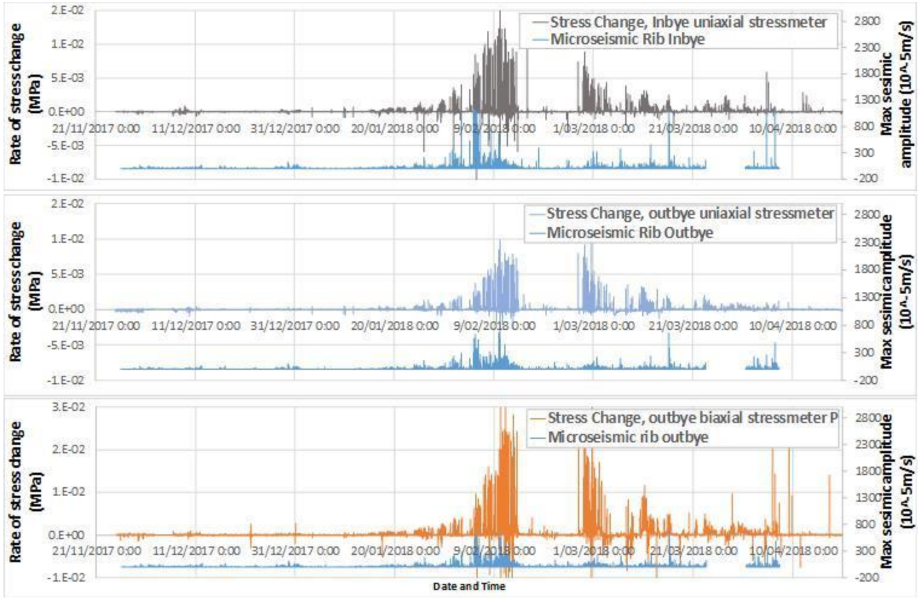

Figure 7: Comparison between the rate of stress change and the maximum seismic amplitude.

It is believed that the progressive caving events after chock advance following the shearer movement was the main cause for the recorded stress change and seismicity events at the monitoring location. These caving events had changed the overall stress distribution in the vicinity of the longwall face and caused abutment stress increase. These stress changes could be very small if the longwall face was some distance away. However, with the very sensitive stress and seismic sensors, they could still be received and identified. These results demonstrate that the vibrating wire stressmeter has the potential to be used together with geophones to monitor rock fracturing or failure events at a distance.

CONCLUSIONS

In this study, (1) a comprehensive field monitoring program in the vicinity of a major geological structure was undertaken in a selected mine site; and (2) detailed analysis of monitoring data to identify the stress anomalies near the geological structure was analyzed and evaluated to determine the possibility of using the monitoring tools for coal burst forecasting. Mine A was selected as the monitoring site where pressure bumps had been experienced in roadways due to the existence of a strong conglomerate unit in the overburden strata. Overall, the monitoring program has been successful, and it recorded valuable stress and seismic data during mining. The key conclusions from the field monitoring program are:

Seismicity: A significant number of microseismic events at the monitoring site were induced by longwall mining of LW107. Seismic activities near the longwall face and the dyke were both captured during the monitoring period. Most of the significant seismic events were located near the longwall face and most of the moderate seismic events were clustered around the dyke. Rock fracturing on both inbye and outbye sides of the dyke was identified. The seismic energy released on the inbye side was significantly greater than that on the outbye side. The seismic signals of these events showed clear arrivals of S-waves, which is associated with shear failure, indicating the existence of shear fractures in the rock mass. Most of the seismic events were in the immediate roof and coal seam.

Stress regime: The stress monitoring results indicate that the stress regime was clearly different on the inbye and outbye sides of the dyke. The inbye side had a much higher stress than the outbye side before and during the longwall mining. It is apparent that the dyke had caused stress redistribution in its vicinity, which led to stress concentration in the “hanging wall” and stress release in the “footwall”.

Monitoring system sensitivity: Both the stressmeters and microseismic systems were highly sensitive and had picked up subtle stress or fracturing activities caused by mining and caving. When the longwall face was at a distance of 60 m from the dyke, the stressmeters and the microseismic system were able to detect the movement of the shearer (or the roof caving related to it). In most cases, the monitored stress changes and the seismicity were closely correlated, and they both responded well to the same geotechnical events (such as caving or rock fracturing). This makes it possible to use one or both of the two techniques to monitor the change of rock mass conditions for forecasting rock burst.

In summary, this study provided quantified field evidence that stress concentration occurs near major geological structures. This stress concentration could lead to high strain energy concentration in the rib of a roadway, and hence increase the risk of coal burst.

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