An Integrated Real-Time Roof Monitoring System for Underground Coal Mines

B. Shen  
CSIRO Exploration and Mining, Queensland

H. Guo  
CSIRO Exploration and Mining, Queensland

A. King  
CSIRO Exploration and Mining, Queensland

M. Wood  
Ulan Coal Mines, Australia

Publication Details
AN INTEGRATED REAL-TIME ROOF MONITORING SYSTEM FOR UNDERGROUND COAL MINES

Baotang Shen¹, Hua Guo¹, Andrew King¹ & Murray Wood²

ABSTRACT: CSIRO has been conducting a five-year research project under the sponsorship of JCOAL and Ulan Mine to develop a real-time roof monitoring and roof fall warning system for underground coal mines. A preliminary system has been developed and successfully trialled twice in the gateroads at Ulan Mine during 2004 and 2005. The system integrates the displacement monitoring, stress monitoring and seismic monitoring in one package. It includes:

- GEL multi-anchor extensometers
- Vibrating wire uniaxial stress meters
- ESG seismic monitoring system with microseismic sensors and high frequency AE sensors.

The monitoring system has been automated and the data are automatically collected by a central computer located in an underground non-hazardous area. The data are then transferred to surface via an optical fibre cable. The real-time data can be accessed at any location with internet connections.

The trials of the system in two tailgates at Ulan Mine have demonstrated that the system is effective for monitoring the behaviour and stability of roadways during longwall mining. The continuous roof displacement/stress data have showed clear precursors of roof falls. The seismic data (event count and locations) have provided insights into the roof failure process during roof fall.

The sensor type and real-time communication system are flexible and can be tailored to meet site-specific monitoring needs.

INTRODUCTION

Roof fall is a major hazard in underground coal mines in Australia. It can cause fatalities, injuries and significant economic losses. Fatalities and injuries due to roof falls in Australian underground coal mines have been significantly reduced in recent years, thanks to the efforts of mine operators and industry regulators. Production loss due to roof falls continues to be a major industry concern for underground coal mines. Roof falls have caused the stoppage of longwall mining and/or roadway development for days or weeks.

Real-time monitoring and early detection of imminent roof fall allowing preventative action to be taken, will increase safety margins and bring significant economic benefit to the mining industry.

A research project was established in 2002 under the sponsorship of JCOAL and CSIRO to develop a roof fall monitoring and warning system for underground coal mines. The project is of 5 years duration total. During the past 4 years, an integrated real-time roof monitoring system has been developed. The system has been successfully trialled twice at the tailgate of longwall panels 20B and 21 at Ulan Mine. This paper presents the key feature of the system and the results from the first field trial at LW20B. More details can be found in Guo et al. (2004).

INTEGRATED REAL-TIME MONITORING SYSTEM

The integrated CSIRO roof monitoring system consists of:

1. Extensometers (measuring roof displacement);
2. Stress meters (measuring stress change in roof and rib);
3. Seismic sensors (detecting seismic events and mapping roof damage);
4. Real-time data acquisition and communication system.

¹ CSIRO Exploration and Mining, PO Box 883, Kenmore, QLD 4069, Australia
² Ulan Coal Mines Limited, Ulan, NSW 2850, Australia
Extensometer

GEL extensometers manufactured by GEL Instrumentations Pty Ltd have been used (see Figure 1). The extensometers used have 6 anchors which were specifically made for CSIRO. The technical specifications of the 6 anchor GEL extensometers are given below:

- Measurement range: 0 – 170 mm
- Accuracy: 0.5 mm
- Borehole diameters: 27 mm – 55 mm

Stress sensors

The stress monitoring device used in the monitoring system is the 4300 EX vibrating wire stress meter (Figure 2) supplied by Geokon Geotechnical Instrumentation. It measures the stress change (not the absolute stress). The features of this type of stress meter include:

- High sensitivity (sensitivity = 0.014-0.07 MPa);
- High range (compression = 0-70 MPa, tension = 0-3 MPa);
- Simplified installation. Borehole grouting is not required;
- Corrosion resistant;
- Waterproof;
- Long-term stability;
- Suitable for remote reading and automatic logging.

The required borehole diameter is 37-39 mm.

Seismic monitoring system

The seismic system includes seismic sensors (both low and high frequency) and a data acquisition system. The new acquisition system is the ESG HMSi integrated seismic monitoring system (http://www.esg.ca/home/products/hmsi1.htm) modified to enable low-frequency microseismic (MS) and high-frequency acoustic emission (AE) data acquisition cards to be combined on one chassis. This system can run on a standard PC under the MS Windows operating system. The system is capable of acquiring eight channels of MS data, at a sampling rate of up to 40 kHz, as well as four channels of AE data, at a sampling rate up to 40MHz. Extra cards can be installed to increase the number of MS and AE channels available.

There are two different types of sensors used in the monitoring system: the low-frequency MS sensors, which includes uniaxial and triaxial accelerometers, and high-frequency AE sensors with built-in preamplifiers for the AE signal detection. The MS sensors are used to detect larger events with fracture radii of tens of centimeters or greater, whereas the AE sensors are aimed at the small, grain-to-centimetre sized fracturing events.

The MS accelerometers used are the A1030 and A3005 accelerometers from ESG with a frequency range of 50Hz to 5 kHz, and 3 Hz to 8 kHz, respectively. The R6 sensors used as ultrasonic sources, and the R6i sensors, used as AE receivers, are made by Physical Acoustics Corporation. They have an operating frequency ranging from 40 to 100 kHz.
System integration and communication

The three components (extensometer, stressmeter and seismic system) of the monitoring system were integrated as shown in Figure 3. The extensometers and stress meters installed in the gateroad (hazardous area) are cabled to a data logger via safety barriers. The data logger logs the data at a specified time interval (30 minutes during the first field trial) and passes the data to the seismic data acquisition system. Thus the seismic acquisition system obtains all the seismicity, displacement and stress data. In the trial at Ulan, these data were transferred from the acquisition system in the underground to the surface via an optical fiber cable, then to CSIRO’s office at Brisbane via the internet and Xstrata and CSIRO networks.

Fig. 3 - Integrated CSIRO roof monitoring system.

REAL-TIME MONITORING OF TAILGATES AT ULAN MINE

A trial of the integrated monitoring system was conducted at LW20B tailgate at Ulan Mine in 2004. A roadway length of 800 m from 1 C/T to 8 C/T was monitored with special focus on the 4th cut-through (4 C/T). The monitoring layout is shown in Figure 4.

Displacement sensors

A total of 12 GEL extensometers were installed in the roadway roofs, eight of which were located at the centre of the intersections at cut-throughs 1 - 8, the rest were located at the roadway centre close to 4 C/T. Figure 5(a) shows the anchor position of each extensometer.

Stress meters

A total of 21 stress meters were installed in three roof and two pillar locations. At each roof location, three stress meters were installed in different directions in the horizontal plane to ensure the measurement of the two dimensional stress change in the roof rock. Stresses at different locations into the roof were measured, see Figure 5(b). At each pillar location, three stress meters were installed at a distance of 2 m, 5 m and 10 m from the roadway rib, respectively. They were designed to measure the vertical stress change in the pillar during longwall mining.
Fig. 4 - Layout and sensor locations of the 1st field monitoring trial at Ulan Mine

Fig. 5 - Sensor locations in the roadway roof
Seismic sensors

A total of 12 seismic sensors were installed in two locations. 11 of them were installed at the fourth cut-through (4 C/T) where the roof fracturing and damage during mining was monitored in detail. One sensor was installed at the sixth cut-through (6 C/T) to monitor the initial caving during the start-up of LW20B at 8 C/T. Figure 6 shows the sensor arrangement at the fourth cut-through (4 C/T).

![Seismic sensor array geometry in roadway roof at the fourth cut-through](image)

All the sensors were installed during the period from 25 April to 1 May, 2004. Mining at LW20B commenced on the 12th of May, 2004 at 8 C/T. On the 14th of May 2004 when the longwall face progressed about 20 m, the longwall roof started to cave behind the longwall chocks. The longwall face reached the 4 C/T (where the monitoring was concentrated) on the 11th of June, 2004. The longwall panel was completed in August 2004 at 1 C/T.

Upon the completion of installation on the 1st of May 2004, the extensometer and stress meter monitoring commenced. The data logger was set to record and store the data every 30 minutes. The stress monitoring continued until the 12th of June 2004 when the last stress meters at 4 C/T - 20 m were buried. The displacement monitoring continued to August 2004 when the whole Longwall panel 20B was mined.

The seismic system commenced operating on the 7th of May 2004 after a problem with the hardware was fixed. The seismic monitoring continued until the 11th of June 2004 when the longwall face reached the monitoring location (4 C/T) and the roof collapsed. Most of the seismic sensors were damaged or destroyed during the 10th and 11th June.

During the period of monitoring, data were collected daily from CSIRO’s office at Brisbane. The data were processed, analysed and plotted daily. They were then sent back to Ulan Colliery with comments on the roof condition to help their strata control and mining operations.

Overall, the monitoring ran smoothly and was very successful. For the first time in Australia, we have achieved a remote, real-time, continuous, and integrated monitoring of roof behaviour during longwall retreat in an underground coal mine.

**MONITORING RESULTS**

The results from the first field trial of the integrated real-time monitoring are extracted and analysed in this section. The following aspects directly related to the strata behaviour during mine operations are discussed:

- Initial caving
- Caving progress
- Tailgate roof displacement and stress
Initial caving

Longwall mining at LW20B started at 8 C/T. The roof behind the longwall face did not cave until the face advanced by about 12 m. At this time, the roof span behind the chocks is about 20 m after adding the initial width of the installation road (8 m). Figure 7 shows the response of the stress meters at 4 C/T (top figure), extensometers at 8 C/T (bottom figure) and the seismic sensors at 6 C/T and 4 C/T (in both figures) during this period.

The mining started on 12/05/2004 11:00am. The operators observed the initial caving starting at around 13/05/2004 0:00 am. The following records were extracted from the mine shift report:

1. 7:50 pm-1:20 am (chainage=690-688 m): Chock leg pressures are high (300-400 bars); Goaf starts to form at the middle of the panel face.
2. 1:27 am-6:22 am (chainage=688-685 m): Goaf has fallen over nearly the entire length of the face. It still hangs up near the maingate and tailgate.
3. 11 am (chainage=685-683 m): Large chock converging movement occurs from mid face toward the tailgate.

The roof stresses as monitored at 4 C/T, 400 m away from the caving activity, showed a clear response to the above events of caving. At point 1 (caving started), the stress parallel to the roadway started to decrease. At point 2 (caving propagated), the stress at 45° angle showed a sudden drop. At point 3 (cave completed), the stresses in all the three monitored directions rebounded sharply.

The monitored displacement at 8 C/T showed a rapid roof movement between points 2 and 3, confirming that the caving had propagated from the mid-face to the tailgate during this period.

The seismic sensors at 6 C/T and 4 C/T received an increased number of seismic events at the end of the initial caving. The peak of the seismic event count corresponds to the sharp stress rebound. Note that the seismic system during this period was frequently interrupted by unexpected computer rebooting. Therefore, not all the seismic events were recorded.

The monitoring results demonstrated that the stress meters are adequately sensitive to pick up the caving activities 400 m away from the monitored location. The changes in the roof stress, however, were very small (<0.05 MPa). Only the automated and continuous monitoring system, as used, could pick up the subtle changes. Traditional...
manual monitoring with daily or weekly reading frequency will not be able to show the subtle changes on its data chart.

**Caving process**

A typical variation of the monitored roof stresses with the longwall face position is given in Figure 8. The variation of the number of seismic events received against the longwall face position is shown in Figure 9.

![Figure 8 - Typical variation of the monitored roof stresses with the longwall face position](image1)

**As seen in Figure 8, there is a close correlation between the monitored roof stress and the longwall face position when the longwall face progressed from 8 C/T (chainage = 700 m) to 5 C/T (chainage = 300 m). This correlation diminished when the face was within 100 m from the sensor position at 4 C/T - 20 m (i.e. between 3 C/T and 4 C/T, or chainage of 200 m-300 m).**

The seismic event counts also showed a clear response to the mining progress (Figure 9). When longwall faces progressed, increasing seismic activity was recorded. When the longwall face stopped for a prolonged period, little seismicity was recorded. The monitored seismicity peaked when the longwall face was about 20 m from 4 C/T where most of the seismic sensors were located. It is interesting to note that, when the longwall face was closer than 20 m from 4 C/T, the monitored seismicity reduced.

The close correlations between the seismicity/stress and the position of caving may be used to study the development process of longwall caving. For instance, if the monitored results suddenly deviate away from an
established trend when the longwall face is still progressing, it may indicate that the caving of the roof is not developing normally. The caving of the immediate coal roof can be observed from the longwall face, but the behaviour of the overlying sandstone roof may not be easily observed. Together with other operational data (such as the chock pressure and convergence), the monitoring data could alert the operators if the sandstone roof hasn’t caved smoothly.

**Tailgate roof displacement and stress**

The monitored roadway roof displacements at two selected locations are plotted against their relative distance to the longwall face, see Figure 10. The roof started to deform when the longwall face was about 10 - 32 m away, depending on the specific location of the roadway. It appears that the above distance reduced gradually from 32 m at 7 C/T to 10 m at 4 C/T. It is uncertain whether this reduction was due to stronger stress bridging effect closer to the longwall start-up or due to the possible change of roof geology and roof support design.

The roadway roof at the monitored cut-throughs stayed up until the longwall face passed the sensor locations by about 15 m in most cases. In the figure, the roof collapse was indicated as a sudden displacement drop or irregular variation when the extensometer or cable was destroyed. The process of roof deformation and collapse could only be monitored by the remote, automated system. Because the areas were inaccessible near or behind the longwall face, traditional manual monitoring methods could not be used. A typical variation of the roof displacement with depth is shown in Figure 11. It indicates that major roof delamination occurred in the vicinity of a claystone layer (C-marker) about 1 m above the roof line.

The monitored roof stresses at a selected location are plotted against its relative distance to the longwall face, see Figure 12. A rapid change in roof stress was observed when the longwall face was about 20-30 m away from the sensor location. Horizontal stresses in all the three directions (parallel, perpendicular and 45° to the roadway axis of a horizontal plane) dropped rapidly (within 1 - 2 hours) prior to the collapse of the roof. Similar stress drops have been observed in the post peak stage in laboratory compression tests. At this stage, the load bearing capacity of the roof rock was reducing while the deformation was increasing.

---

**Fig. 10 - Variation of roadway roof displacement against the relative distance to longwall face**

The roadway roof at the monitored cut-throughs stayed up until the longwall face passed the sensor locations by about 15 m in most cases. In the figure, the roof collapse was indicated as a sudden displacement drop or irregular variation when the extensometer or cable was destroyed. The process of roof deformation and collapse could only be monitored by the remote, automated system. Because the areas were inaccessible near or behind the longwall face, traditional manual monitoring methods could not be used. A typical variation of the roof displacement with depth is shown in Figure 11. It indicates that major roof delamination occurred in the vicinity of a claystone layer (C-marker) about 1 m above the roof line.

The monitored roof stresses at a selected location are plotted against its relative distance to the longwall face, see Figure 12. A rapid change in roof stress was observed when the longwall face was about 20-30 m away from the sensor location. Horizontal stresses in all the three directions (parallel, perpendicular and 45° to the roadway axis of a horizontal plane) dropped rapidly (within 1 - 2 hours) prior to the collapse of the roof. Similar stress drops have been observed in the post peak stage in laboratory compression tests. At this stage, the load bearing capacity of the roof rock was reducing while the deformation was increasing.
Fig. 11 - Variation of roof displacement with depth into roof at 4 C/T. Results at different longwall face positions are shown.

Fig. 12 - Variation of roadway roof stresses with the distance to longwall face

Pillar stress

The variation of the monitored stresses in the coal pillar as the distance to longwall face changes are shown in Figure 13. The vertical stress in the pillar showed a classic pattern. As the longwall face approached the sensor location from 400 m to 90 m, the vertical stress at the edge of the pillar (2 m into pillar) increased gradually with a peak of about 1.3 MPa at 90 m. When the longwall face progressed closer than 90 m, the vertical stress at the edge of the pillar started to decrease, indicating yield might have occurred at least within the outer 2 m of the pillar. The pillar stress in the inner part of the pillar, however, started to increase rapidly (see Figure 13) while the stresses at the edge decreased. This was probably caused by stress redistribution after part of the pillar had yielded. When the longwall face was far away, the monitored pillar was largely intact. Therefore, the stress at the edge of the pillar is higher than in the centre. When the longwall face aligned to the pillar, the pillar yielded partially and the resultant stress in the pillar centre was higher than at the edge.
Integrated monitoring of roof behaviour

The roadway roof at 4 C/T was monitored comprehensively by extensometers, stress meters and seismic sensors. The integrated monitoring results from all the three monitoring devices showed many exciting insights of the roof failure development process.

Figure 14 shows the monitored roof displacement, roof stress change, and seismic events count at 4 C/T when the longwall face approached and passed the monitored location.

During 9/06/2004, 0:00 – 10/06/2004 12:00 (the long wall face distance = 30 m - 10 m), neither the roof extensometer nor the stress meter recorded any significant change in roof displacement and stress. The seismic system, however, recorded a major increase in the seismic events. The event count peaked periodically every 1.5 hours, coincident with the longwall advancing cycle. The longwall support was moved forward 1.2 m in every 1.5 hours after each shear cycle, leaving the roof behind the chocks to cave.

During 10/06/2004 12:00 – 11/06/2004 0:00 (the longwall face distance = 10 m – 0 m), the roof stress showed a major increase then decrease, while the roof displacement started to increase. The seismic events however, started to show a decrease during this period, before two of the five sensors failed as they were damaged or destroyed by the rock movements.

During 11/06/2004 0:00 – 12/06/2004 12:00 (the longwall face passed 4 C/T by 0 - 10 m), the roof displacement increased significantly to about 200 mm, while the stresses showed a major decrease. The remaining seismic sensors were destroyed during this time, so it is impossible to say anything about seismicity levels.

The above results suggest that in the early stage of the roof failure, seismicity is more active than the stresses or displacement. However, in the later stages of the roof failure, the stress change and roof displacement become more obvious while seismicity decreased.

The monitoring results provided a better understanding the roof behaviour during failure (Figure 15). In the early stage of the failure, roof rock under increased stresses started to fracture or delaminate at a local scale. Fracturing of roof rock caused many seismic events. But the rock was confined and remained relatively intact and hence there was insignificant change in the roof stresses and displacement.

At the later stage of the failure, local fractures started to coalesce and form large fractures or failure planes. At this stage roof stresses changed significantly and roof displacement increased rapidly. However, the seismic activities reduced since the rock mass had already released its elastic energy.
The monitoring results highlighted some issues with the traditional displacement-only monitoring. By the time the extensometers have shown significant roof movement, a major roof damage had already occurred and any remedial reinforcement measures could be less effective and more costly.

Seismicity monitoring and stress monitoring are effective in forecasting the early damage of the roof. They should be used together with the displacement monitoring to provide an “early” warning of imminent roof failure. Since they can pick up the early sign of any upcoming roof failure, roof reinforcement installed during this stage will be much more effective and less costly.

**Seismic event locations**

Over 300 seismic events were located in the vicinity of the monitored roadway roof at 4 C/T. The results are shown in Figure 16. The seismic events illustrate several failure planes in the plan view and the cross section views. The interpreted failure plane in the plan view appears to represent a damage zone developed ahead of the longwall face. In the section views, the horizontal failure planes coincide with the interface of the roof coal and rock at a height of 5 m, whereas the inclined failure planes close to the pillar could represent the breakage line of a beam due to the longwall caving.
SUMMARY AND CONCLUSIONS

The first field monitoring trial of CSIRO integrated real-time monitoring system at Ulan Mine has provided many interesting results. For the first time in Australia, an integrated monitoring system has been used to monitor underground roadway stability remotely and in real time. The integrated monitoring system successfully monitored the longwall initial caving. It has also provided a large amount of data on roof deformation, stress change and seismicity, which has improved our understanding of roof behaviour and failure processes.

Roof fall precursors and patterns have been observed at Ulan. Roof falls were observed to follow the sequence: seismicity, → stress change → displacement change. This process is believed to be applicable to most roof fall failures, but the timing and intensity of each stage will vary according to site specific conditions. Seismicity and roof stress signals appear to provide warnings for the imminent roof falls earlier than the roof displacement signals.

The monitoring results have the following implications to the mine operations:

- Roadway roof reinforcement should be installed in the roof loading stage, i.e. 30 m ahead of LW face. Otherwise damage may have already occurred.
- Displacement monitoring alone may not be adequate for early roof fall warning, because roof damage is likely to have occurred by the time extensometers show any noticeable deformation.
• Stress and seismic monitoring can reliably warn of the caving events. They could be considered for routine monitoring.

ACKNOWLEDGEMENTS

The work presented in this paper was sponsored by JCOAL, CSIRO and Ulan Mine. We acknowledge the contribution to this study by Mr Peter Ostermann, Mr Richard van Laeren, Mr David Jackson (Ulan), Dr. Shinji Tomita and Dr. Shinichi Uchida (JCOAL), our former CSIRO colleague Dr David Cousens, and Mr Gavin Langerak of GEL Instrumentations Ltd.

REFERENCE