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ROADWAY SPAN STABILITY IN THICK SEAM MINING - FIELD MONITORING AND NUMERICAL INVESTIGATION AT MORANBAH NORTH MINE

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ABSTRACT: Comprehensive field monitoring and numerical analyses of roadway span behavior have been conducted at Moranbah North Mine as part of an ACARP Project for Rapid Roadway Development. The response of the coal roof to roadway development in a 5.5m thick seam was studied. The monitoring program was highlighted by successfully measuring the roof stress change prior to, during and after the roadway excavation. Roof displacement was also monitored after the installation of roof support.

Measured *in situ* stresses in the coal seam were much lower than estimated from the overburden depth. The monitored vertical stress in the coal roof exhibited a rapid drop immediately after the roadway face passed the monitored locations. It however, recovered substantially (up to 50%) in the next 10 hours. Two roadway sections 60m apart were monitored. The monitored roof displacements and stresses in the two locations showed a significant difference. The sites were separated by two normal faults.

The monitored roadways were simulated using fully coupled mechanical-flow models. The numerical results suggested that the drainage of gas/water around the roadways was likely to be the main cause of the observed stress recovery in the coal roof. It was also found that the presence of high gas/water pressure in the coal seam would result in lower stress readings with the stress measurement technique. The measured stress is close to but not necessarily equal to the effective stress.

INTRODUCTION

A research project sponsored by JCOAL/CSIRO and ACARP is in progress to develop an automated roadway development system. The system consists of an Autonomous Conveying/Bolting Machine (ACBM) and a continuous miner. The system will enable a continuous and rapid roadway advance. Successful application of the system requires stable roadways before full support can be installed. The potential unsupported (or lightly supported) span inbye of the system is about 12m. It is important that the stability of unsupported spans in various geotechnical conditions are fully understood to assess the applicability of the Rapid Roadway Development System in different mines. This paper will focus on the study of coal roof behaviour for the application of the ACBM system in thick seam mining.

It is known that the behaviour and failure mechanisms of unsupported spans are complex, affected by many factors such as rock strength, roof geology, stress and roadway geometry. Strata Engineering Pty Ltd (Frith, 1998) considered that span failure is dominated by beam bending or shearing; Seedsman (2001) suggested that span instability often starts from shear failure of the roof bedding planes. Strata Control Technology Pty Ltd (SCT) (Gale, 1991) considers the roof to be a yielding material and continuum numerical modelling has been used to assess the span stability. Shen and Duncan Fama (1996, 1999) studied the failure mechanisms of unsupported spans of highwall mining entries and proposed analytical methods for their stability assessment.

Many Australian longwall mines operate in thick coal seams and leave coal in the roof on development. The behaviour of a coal roof differs from that of bedded rocks due to the coal cleating, low coal strength, possible low stress environment, and high gas content. The understanding of coal roof behaviour is limited, and requires further investigation.

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With the support of Moranbah North Mine and help from SCT, CSIRO has conducted a comprehensive field and numerical study of coal roof behaviour at Moranbah North. Two sections of the Longwall 104 gate roads at Moranbah North were monitored and investigated. The study consisted of the following components:

- Geological and geotechnical investigation of the roof conditions in the monitored area.
- Determination of the strength of roof materials.
- Monitoring of the stresses and displacement in the roadway roof strata.
- 3D mechanical numerical modelling.
- 2D coupled mechanical and fluid flow modelling, including impact of increased mining depth.
- Roadway stability assessment for the potential application of the ACBM system.

GEOLOGICAL AND GEOTECHNICAL CONDITIONS

Moranbah North Mine is located at the Bowen Basin Coal Field, Central Queensland. The primary mining seam is the Goonyella Middle (GM) seam which varies in total thickness across the mining resource from 5.2m to 6.4m, with a total thickness in the study area of approximately 5.5m. The seam comprises moderately weak coal which is dull at the top and grades to dull and bright banded, and is bright banded at the base. The GM seam has an estimated gas content of $5m^3/t$ at the depth of current roadway development.

The gateroads at Moranbah North Mine are nominally cut to 5.2m wide and 3.0 – 3.2m high, excavated in the lower part of the seam. Current development cuts to the floor of the coal seam and is designed to leave at least 1m of coal in the immediate roof. The stability of the roof is believed to be strongly dependant on the thickness of coal left in the immediate roof. The place-change roadway development method is used. The typical cut-out distance ranges from 6m to 15m depending upon the local roof conditions and the overburden depth.

A decision was made to monitor roadways in 104 panel. As a preliminary site investigation, five cored boreholes were drilled into the roof and coal ribs at 47C/T and 49C/T to investigate the geological and geotechnical conditions at the monitored sites. The cores were geologically and geotechnically logged. Samples were selected for laboratory testing to determine the strength of coal and rock material.

The geology from the drill holes is generally consistent. The typical roof geology in the monitored area is shown in Figure 1. The immediate roof is 1.7m coal. It is of C3 type (40-60% bright) immediately above the roof and becomes dull coal with bright bands at the top of the seam. Overlying the coal seam is a weak to very weak mudstone unit. The mudstone unit has a thickness of about 1.8m. Above this unit is the Goonylla Rider Seam (GMR) which has an average thickness of 0.2m. Above the GMR unit is a sequence of mudstone/siltstone/sandstone units.

Also shown in Figure 1 is the Coal Mine Roof Rating (CMRR) for different roof units. The roof coal and the mudstone units have a CMRR value ≤ 35 (Figure 1). According to Mark (1999), unsupported roadway spans with a CMRR less than 46 are considered to be unstable in the long term.

Fourteen coal and rock samples selected from the roof cores were tested in uniaxial compression to determine the strength and deformability (Cunnington and Boland, 2002). The tested Uniaxial Compressive Strength (UCS) and Young's modulus (E) are also plotted in Figure 1.

The average UCS and Young's modulus of the roof coal and rocks are summarised in Table 1.

Table 1. Strength and deformability of roof units, based on laboratory tests results

Roof unit	UCS (MPa)	Young's modulus (GPa)
Immediate roof coal:	8.0	2.2
Mudstone:	Weak, no samples were recovered	
GM Rider Seam:	10.5	3
Mudstone/Siltstone	13.0	2.8
Sandstone (lower part):	19.5	3.7
Sandstone (upper part):	59.5	14.6

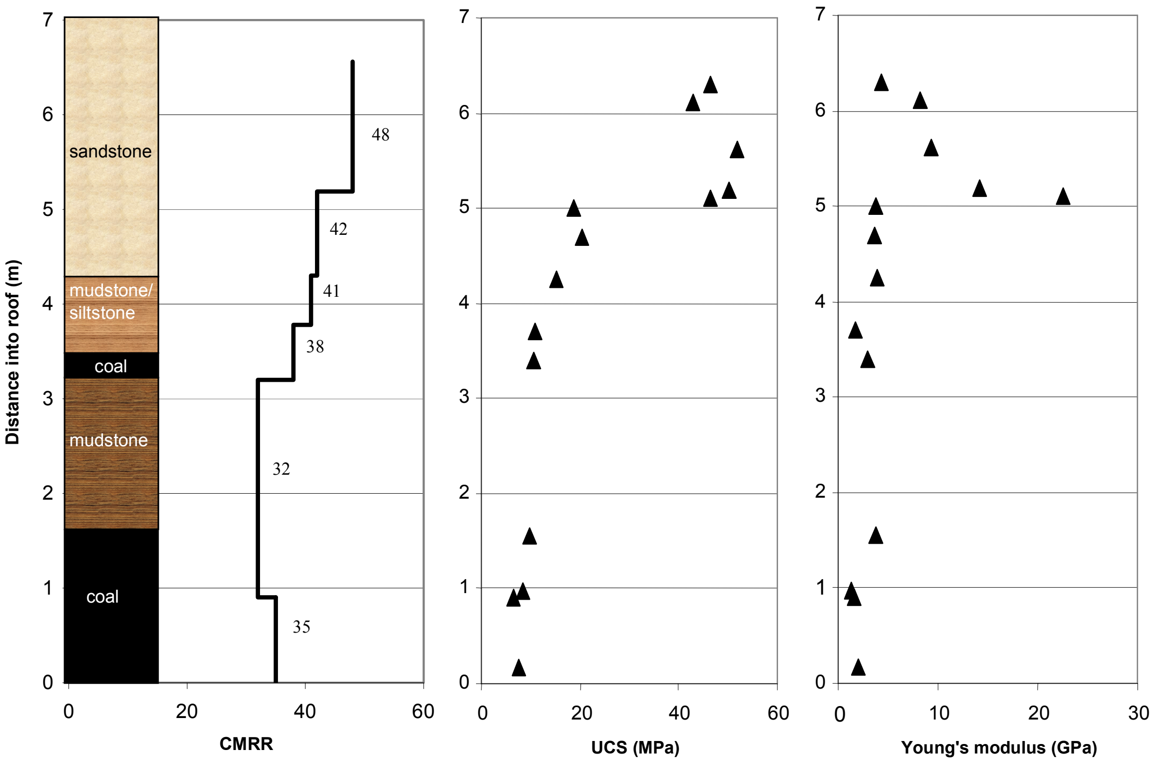


FIG. 1 - Roof geology, CMRR, rock strength and Young's modulus in the monitored holes

FIELD MONITORING

Two sections of Roadway A at LW 104 (Figure 2) were monitored in the vicinity of the 51 and 52 C/Ts where overburden depth is 220m. The monitoring program included three main components:

- Monitoring of stress change in the roof *during* roadway development;
- Monitoring of roof displacements *after* the excavation of the roadway; and
- Measurements of *in situ* stresses in the vicinity of the monitored area.

The stress change monitoring was designed to record the stress change in the roadway roof prior to, during and after the roadway excavation. This method overcame the shortcomings of the conventional displacement monitoring techniques which can only monitor the roof response after the excavation of the roadway (and usually after bolting), missing the period when the crucial roadway reaction is occurring.

Four ANZI stress cells were installed at Site 1 and two at Site 2, see Figure 3. The stress cells were located in different roof units and they were installed in boreholes drilled from the cut-throughs prior to the excavation of the monitored roadway sections. Figure 4 shows one such arrangement. After the installation of the stress cells, the roadways were cut in the sequence marked in Figure 4 i.e. 1→2→3→4. The changes of the stresses in the roof were monitored withfrequent data reading (every 30 minutes) when the monitored roadway sections were cut.

Four sonic extensometers were installed in the centre of the roadway in the monitored section at each site. The extensometers were installed after the completion of the roadway cutting and roof bolting.

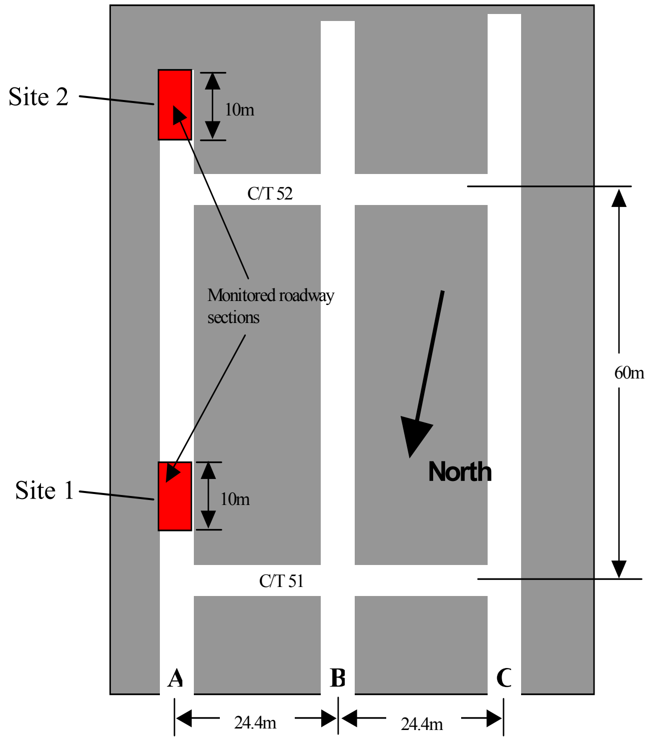
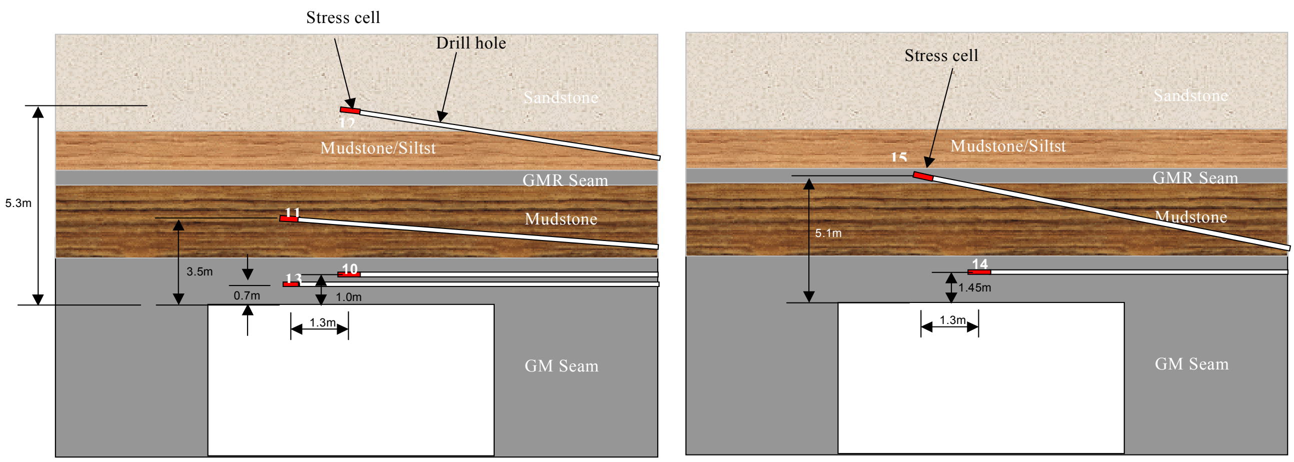


FIG. 2 - Mining layout and the monitored sections of the roadway heading A.

The *in situ* stresses in the coal seam and roof rock were measured in the vicinity of the monitoring sites using the overcoring technique. The *in situ* stress measurements were conducted in the pillar between 49 and 50 cut-throughs (SCT, 2002).



(a) Site 1 **(b) Site 2**

FIG. 3 - Location of stress cells in roof at the two monitoring sites

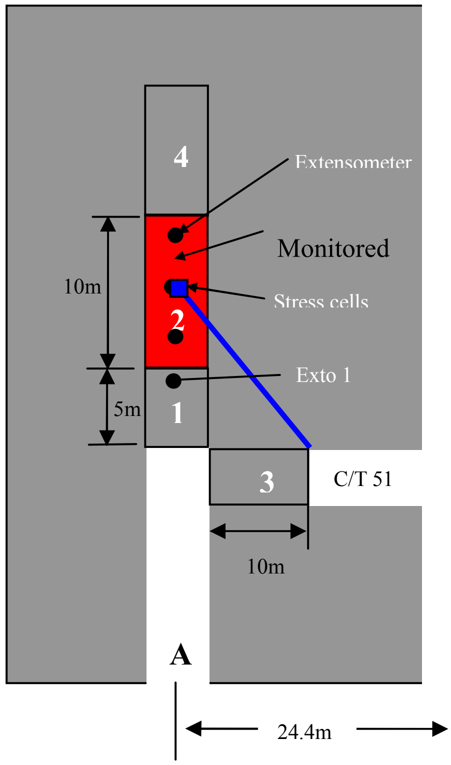


FIG. 4 - Drilling arrangement for stress cell installation and mining steps during monitoring.

In situ stresses

The *in situ* stress measurement results are given in Table 2. The *in situ* stresses in the coal seam are much lower than that estimated from overburden depth. The measured vertical stress is only 1.3MPa, compared with the calculated vertical stress of 5.5MPa from overburden depth of 220m. It is believed that the measured results have been affected by gas/water drainage around the measurement borehole. The measured stress is likely to be close (but not necessarily equal) to the effective stress (Shen, Poulsen and Kahraman, 2002)

Table 2 Summary results of the *in situ* stress measurements

Strata	Principal stresses	Magnitude (MPa)	Dip (degrees)	Strike from North (degrees)
Coal	σ_1	1.83	60	355
	σ_2	0.46	10	245
	σ_3	-0.27	28	152
	σ_v	1.3	90	0
Roof sandstone	σ_1	13.97	6	4
	σ_2	7.94	31	271
	σ_3	5.95	59	105
	σ_v	6.5	90	0

Stress changes in roadway roof

The measured stress changes in the roof coal, mudstone and sandstone during roadway advance are shown on a vertical section in Figure 5. The vertical stress change in the roof coal with time is shown in Figure 6

Stresses in the roof rotated when the roadway face approached and passed the monitored locations (FIG. 5). At Site 2, cell 15 in the Rider Seam indicated a change in level and orientation implying shearing along the Rider Seam. Vertical stress in the roof dropped sharply immediately after the roadway face passed the monitored locations (Figure 6).

After the initial stress drop, the vertical stress recovered partially in the next 2-3 hours in the GM Seam (Figure 6) and the mudstone unit. The recovery continued in the next 12 hours at a reduced rate. No vertical stress recovery was observed in the sandstone roof.

The magnitude of the vertical stress change in the GM Seam at Site 1 was generally consistent with that of *in situ* vertical stress obtained from the overcoring stress measurements. The maximum vertical stress drop is about 1.2-1.3MPa, while the measured *in situ* vertical stress in coal was 1.3MPa. This implies a nearly total release of vertical stress after roadway excavation.

At Site 2, the maximum vertical stress drop in coal roof is about 2MPa, much higher than that at Site 1 and the *in situ* vertical stress measured in the coal pillar between 49 C/T and 50 C/T. The results suggest that Site 2 had a different stress regime from Site 1, and the *in situ* stresses were higher. The difference might be influenced by unknown local geological variations and the existence of geological structures. Two normal faults exist between Site 1 and Site 2. The faults are nearly perpendicular to the roadway axis, both dip in an angle of 70 degrees inbye. One of the faults has no obvious displacement, and the other has a displacement of 0.2m. The fault surfaces are clean and tight. Minor displacement normal faulting of this nature is not uncommon at Moranbah North.

Roof displacement

Four sonic extensometers were installed in the monitored roadway roof immediately after roof bolting at each site. Displacement data were read as the roadway advanced. The maximum displacement was obtained at the monitored location closest to the cut-throughs (Extensometer 1 at Site 1, see Figure 4, and Extensometer 5 at Site 2). The two extensometers were installed close to the face of previous cut and therefore measured the full roof response to the roadway advance. Other extensometers were installed within the length of the full bolted roadways where much of roof displacement might have already occurred. They hence measured much less roof displacement. The monitored roof displacement from Extensometers 1 and 5 are shown in Figure 7.

A maximum of 18mm roof movement was recorded at Site 1 (Figure 7a). The recorded displacement is relative to the upper end of the extensometers (7m into roof). The deformation zone extended about 4m into the roof. It is apparent that the bolted roof remained intact as the deformation in the roof coal layer was almost uniform.

The Extensometer 5 at Site 2 recorded a maximum of 50mm roof displacement (Figure 7b), substantially higher than that at Site 1. The deformation zone extended at least 6m into the roof, also higher than that at Site 1.

The larger roof movement at Site 2 is consistent with the higher stress change at this location. The roof displacement data support the suggestion that a different stress regime existed at Site 2 which is separated from Site 1 by two normal faults.

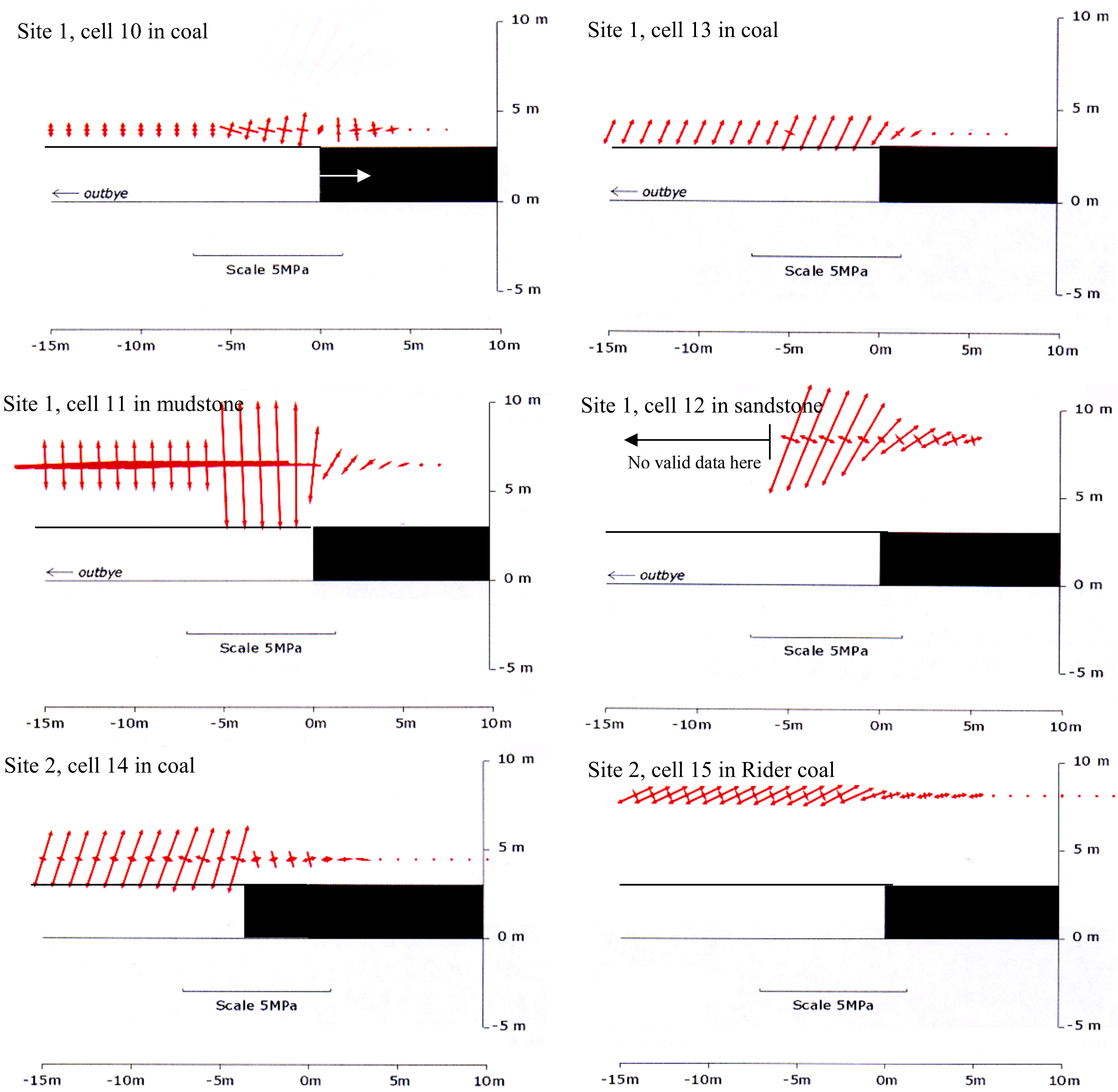


FIG. 5 - Monitored stress change in roof coal and rock units versus roadway face position in a vertical cross section parallel to the roadway axis. Outward arrow indicates reduction of compressive stresses

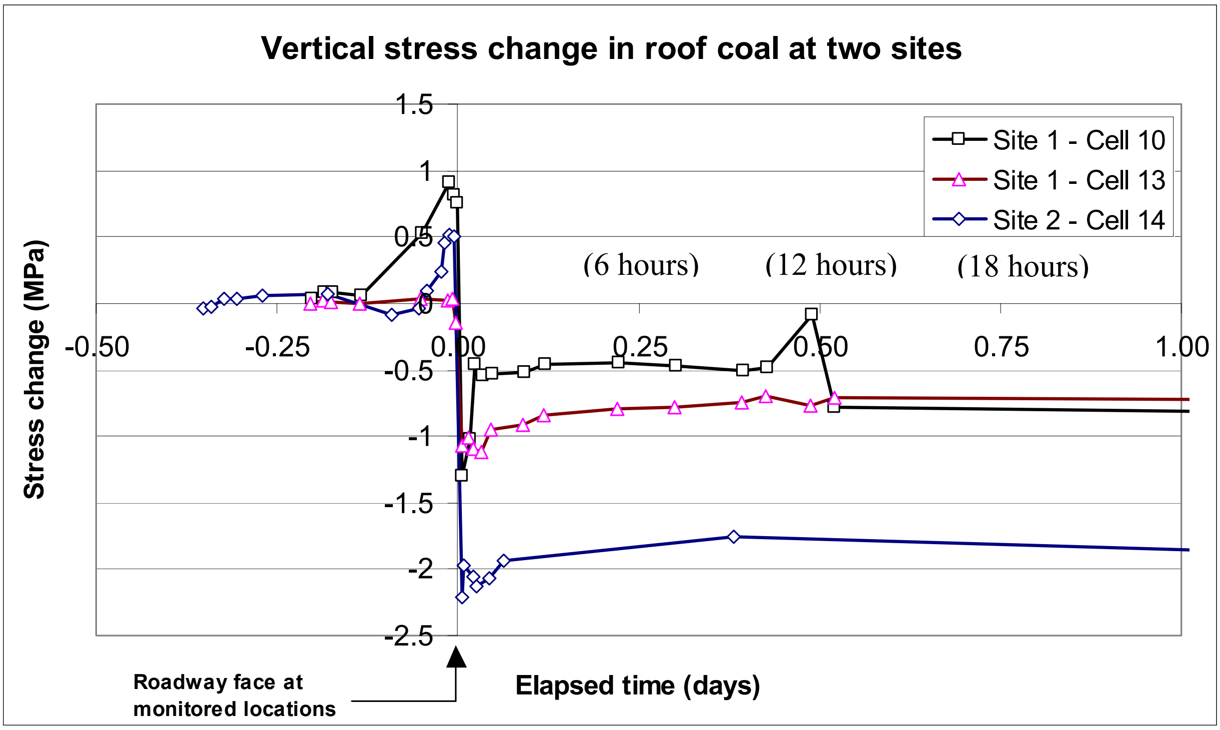


FIG. 6 - Change of vertical stress in the roof coal at the two monitored sites.

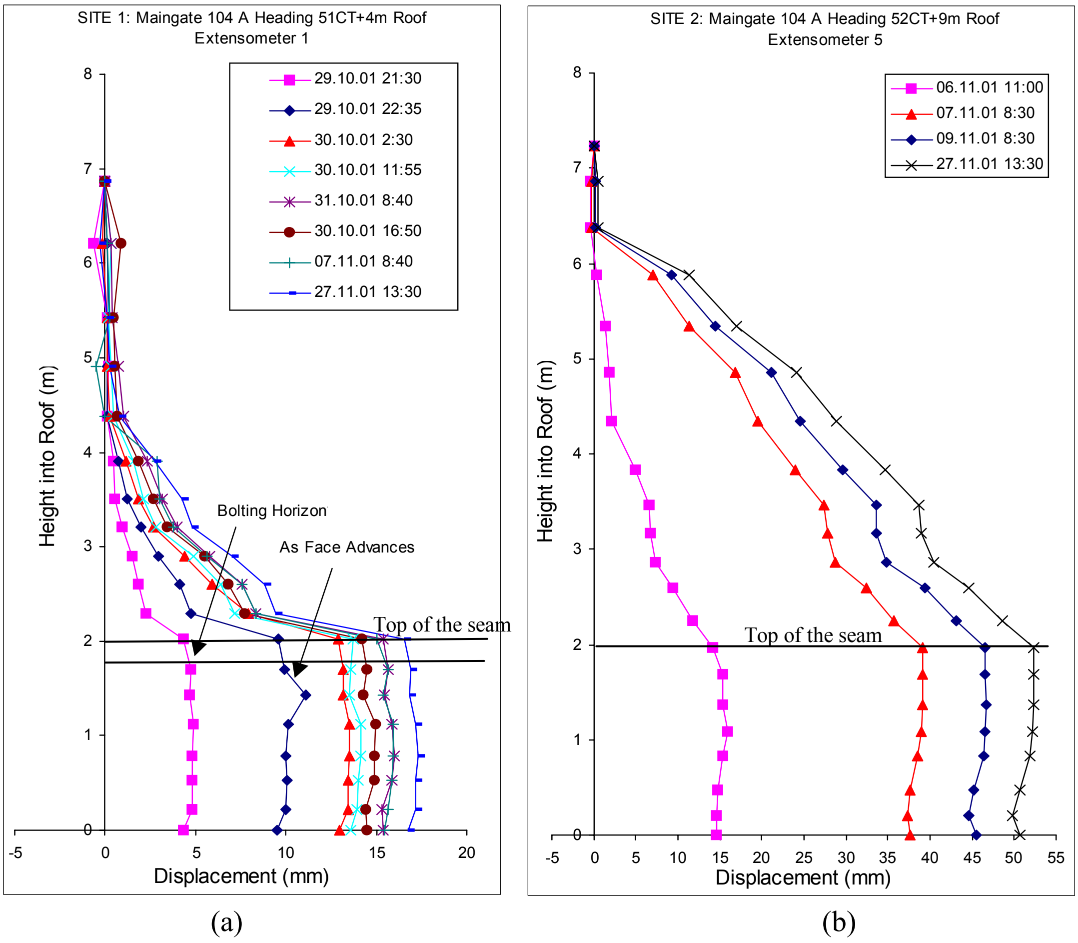


FIG. 7 - Roof displacement at the two monitored sites.

NUMERICAL MODELLING

Numerical modelling was conducted using two and three dimensional models. The aim of the numerical modelling was to reproduce and interpret the measurements and hence to better understand the roof behaviour at the monitored sites.

The three dimensional numerical simulation of the monitored roadway was conducted used FLAC^{3D} (Itasca, 1997). A 3D numerical model was set up based on the simplified geological log shown in FIG. 1. The true mining sequence, including roof and rib bolting, was simulated. The modelled stress change and displacements in the roof were investigated and compared with the measurements. The model geometry is shown in figure 8.

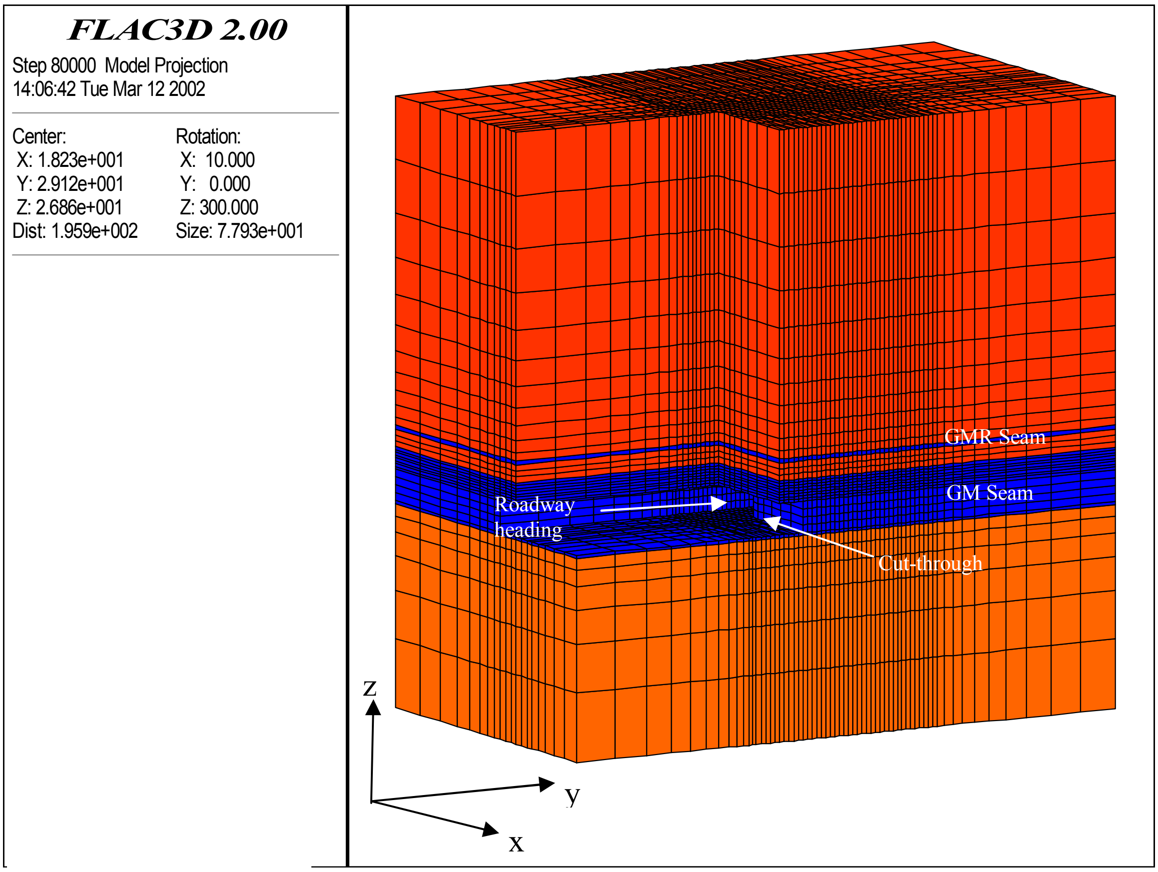
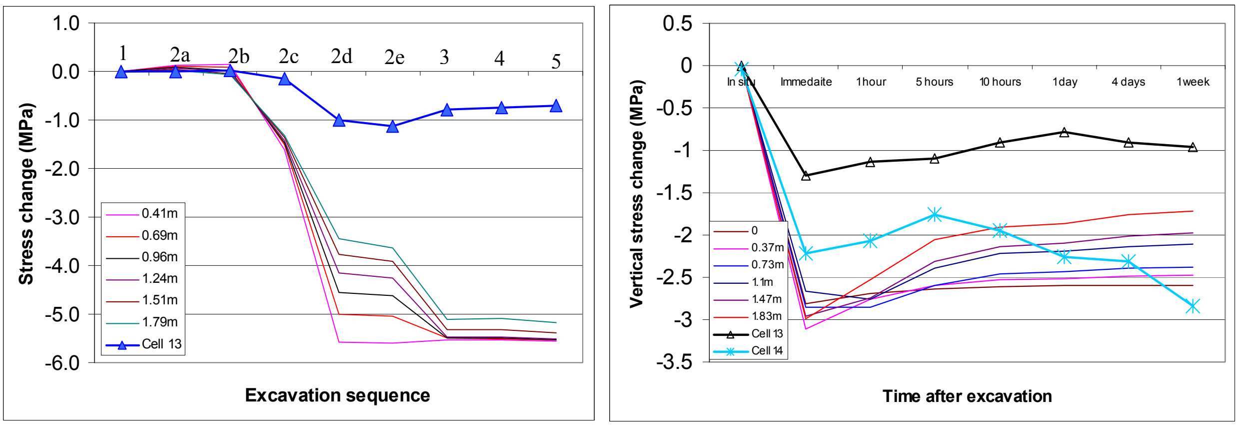


FIG. 8 - A 3D numerical model for roadway stability at Moranbah North

The two dimensional numerical modelling used FLAC with full mechanical-fluid flow coupling (Itasca, 1999). Roof and rib bolting were installed 5 hours after the cut of roadway section. The initial gas and water pressure in the coal seam was assumed to be 3.0MPa. Fluid flow in the coal seam during roadway excavation was modelled. For simplicity, the gas and water were treated as the same fluid medium and hence only single phase fluid was modelled.

The predicted stress changes in the coal roof from the 2D and 3D modelling are plotted in Figure 8..



(a) 3D mechanical modelling results **(b) 2D coupled modelling results**

FIG. 9 - Modelled vertical stress change (un-marked lines) in roadway roof at Site 1 in comparison with the measurements (marked lines). The modelled results are given at different distances into the roof. Excavation steps correspond to the roadway sections marked inFgiure 4. Steps 2a-2d are excavations of the 10m section 2 with 2.5m increment, 2e is after roof bolting. Step 5 is further advance of the roadway.

Using the 3D model without considering gas/water pressure, the predicted change of vertical stress in the coal roof during roadway excavation was about 5.5MPa, much higher than measured (see Figure 9a). Unlike the measurements, the model predictions did not show any recovery of the vertical stress in the coal roof after the initial drop.

The 2D model simulated the gas/water pressure and fluid flow in the coal seam during the excavation process. Figure 10 shows the modelled pore pressure distribution 5 hours after roadway excavation. The predicted vertical stress change in the coal roof was in general agreement with the measurements (Figure 9b). The predicted maximum magnitude of the vertical stress change was 2.5-3.0MPa, closer to the measurements of 1.3MPa at Site 1. More importantly, the modelling results showed a clear stress recovery after the initial stress drop, consistent with the measurements.

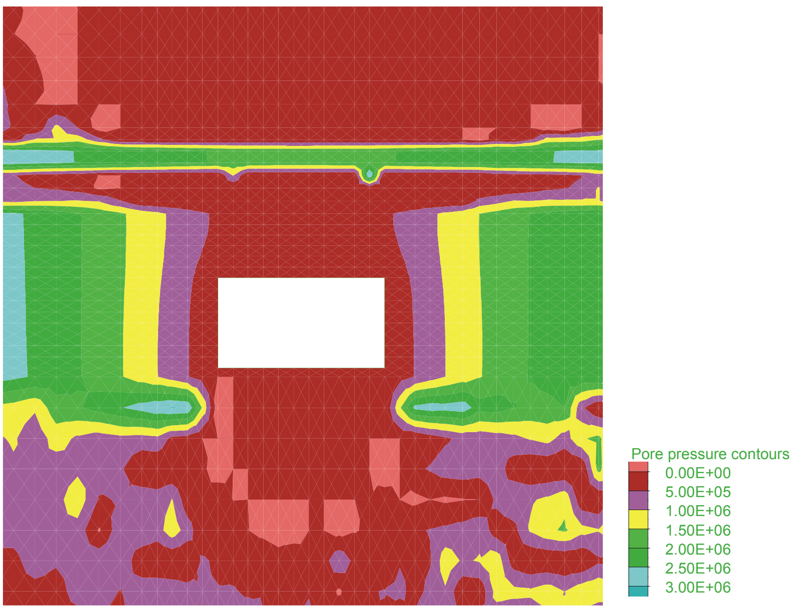


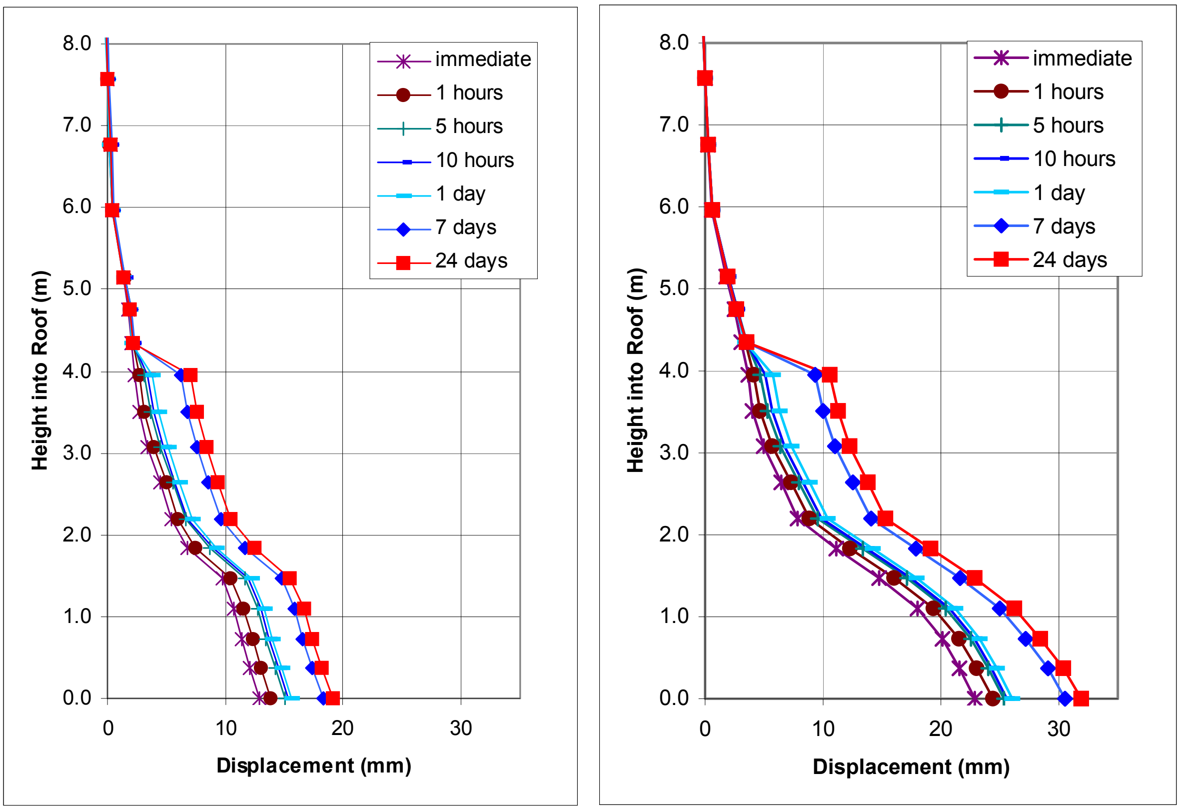
FIG. 10 - Pore pressure distribution around roadway, 5 hours after excavation

The modelling results demonstrated that, in thick seam mining where gas and water pressure exert an influence on the overall properties of the coal seam, the pore pressure and fluid flow could play an important role in the behaviour of the roadway. The effects of pore pressure and fluid flow need to be considered in the stability assessment of the roadway spans.

Additional modelling was conducted using the 2D coupled mechanical-fluid flow model at different depths. The modelled roof displacement at two depths (220m and 300m) are plotted and compared in FIG. 11. The case of increased depth will also be relevant to the Site 2 condition where higher *in situ* stress existed, equivalent to a deeper location.

At the current depth of 220m where the measurements were conducted, the predicted maximum roof displacement is 19 mm. The predicted roof displacement is in a close agreement with the measurements from roof Extensometers 1 (FIG. 7a). The model predictions also show a clear time variation due to the fluid flow after excavation.

At the depth of 300m, the predicted maximum roof displacement is 32mm, significantly higher than that at the depth of 220m.



(a) Depth=220m **(b) Depth=300m**

FIG. 11 - Modelled roof displacements at two different depths. The time dependency is caused by fluid flow in the coal seam after roadway excavation.

CONCLUSIONS

The main results of the study are summarized below for the site specified conditions at Moranbah North Mine.

- The monitored roadways at a depth of 220m were stable. However, the roadways at the two monitoring sites 60m apart showed significantly different roof behaviour. The roadway at the second site showed significantly larger roof displacement (50mm) than that at the first site (18mm). The monitored stress change in the roof at the second site was also higher than that at the first site.
- Major geological structures may have affected the roadway roof conditions in the monitored area. The two monitored sites were separated by two normal faults, perpendicular to the roadway axis. The

faults have up to 0.2m displacement and their surfaces are tight. This type of fault is not uncommon in the mine. The monitoring results suggest that the existence of faults has changed the stress regime and altered the mining conditions.

- The measured *in situ* stresses in the coal seam are much lower than those estimated from the overburden depth (the measured vertical stress of 1.3MPa compares with 5.5MPa estimated from overburden depth). The gas/water pressure in the coal seam would have affected the measurement results. The measured stress is close (but not equal) to the effective stress.
- The vertical stress in the immediate coal roof is found to drop immediately after roadway excavation. The magnitude of the stress drop suggests that the vertical stress in the immediate roof may have become tensile immediately after the roadway excavation. It is likely that roof delamination would have occurred in the immediate roof before the installation of roof bolts.
- After its initial drop, the vertical stresses in the coal roof are found to recover substantially (up to 50%) within 10-12 hours after excavation. Numerical modelling results suggest that the stress recovery was caused by the drainage of gas/water and the redistribution of the stresses around the roadway.
- It is geotechnically feasible to apply the ACBM system at the current depth in Moranbah North Mine. It is emphasized however, that geotechnical conditions (including *in situ* stresses) may vary significantly, particularly where faults exist. The localized deterioration needs to be considered in mining planning and design.

It is emphasized that, when mining in thick seams particularly with high pore pressure, fluid flow has significant impact on the stability of the roadways. It is recommended that the effects of pore pressure and fluid flow be considered during roadway support design and strata control. The study results also demonstrated the need for a better understanding of the stress and stress measurement results in the coal seam. A clear, quantitative relation between the measured stress and the effective stress/total stress in the coal seam should be developed for the conventional stress monitoring techniques.

ACKNOWLEDGEMENTS

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