ROCK FRACTURE, CAVING AND INTERACTION OF FACE SUPPORTS UNDER DIFFERENT GEOLOGICAL ENVIRONMENTS. EXPERIENCE FROM AUSTRALIAN COAL MINES

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Abstract

This paper is presents a summary of recent investigations into fracture and caving about longwall panels. The results of these investigations indicate that rock failure initiates well ahead of the longwall face. Rock fracture typically forms in response failure through the material and bedding planes. Tensile fractures also form in massive units. These fracture patterns typically create a fracture network which determines the caving characteristics encountered at the faceline. The action of longwall face supports under such conditions is to maintain confinement to the fractured ground and develop a consistent caving line. The confinement developed above the canopy under these conditions can be variable on a shear by shear basis and the operational face support procedures play an important role in stability about the face area.

INTRODUCTION

This paper is presents a summary of recent investigations into fracture and caving about longwall panels. The aim of the work was to provide a greater understanding of the ground caving process and the implications to longwall support operation and design.

This work has been undertaken utilising computer simulation of the ground fracture process and stress redistribution about longwall panels together with micro seismic monitoring and geotechnical monitoring. Monitoring of support pressure, subsidence and stress distributions were undertaken to provide validation data for the models. Much of the work represents a collaborative effort undertaken by SCT Operations, CSIRO and Mine Operators.

The primary aim of the computer modelling was to:

i. simulate the fracture distribution and caving mechanics within a range of different strata sections;
ii. assess the interaction of longwall supports on ground behaviour.

The aim of the micro seismic investigations was to determine the location of rock fracture about longwall panels.

The minesites studied represent a significant range in the geological and geotechnical characteristics of the overburden strata. The range extends from a massive sandstone (20-30m thick) to weak interbedded strata.

Computer modelling has provided a significant insight into caving mechanics and has been extensively used in the investigations.

COMPUTER SIMULATION METHOD

Computer simulations have been undertaken at a wide variety of minesites and found to display a good correlation to field measurements and visual observations of longwall behaviour. Examples of the method have been published (Gale, 1998), (Sandford, 1998) and Kelly et al, 1998 Kelly and Gale 1999.

The model is two-dimensional and represents a longitudinal slice along the central zone of the longwall panel. Three dimensional effects about the gate ends are not represented in this model, however field monitoring indicates that the central section of the longwall panel is represented very well, particularly for panels which are significantly wider than deep (e.g. supercritical width panels).

The code used in the model is FLAC and uses a coupled rock failure and fluid flow system to simulate the behaviour of the strata and fluid pressure/flow effects. The rock failure and permeability routines have been modified to enhance the representation of the rock fracture characteristics. Rock failure is based on Mohr-Coulomb criteria relevant to the confining conditions within the ground. The intact and post failure characteristics of the rock units are simulated. Permeability in the horizontal and vertical planes is determined on the basis of the confining stress normal to the flow plane. The permeability of fractured coal has been defined on the basis of confining stress and the fractured state.

Computer models are developed on the basis of detailed geotechnical testing of strata properties. Detailed models of the geology are necessary to obtain a satisfactory simulation of the rock failure mechanics. Definition of the rock intact and post failure strengths, stiffness, in situ stresses, permeability and bedding plane characteristics are key factors to be quantified.

The in situ strength of the rock materials is reduced to 0.58 the laboratory UCS. This is consistent with the general Hoeke & Brown relationships but also is consistent with “scale effects” as reported from other methods.

The model simulates rock fracture and stores the orientation of the fractures as potential ubiquitous planes. Shear fracture, tension fracture of the rock, bedding plane shear and tension fracture of bedding is determined in the simulation. The stability of pre-existing jointing, faults or cleat is also addressed in the simulations where appropriate.

Longwall supports are simulated with a hydraulic set and yield function. The support pressure is transferred into the strata via a canopy and base structure. The support pressure and the canopy distance to the face can be varied to assess operational variations on stability about the face area.

The model simulates the mining process by progressively excavating approximately 1m shears, allowing caving and then excavating the next shear and advancing the face supports. Goaf formation occurs and is controlled by consolidation stiffness and post failure criteria of the caved material. Ground movement, rock fracture zones, water pressure, longwall support load/convergence and abutment stress distributions are determined and recorded for each "shear" as the longwall retreats. A movie of each mining shear is recorded to show the progressive rock fracture, stresses and support behaviour. Ground displacements, rock fracture and stress redistributions can be assessed within various rock units and geometries about the extraction panel.

The overall scale of the model is presented in Figure 1 together with the window area where the detail is increased and where most of the figures presented below will be taken from. The grid size in the detailed area is typically 0.5-0.6m.

GENERAL GROUND BEHAVIOUR ABOUT A LONGWALL FACE

The mode of rock fracture and the location about longwall panels has been reported (Kelly and Gale, 1999, Gale et al, 2001, Hatherly et al 2003, Gale, 2001). These studies and others have used computer modelling and micro seismic monitoring. Micro seismic monitoring was used to determine the distribution of rock fracture and in some instances the focal plane solutions are used to determine the fracture orientation. The micro seismic monitoring was undertaken using multiple three dimensional geophones in boreholes. Location accuracy of events was estimated to be within approximately 10m.

Ground behaviour ahead of the face is influenced by the effective stress conditions within the rock. The work indicates that shear fracture of materials and bedding interfaces occurs well ahead of the faceline.

The rock failure occurs in relation to the stress changes generated in the rock. Typically the stress changes are:

i. an increase in the maximum principal stress due to stress concentration effects about the goaf,
ii. a decrease in the confining pressure resulting from stress relief into the goaf,
iii. an increase in the pore fluid pressure within the strata,
iv. variation in stresses due to ground flexure.

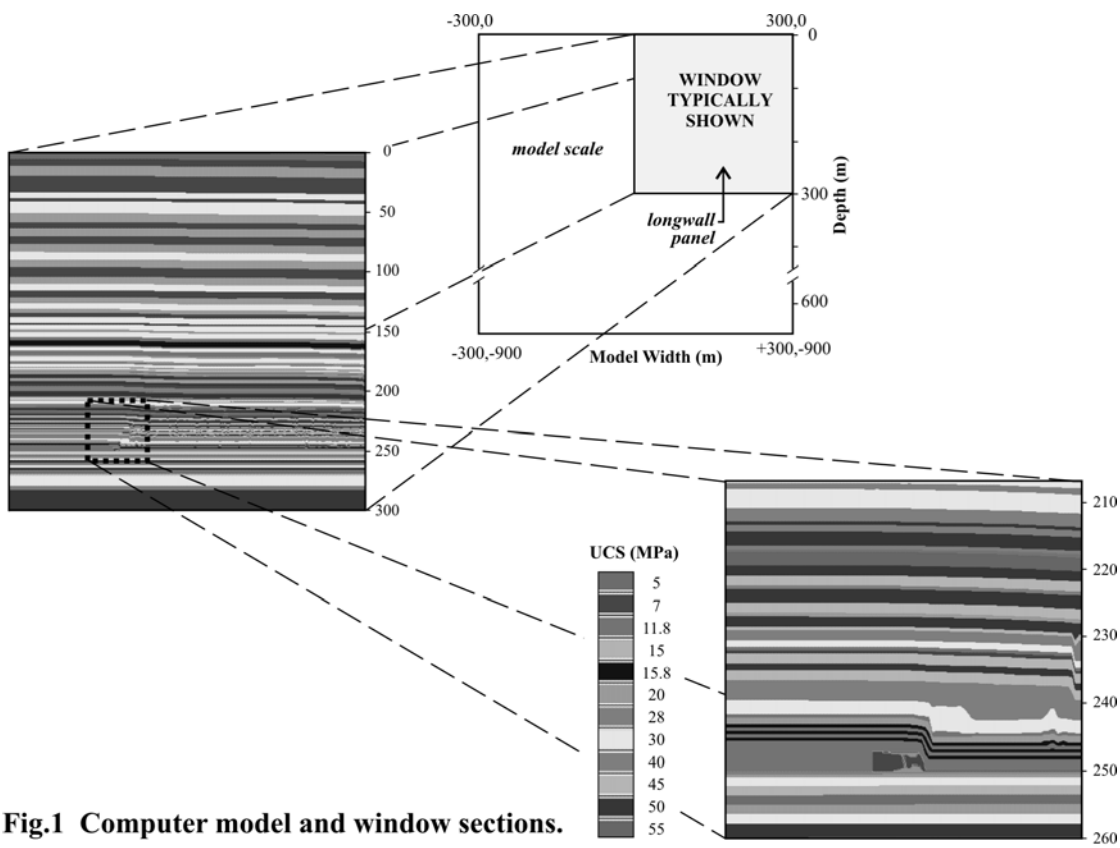


Fig.1 Computer model and window sections.

These stress changes will generate an individual stress path for a particular section of rock within the overburden. Considering the variations in material properties and their distribution, the stress paths within the strata may be quite variable and generate a variety of fracture modes which thereby creates a fracture network. Analysis of micro seismic events indicates that the magnitude of events recorded about the face area of longwall panels is typically less than a Richter magnitude of 0. The size of the typical fractures formed during the events recorded are estimated to be typically less than 3-5 m in length (Hatherly et al, 2003).

CAVING IN A WEAK TO MODERATE STRENGTH ROOF SECTION

An example of the results of the modelling in a relatively weak geotechnical environment is presented in Figures 2 and 3. Figure 2 shows the geological strata distribution of a small section of a model. The strata are displayed on the basis of their Unconfined Compressive Strength (UCS). The Seam (3m thick) is mined within weak (5–20MPa) laminated siltstone and mudstone. Some stronger sandstone bands occur but are higher in the section or are relatively thin.

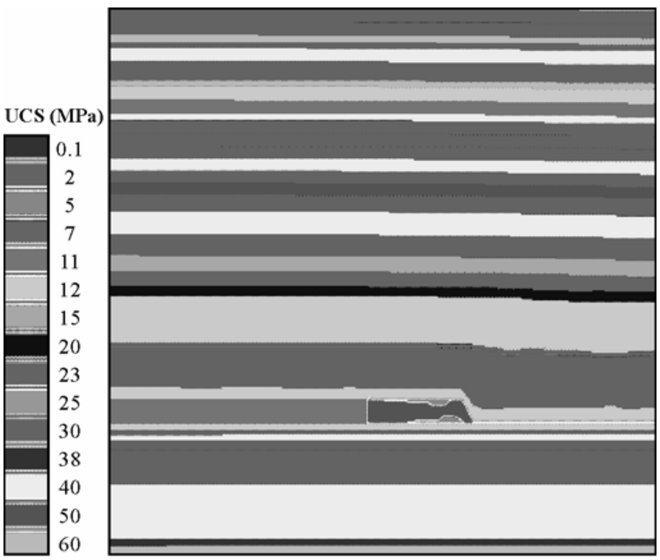


Fig.2 Strata section at this site.

The location and type of fractures about the mining face of a longwall panel within this strata section are presented as a two dimensional slice in the central region of the face in Figure 3.

This shows a combination of bedding plane shear, tensile fracture of rock and bedding together with shear fracture occurring as part of a fracture network. The key feature is that rock fracture is occurring well ahead of the face and is not related to the caving process behind the supports.

Another feature is the general size of the fractures formed in this region. In general, the fracture size is variable, however shear fractures tend to be limited to less than a couple of metres and form in an incremental manner rather than one large event. Tensile fractures are similarly restricted in size and result from bending moments within the stronger sandstone units. These tensile fractures tend to form ahead of the face line also.

Shear of bedding planes may extend over variable distances ahead of the face but typically extend over large scale (often in excess of 100m). Rock fracture typically extends into the floor strata.

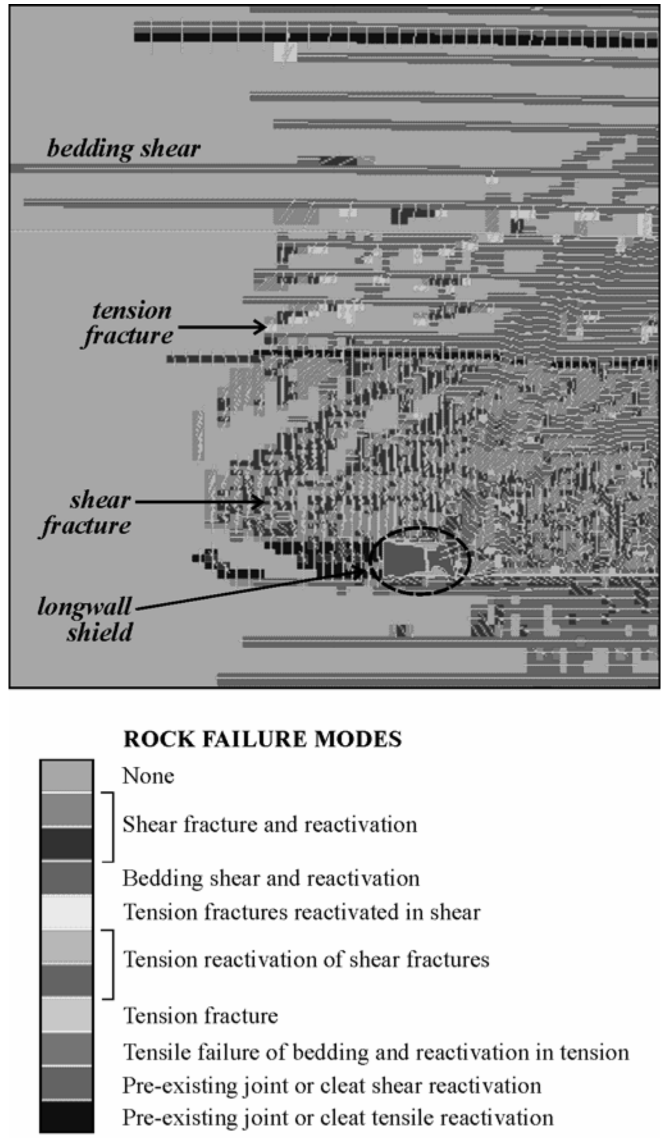


Fig.3 Rock failure mode and fracture orientation.

These fracture sizes will be dependent on the geology of the site and clearly some deviation from this generality will occur. In general, the computer modelling indicates that rock fracture and the resultant seismic activity would be expected to be monitored ahead of the face rather than behind the face. This seismicity would be associated with rock fracture associated with the abutment stress geometry rather than the caving process above and behind the longwall supports.

Micro seismic monitoring associated with this geological setting is presented from a study conducted at Gordonstone Mine. The micro seismic study was reported by Hatherly et al (1995), Kelly and Gale (1999).

The key findings, from a rock mechanics viewpoint, were:

1. The rock fracture was recorded well ahead of the mining face within the roof and floor strata.
2. The dominant rock failure modes recorded were shear fracture of rock and bedding.
3. The relative absence of caving related failure recorded within the strata.
4. Focal plane solutions for key events confirmed the shear mode of rock failure and geometry.
5. The magnitude of events was typically low (less than a Richter magnitude of -1).

The location of events in a section about the central zone of the longwall panel is presented in Figure 4 and the focal plane resolutions are presented in Figure 5.

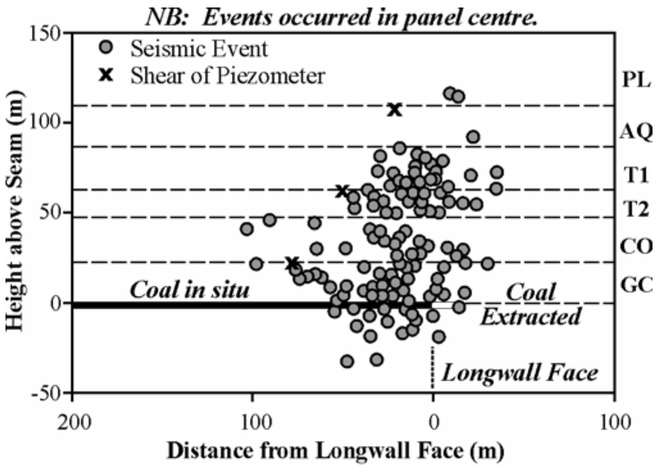


Fig.4 Location of microseismic events.

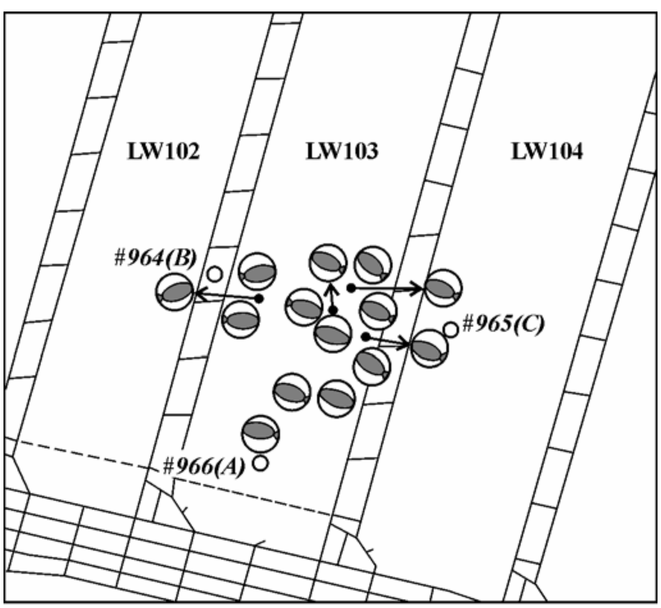


Fig.5 Focal plane resolutions.

Overall, the computer simulation and the micro seismic monitoring show very complementary results. The modelling provides an insight into the mode of failure represented by the micro seismic activity. The overall results indicate that the rock fracture and the caving characteristics were pre determined well ahead of the faceline.

CYCLIC CAVING IN MODERATE STRENGTH MASSIVE STRATA

Cyclic caving is defined as caving and/or support loading which occurs on a regular cyclic basis. This typically takes the form of high support loading and immediate roof and rib fracture occurring in regular cycles of say 10-20m separation.

Significant convergence of the supports may occur in response to overburden movement typically occurring during these cycles. Support loading is less and ground conditions are typically significantly better when mining between cycles than within a caving cycle.

Cyclic caving has been found to occur as a result of a regular fracture network being developed within specific massive units in the caving zone. This typically occurs within sandstone units which have a massive nature (i.e. strong bedding plane characteristics) or which act as a massive unit within a much weaker rock mass. This type of fracture was found in the caving at South Bulga and Moranbah North Mines. An example of the fracture mode modelled for South Bulga is presented in Figure 6a. The UCS of the sandstone unit is approximately 40MPa and has very little bedding definition. The effect on face support pressures is presented in the Figure 6b which shows the cyclic and rapid increase in face support loading within these cycles. Surface extensometers were installed to monitor the overburden caving within this environment.

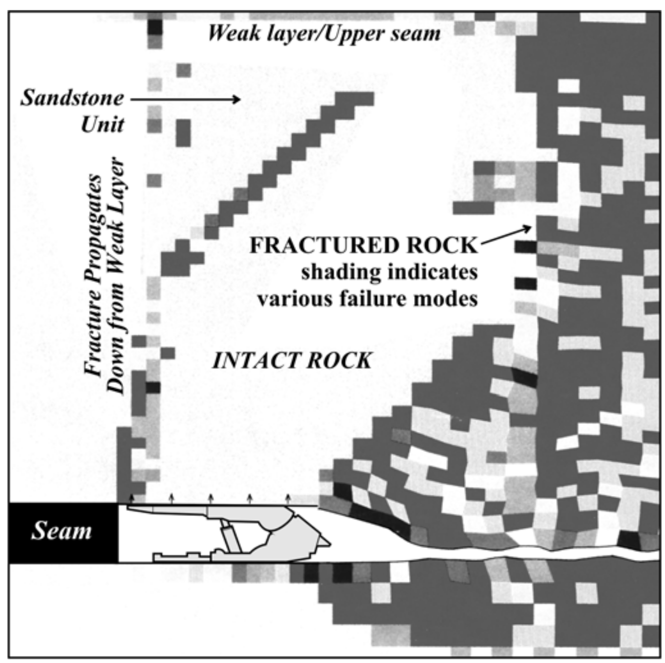


Fig.6(a) Fracture mode developed for South Bulga geological units.

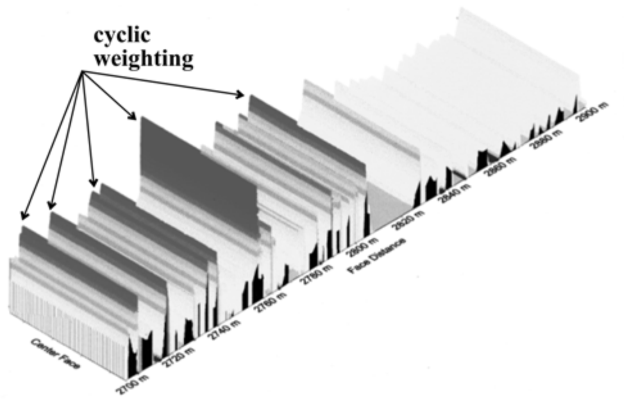


Fig.6(b) Survey showing rate of pressure increase in longwall supports.

The extensometer results together with that obtained from the model simulation is presented in Figure 7. The results indicate the formation of a block in the immediate roof early in the caving process, and display a close correlation in ground displacement profile.

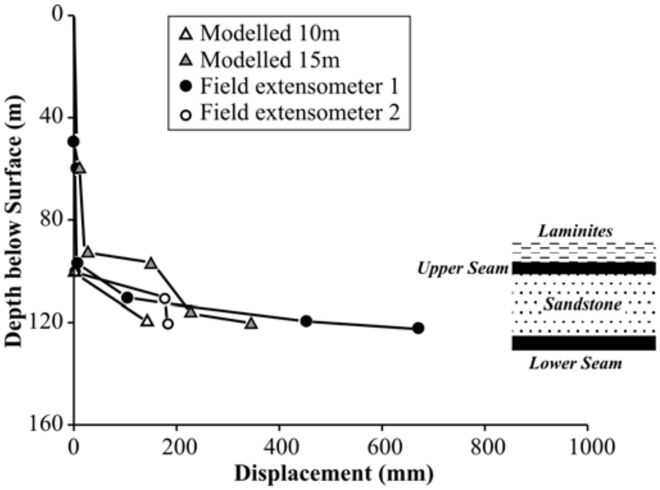


Fig.7 Field and modelled extensometer results with geological section for South Bulga.

The modelling of the process indicates that the massive unit develops bending stresses in response to the overburden subsidence onto the goaf. Fractures initiate ahead of the face.

An example of the stress distribution and fracture modes developed within a massive sandstone unit modelled for Moranbah North Mine geological section is presented in Figure 8. The immediate roof material is a weak mudstone and siltstone sequence (5-20MPa) overlain by a sandstone channel 40-60MPa). This shows the minimum principle stress distribution at the initiation of a cyclic fracture event. This stress distribution is primarily influenced by bending stresses within the unit generated by its resistance to displacement of the overburden above, onto the goaf.

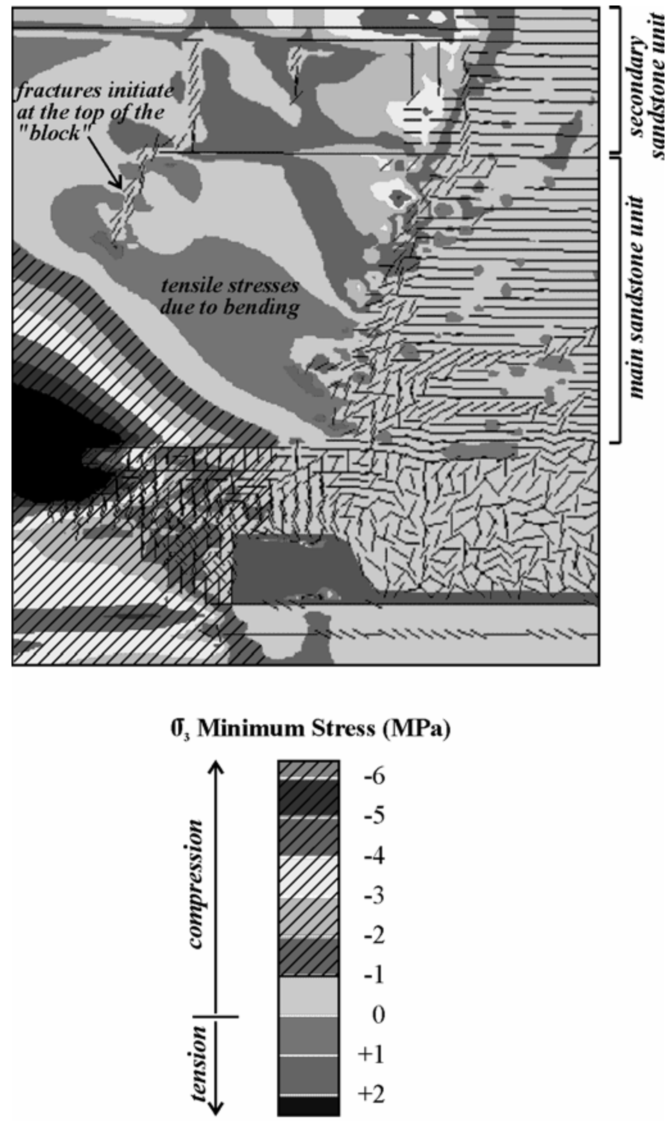


Fig.8 Minimum stress distribution and fracture mode for channel sandstone modelled at Moranbar North.

The massive sandstone unit is 20m thick. Above this is a 10m thick laminated sandstone with a partially failed bedding plane contact to the massive sandstone below. In general, both sandstones act together ahead of the face and the failure of bedding is one part of the fracture process. The fractures forming in a diagonal geometry initiate from the tensile stresses forming at the top of the sandstone unit. These fractures may be shear or tensile depending on the stress path in relation to the material strength properties.

The minimum stress distribution develops incrementally within the sandstone as the mining face moves under the unit, until the failure criteria is met in the upper section and then progresses down toward the seam. At this stage, a rapid fracture network forms and the resistance to overburden movement is lost within the unit.

A consequence of the loss of bending moment in the massive unit is "overburden rebound" whereby the overburden will displace onto the face and goaf area as the fracture network forms. The cyclic weighting or cyclic caving event is a combination of the fracture network being formed and the convergence of the overburden. The (rebound) convergence of the overburden "drives" the convergence which may be experienced at the working face. This convergence may be instantaneous or occur over a number of shears depending on the strata distribution.

This mechanism is a modification to the concept of bending of the strata to form a large block which then loads the supports by its weight. Experience of such cyclic events indicates that a block formed in this manner will be controlled by normal stresses (interlocking stresses) acting on the block and the potential for a free weight loading is low.

Experience at South Bulga, Moranbah North and Clarence Mines indicates that the movement associated with these events has a finite displacement which may occur over a varying timeframe. This is more consistent with overburden rebound driving the convergence than gravity dropout of an isolated block overcoming the support resistance.

The magnitude of the convergences noted at field sites is consistent with the scale of the anticipated overburden rebound. This is typically 0.1-0.6m.

However close to the face rib spall and support rotation can allow falls and "unravelling" of the fractured rock ahead of the supports.

The severity of cyclic caving is related to the thickness of the massive unit, the material below it, the stiffness of the material in the overburden above the unit and face control procedures to maximise the stability of the immediate roof zone and prevent any "unravelling".

This process has been modelled on a large scale indicating the effect of weak ground and a channel sandstone unit. The fracture formation obtained from that work is presented in the movie.

MODERATE STRENGTH INTERBEDDED SECTION

Considering the interbedded nature of sedimentary strata it is common for combinations of the fracture modes discussed above to form within different sections of the overburden. The actual caving mode will be a function of the interaction of the strata about the seam and in the overburden as a whole.

A combination of shear and cyclic fracture modes was noted at Ulan Mine. The strata section is presented in Figure 9 and rock fracture geometry noted in the Ulan model is presented in Figure10.

This was a (relatively) stiff but bedded sequence having UCS in the range of 20-60MPa. A cyclic fracture system formed a block in the intermediate strata below an upper coal seam. The cyclic block formation did not cause significant problems on the face. This is anticipated to result from the bedded nature of the strata which, although it formed an interlocking fracture network ahead of the faceline, the geometry and stiffness of the fractured strata was insufficient to develop a significant overburden rebound effect.

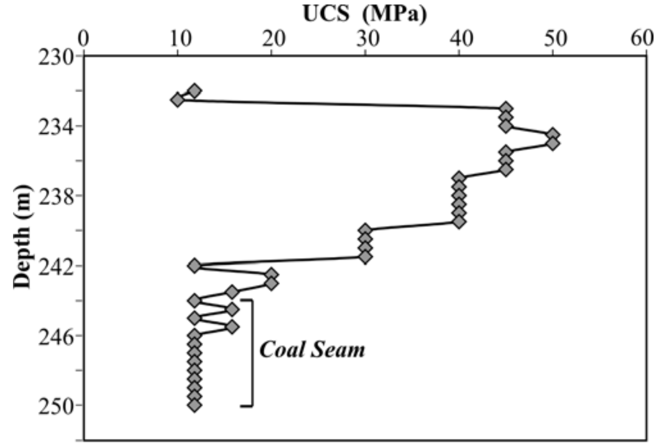


Fig.9 Detailed section above the seam floor.

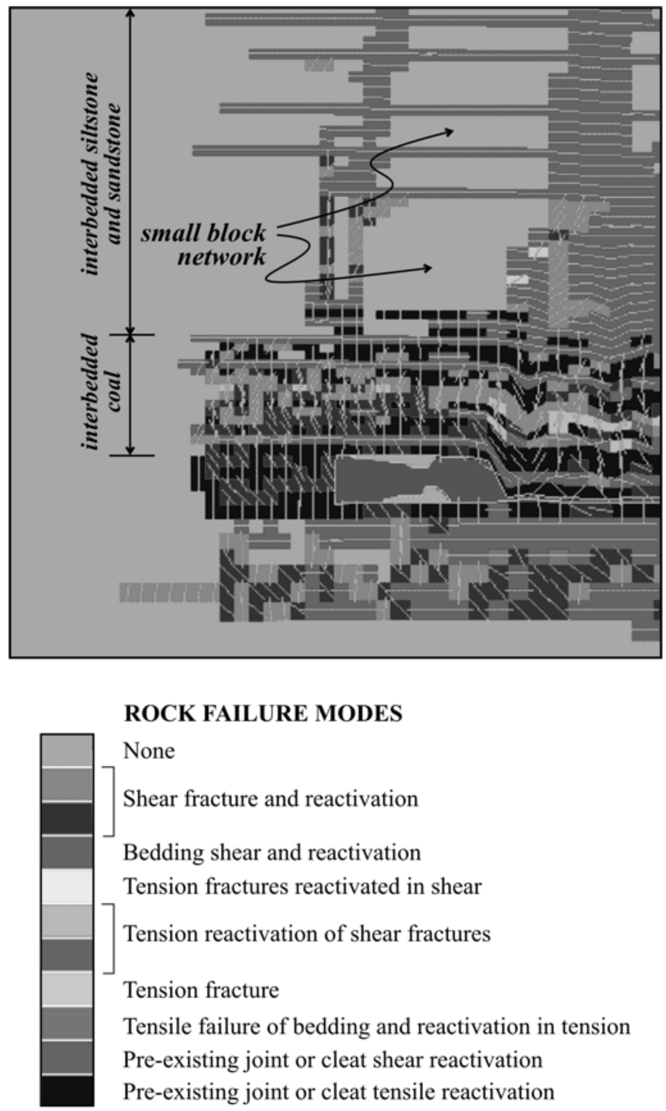


Fig.10 Rock failure network created in this section.

INTERACTION OF FACE SUPPORTS IN THE IMMEDIATE ROOF

The discussion above has related to large scale caving and fracture networks which influence the gross rock movements. In this section, the action of longwall supports and their impact on ground movement about the face area is discussed. The computer modelling was utilized to assess the stresses transferred above the canopy and their impact of ground behaviour about the face line.

The interaction discussed in this paper relates to weak strata sections.

A review of computer models within weak ground indicates that the vertical stress and horizontal stress distributed above the canopy play a major role in maintaining ground control about the longwall. It has also been found that the stress distribution above the canopy can vary on a shear by shear basis and is dependent on the integrity of the rock in the immediate roof above the canopy.

A situation having an optimum vertical load transfer into the roof is presented in Figure 11. In this section the strata are extensively fractured ahead of the face. The action of the vertical stress is to provide a break of line to the goaf (caving line), and to confine the strata above the support canopy. The horizontal stress provides confinement to high angle fractures ahead of the canopy. If both stress distributions are generated, the face area is contained and stable despite being fractured.

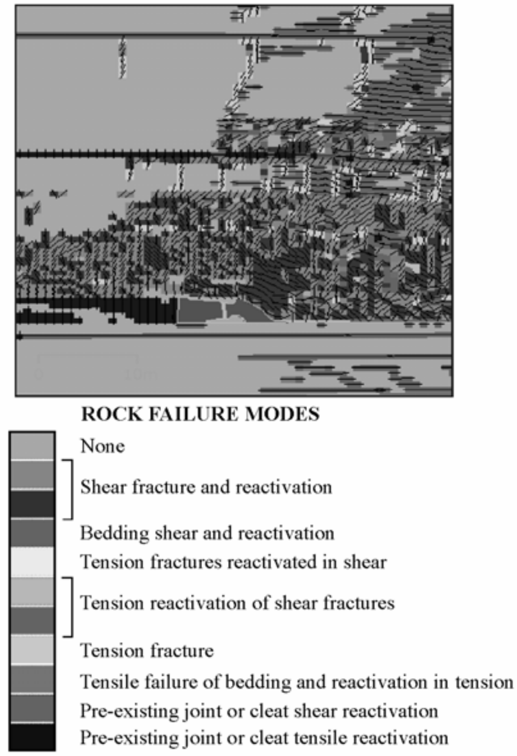
The impact of a poor vertical load transfer into the same roof is presented in Figure 12. This shows a very weak definition of the goaf caving line and the loss in confinement allows loosening of the rock above the canopy to occur from the faceline over the canopy. The effect of this is to allow the canopy to push into the dilated roof rock and induce canopy rotation such that the tip rotates down off the roof. If this occurs the supports typically do not achieve full set load. In this situation, the horizontal stress is not developed in the broken and unconfined strata above the canopy. The effect of this is to allow falls to occur ahead on the canopy as the coal is cut. This can also lead to goaf override of the face supports if the caving line is not sufficiently developed (Nicholls, 2001).

The photograph demonstrates an example of the loss of forward control is considered to be the equivalent situation as depicted within the models.

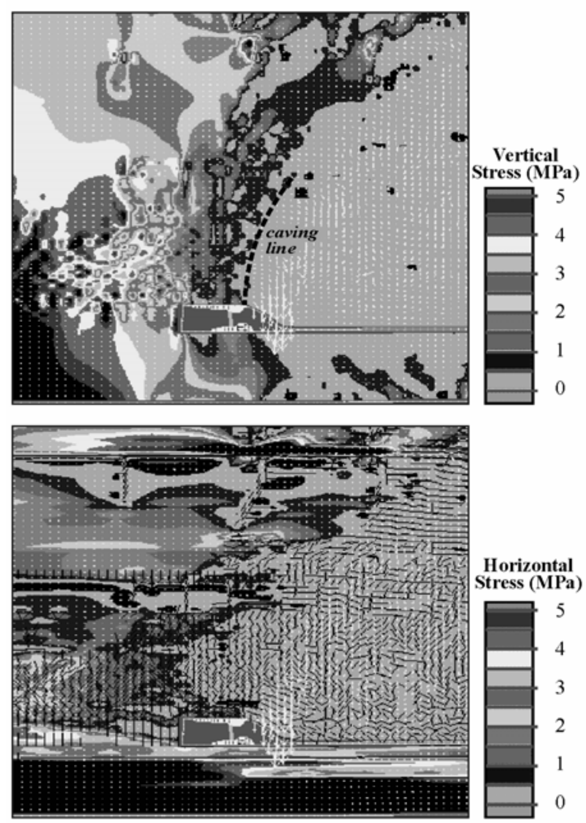
FRACTURE MODE AND GEOMETRY ANTICIPATED HIGHER INTO THE OVERBURDEN

Seismic and micro seismic monitoring have defined the existence of large scale seismic events about longwall panels. These events have been related to re-mobilisation of faults and the fracture of ground in the overburden. Computer modelling of the overburden behaviour with single and multiple longwall panels has been undertaken and indicates the potential for large magnitude seismic events within the overburden (Gale et al, 2001).

The potential exists where key relatively thick strata sections are in the transition geometry from a spanning geometry to a caving geometry. This can occur for a wide range of geometries and caving scenarios. The nature of the deformation and fracture depends on the strata section.

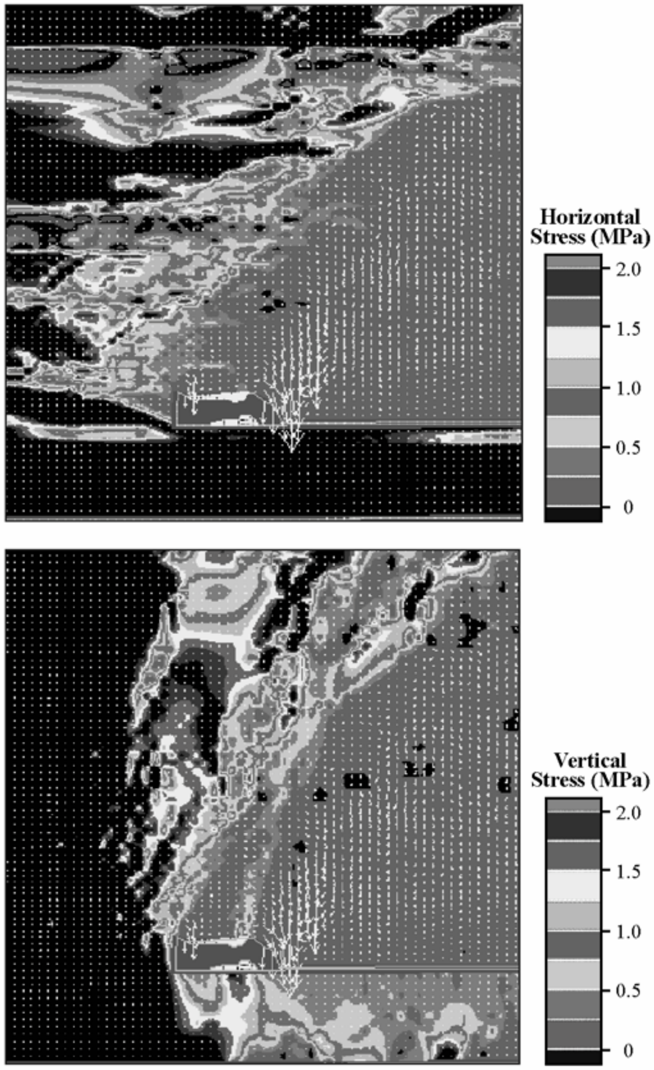


a) Rock failure and fracture mode.



b) Vertical and horizontal stress and displacement indicators.

Fig.11 Stress distributions about longwall supports displaying optimum stress transfer.



a) Vertical and horizontal stress and displacement indicators.

b) Physical representation of the modelled situation.

Fig.12 Stress distributions about longwall supports displaying poor stress transfer.

An example of a fracture pattern consistent with dynamic events which visibly shook and loosened the fractured ground about the face is presented in Figure 13. In this case it was noted during operations that major events were occurring on a "semi regular" basis with a spacing of 40-100m.

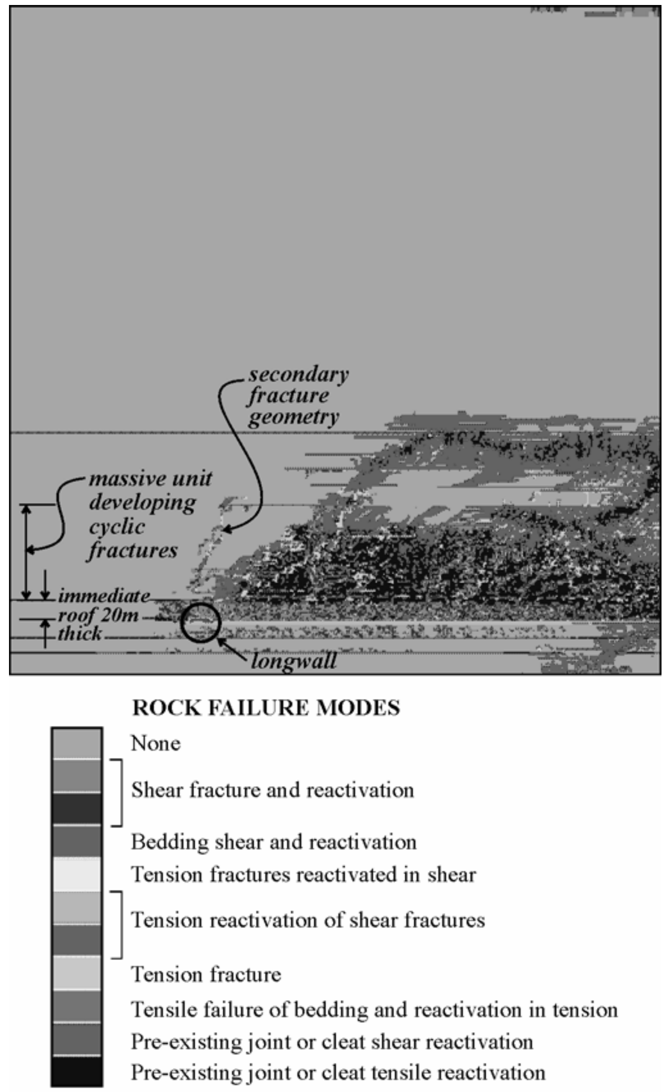


Fig.13 Fracture pattern modelled in overburden consistent with widely spaced dynamic events.

One of the outcomes from the computer modelling of this site indicated that a large scale failure zone would be anticipated higher into the geological section as a result of overburden spanning characteristics. The high angle fractures form within the spanning/cantilevering strata and propagate rapidly. High energy seismic release would be anticipated. There was no micro seismic program at this mine and as such the validation is via site experience.

Another form of overburden fracture causing seismic events about a deep longwall panel was discussed in Gale et al, 2001.

DISCUSSION AND CONCLUSIONS

This paper presents a review of recent investigations and highlights the insights obtained from computer modelling. The results from this approach have required detailed computer models and targeted field investigations. The results also demonstrate the usefulness of micro seismic investigation and targeted geotechnical monitoring in providing a wider understanding of the ground behaviour.

The studies conducted provide encouragement in the capability of computer models to simulate the caving environment, strata fracture characteristics and longwall support interaction. Current application of the caving simulation is being extended to large scale panel interaction and fracture induced permeability below the seam and within the overburden.

REFERENCES

Kelly M., Gale W.J., Luo X., Hatherly P., Balusu R. and Le Blanc G., (1998). Longwall Caving Process in Different Geological Environments Better Understanding through the Combination of Modern Assessment Methods. Proceedings of International Conference on Geomechanics/Ground Control in Mining and Underground Construction 14-17 July 1998, Wollongong NSW Australia Vol 2 pp 573-589.

Sandford J., (1998). Review of Longwall Mining Experience at South Bulga Colliery. Proceedings of International Conference on Geomechanics/Ground Control in Mining and Underground Construction 14-17 July 1998, Wollongong NSW Australia Vol 2 pp 591-597.

Gale W.J., (1998). Experience in Computer Simulation of Caving, Rock Fracture and Fluid Flow in Longwall Panels. Proceedings of International Conference on Geomechanics/Ground Control in Mining and Underground Construction 14-17 July 1998, Wollongong NSW Australia Vol 2 pp 997-1007.

Nicholls B., (2001). Longwall Mining in soft rock environments. Longwall USA Pittsburgh, June 2001

Kelly M. and Gale W.J., (1999). Ground Behaviour about Longwall Faces and Its Effect on Mining. ACARP Project C5017 Report February 1999.

Gale W.J., Heasley K.A., Iannacchione A.T., Swanson P.T., Hatherly P. and King A. (2001). Rock Damage Characterisation from Micro Seismic Monitoring. Proc. 38th US Rock Mechanics Symposium. DC Rocks 2001. pp 1313-1320.

Gale W.J. (2001). Production and Management of Adverse Caving Effects on Longwall Faces. ACARP Project C7020 Report September 2001.

Hatherly P., Gale W.J., Medhurst T., King A., Craig S., Poulsen B. and Luo X. (2003). 3D Stress Effects, Rock Damage and Longwall Caving as revealed by Micro Seismic Monitoring. ACARP Project C9021 March 2003.

Hatherly P.J., Luo X., Dixon R., McKavanagh B., Barry M., Jecny Z. and Bugden C. (1995). Roof and Goaf Monitoring for Strata Control in Longwall Mining. ACARP Project Report C3067 1995.