Combining Modern Assessment Methods to Improve Understanding of Longwall Geomechanics

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ABSTRACT

Ongoing, collaborative research between CSIRO's Exploration and Mining and Strata Control Technology has resulted in a better understanding of rock failure mechanisms around longwall extraction. Failure has occurred further ahead of the retreating face than predicted by conventional longwall geomechanics theory. In some cases significant failure has been detected several hundred metres ahead of the face position with demonstrated influences of minor geological discontinuities. Shear, rather than tensile failure has been the predominant failure mechanism in the environments monitored. Validating technologies of microseismic monitoring and new face monitoring techniques have assisted the development of predictive 2D computational modelling tools. The demonstrated 3D consequences of failure has assisted in the ongoing direction of the project to further investigate these effects.

INTRODUCTION

Despite the impressive growth in Australia's longwall production, many longwall mines have experienced major geotechnical problems. Unexpected geological intrusions and fault zones have resulted in loss of production over extended periods in some mines. Stress concentration in gateroads is another a major problem. In some mines, high gas emissions have resulted in production delays up to 20%, leading to lower production and productivity. Water ingress from overlying aquifers or watercourses has also been an issue. In the past five years, cyclic loading under massive strata and the associated problems with face stability and windblasts has also occurred. Subsidence of surface features, roads, water bodies, dams are some of the other problems which have restricted the longwall operations.

These types of problems are not just confined to Australia and are common in many countries, restricting the production potential of modern longwall faces. In addition, longwall panels have been trending both wider and longer to increase productivity. To support these larger capacity longwalls and to reduce the risk of occurrences that limit productivity, there needs to be an improvement in the understanding of longwall fracturing processes .

In order to improve understanding of longwall fracturing and caving, research into caving processes across a broad range of underground environments is being undertaken by CSIRO Exploration and Mining and Strata Control Technology (SCT). In this paper there is a brief review of the literature, a description of the methods used in this work, and a discussion of the results and insights into longwall caving process that have been obtained.

BRIEF LITERATURE REVIEW

There have been many studies into the geomechanical behaviour of longwall faces, and there is considerable variation in both the approach and underlying assumptions. Attempts have been made to analyse the caving mechanism using numerical models, empirical models, physical models and various forms of field measurement techniques. Most researchers link the extent of fracturing to extraction thickness and a number of relationships have been proposed to predict fracturing extent (Wilson, 1964, 1983; Peng and Chiang, 1984; Kidybinski & Babcock, 1973; Zhu, Qian & Peng 1989; Whittaker, Gaskell and Reddish, 1990). These studies suggest that front abutment pressure reaches a peak value approximately 3 to 5 m in front of the face and is about 4 to 6 times the overburden pressure.

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Most studies suggest that there is vertical fracturing due to tensile failure ahead of the face, because the peak front abutment stress is thought to be very close to the face. However, such models are contradicted by time domain reflectometry (TDR) studies (Dowding, Su and O'Connor 1989; Haramy and Fejes, 1992), which suggest shear rather than tensile failures in the roof rock 15 to 20 m ahead of the face. This suggestion also indicates a different type of stress distribution around a longwall face and raises questions about many of the assumptions in current longwall design methods. In addition, knowledge of actual fractures zones and failure mechanisms ahead of the face and in the floor is limited.

Conventional field investigations (Wilson, 1964; Wagner and Steijn, 1979; Christiaens, 1982; Freeman and O'Grady, 1992) using stress cells, extensometers and convergence measurements often refer to the region very close to the face, and are insufficient to understand the rock mass behaviour further ahead of the face. Investigations involving surface boreholes and extensometers, such as camera surveys of borehole walls before and after mining, give some idea on the vertical extent of fracture zones. However, they are difficult to undertake, time consuming and expensive. In addition, the amount of data that can be obtained from such field studies, including TDR monitoring, is limited and is insufficient to characterise the complete caving process.

It would therefore seem that there is no clear understanding of the stress distribution and failure mechanism ahead of a longwall face, and that more comprehensive and thorough investigations are necessary to achieve such an understanding. However, this now appears to be possible with investigations by Sato and Fujii (1988), Styles, Bishop and Toon (1992) in Britain and by Hatherly et al (1995) at Gordonstone Mine showing that microseismic monitoring can provide large sets of three dimensional and dynamic data on stresses and failure mechanisms at minimal cost. Such data provide validation for the numerical simulations, which can now be produced with increasing sophistication and accuracy.

THE CURRENT STUDY

This current longwall study is aimed at improving face design and control methods by better defining strata failure mechanisms around the face. It will allow design and predictive tools to be developed for a broad range of underground environments. Specific mines are being studied to allow a rational understanding of the caving process and in turn its relevance to fluid flow, stress distribution and support interaction. Microseismic monitoring, 2D and 3D computational modelling, longwall face monitoring and new soft rock testing procedures are being used.

Microseismic monitoring

Most microseismic monitoring is mainly undertaken for the forecast and control of rockbursts, mine bumps and failures (Young, 1993; Coughlin and Rowell, 1993; Miller and Descour, 1996). This is an important application but represents only one aspect of its geotechnical uses. The potential of microseismic monitoring in understanding the longwall caving processes has been largely unexplored until recently.

The microseismic monitoring is utilising arrays of three-component geophones grouted within boreholes drilled from the surface to the working seam. Microseismic activity is monitored continuously as mining progresses. The number of boreholes and location of geophones depends on the geology and geometry of the area being monitored. The system includes a monitoring unit and computer data storage devices installed on the surface in a modified shipping container. The system is self contained with diesel generators providing power and a mobile phone with modem providing remote phone-in access. Geophone orientations and seismic wave velocities are established by firing of shots at known locations.

Numerical modelling of longwall caving

The program FLAC (Itasca, 1995) is used as the basic numerical modelling program with additional proprietary rock failure and goaf consolidation subroutines which simulate the longwall caving process and allow more rational prediction of stress distributions and displacements occurring around longwall faces. The code can handle the wide range rock mass failure conditions which exist around a forming goaf and complex fluid and ground deformation capabilities.

The rock failure routines define the orientation and properties of fractures created in the rock mass from various failure models. These are: (i) shear fracture through intact rock, (ii) shear failure along bedding, (iii) tensile fracture of intact rock, and (iv) tensile breakage along bedding planes. In addition, the orientation of pre-existing joints and the failure planes generated are analysed to assess stability under conditions of tension and shear, as the ground moves backwards into the extracted void. The goaf consolidation routine assesses stiffness of the caved material as a function of load and void space. The type of fracture and its orientation are displayed in the output.

The approach used in modelling is to excavate an approximately one metre wide 'web' (shear slice), calculate the ground response and then to repeat the process. The simulations also include coupled fluid pressure as part of the rock failure process. To date, the simulations have been two-dimensional simulations of the central part of a longwall panel where the panel is of supercritical width and the out-of-plane third dimension has least effect.

The question of 3D modelling versus the 2D used in the study needs comment. The level of detail required to adequately represent failure development using a discrete web width of one metre is such that the model requires a three week continuous run on a fast work station. A 3D model of the same detail is therefore not practical. However, we have commenced to model a broader, less detailed situation using the 3D code ABAQUS (Hibbit, Karlson and Sorenson, 1995) to understand the influence of structure and adjacent longwalls on the failure mechanisms of the current block.

Face monitoring

The longwall face monitoring component of this work has involved the monitoring of chock leg pressures, face convergence and goaf pressure. A new longwall powered support closure measurement system which does not depend upon potted wires has been developed for convergence monitoring. This system has several advantages over current closure measurement such as spring tensioned wire transducers. By utilising robust transducers mounted in relatively protected areas on the longwall support, the system has greater reliability. The system also provides additional information on the reaction of the base and canopy to loading, which can be used to help analyse support performance. This system is being used in conjunction with support manufacturer's monitoring packages for the monitoring of both leg pressures and convergence on each longwall face during the microseismic monitoring.

Other technologies

A sophisticated triaxial testing facility at CSIRO is being used to quantify rock and coal strength parameters at field sites. The soft rock triaxial testing facility consists of an automated cell pressure control, measurement and data acquisition system. The system can accommodate samples up to 300 mm in diameter. Pre- and post-failure characteristics and volumetric strain response are typically recorded to within 1% accuracy.

In addition, 'Goafmon', an instrument system designed to measure the load exerted by the caved strata in a goaf, has been used. Goafmon comprises a 400 mm diameter flatjack with associated electronics installed in the floor of a goaf, and connected by robust cables to the controller module located in an adjacent roadway. The frequency with which the pressure is monitored is user selectable, and to maintain the integrity of the data there is a full suite of real time synchronisation and error checking routines.

WEAK ROOF STUDIES - RESULTS FROM GORDONSTONE MINE

The Gordonstone Mine is located in the Bowen Basin in Central Queensland. The geology is described by Kelly, Lawrence and Devey, (1994). In the area of the study the 3 m thick German Creek Seam is being mined at a depth of about 235 m. Mining is by the longwall method, with a face width of 250 m. The immediate roof and floor are particularly weak, with UCS values of only 5 - 15 MPa. Stronger bands (UCS of about 50 MPa) occur above the Corvus Seam, some 25 metres above the worked seam. The dominant horizontal stress is NNE, parallel to the panel direction and sub-parallel to the dominant coal cleat and strata joint directions. The thickness of the Tertiary sediments and volcanics is about 70 m.

Microseismic monitoring results

In 1994 a microseismic study was undertaken with the objective of determining whether caving from longwall mining extended to overlying unconsolidated Tertiary sediments and volcanics Hatherly et al (1995). Three boreholes were drilled, and nine triaxial geophones were installed in each. All but the shallowest were below the Tertiary/Permian unconformity. Piezometer readings to supplement the microseismic data were made at depths of 205 m, 170 m and 125 m, from a hole drilled in the centre of the longwall panel and within the microseismic array. The microseismic activity was monitored during September and October 1994. The activity was closely correlated with mining, and in all 1200 events were detected. Of these, 629 with sharp P-wave onsets were located. The remaining events were of lesser magnitude, with indistinct onsets; these are thought to have been from within the goaf and to have occurred after initial failure.

The locations of the microseismic events are summarised in Figs 1 and 2. They are estimated to have an accuracy generally better than 5 m within the microseismic network and 10 m outside. In plan view (Fig. 1) it is apparent that the majority of the events occurred within and above the panel (LW 103) which was being mined. There is a tendency for events to occur on the sides of the panel, and in cross section (Fig. 2) it can be seen that they generally lie within an envelope at some 15° from the vertical above the gateroads. Fig. 2 also shows that the events extend to a height of about 120 m above the German Creek Seam, and to a depth of about 30 m into the floor. Fig. 3 shows the locations of the events relative to a fixed face position. This figure shows that the events tend to occur up to 100 m ahead of the face and that this seismically active zone extends upwards at an angle of about 50° from the horizontal.
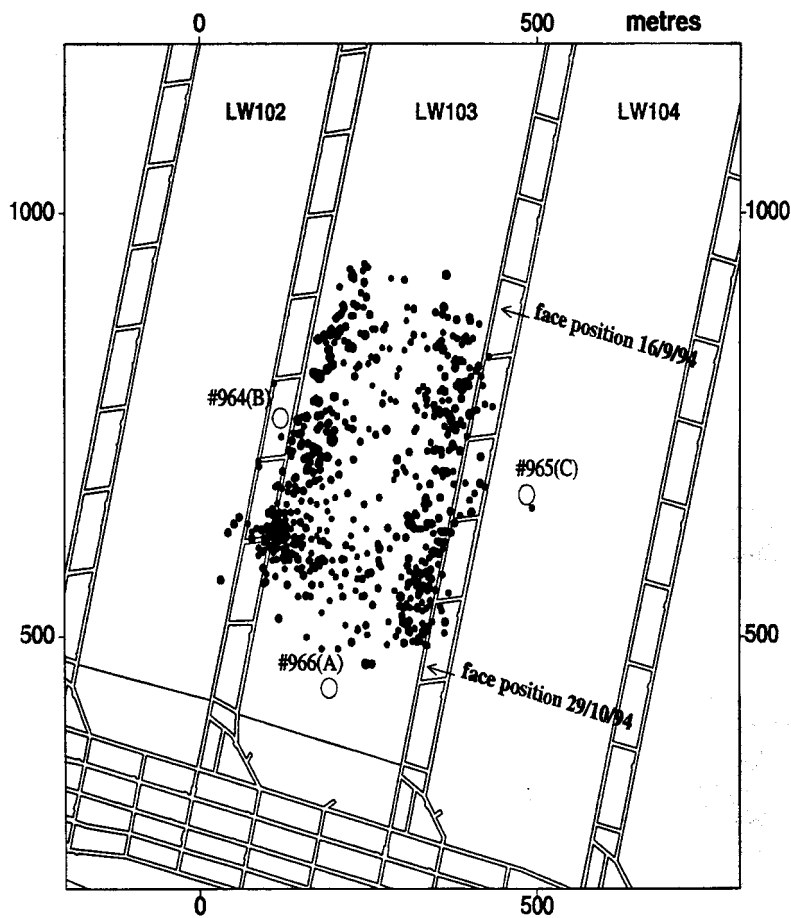

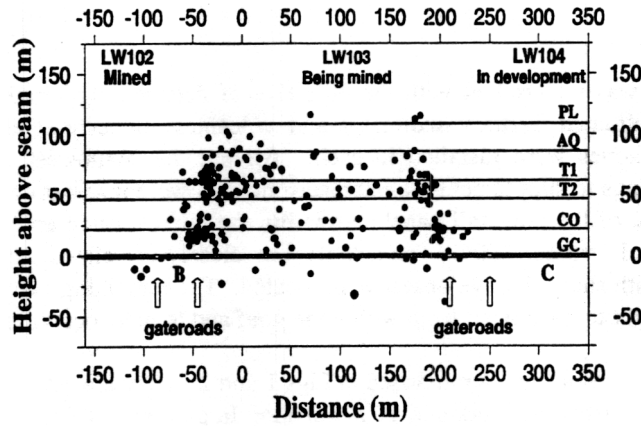Fig. 1 - Microseismic events location in plan view - weak roof

Fig. 2 - Microseismic events locations for part of the panel, viewed in cross section (GC - German Creek seam; CO Corvus seam; T1 & T2 - Tieri seams; AQ - Aquila seam; PL - Pleiades seam)

It has also been possible to determine source mechanisms for a number of the events. The nodal planes are approximately parallel to the longwall face and a compressive shear fracture pattern is indicated with fault planes dipping at an angle of approximately 50°(+/-10°). Piezometer data confirm these microseismic results. In the upper piezometers, increases in pore pressures occurred up to 170 m ahead of the face and varied according to mining activity. The piezometer cables were also sheared progressively up the hole at distances of 73 m, 53 m, and 25 m ahead of the face respectively. These distances coincide with the onset of the microseismic activity.
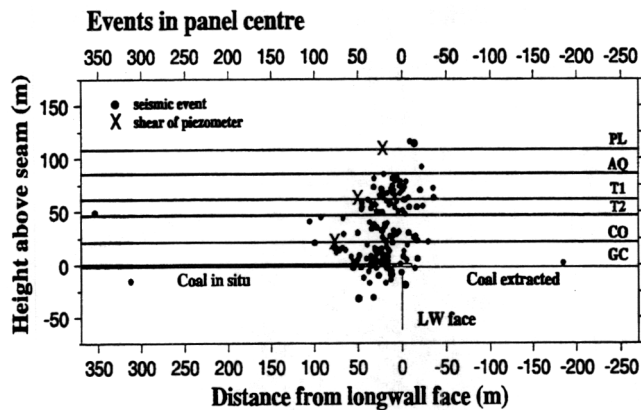

Fig. 3 - Microseismic events distribution relative to a fixed face position in side view (GC - German Creek seam; CO - Corvus seam; T1 & T2 - Tieri seams; AQ - Aquila seam; PL - Pleiades seam)

Numerical modelling results

The numerical model for Gordonstone, Fig. 4, extends from the seam to the surface and 500 m below the seam. The results of simulated longwall mining at Gordonstone are presented in Fig. 5. A number of key features are indicated:

- Failure of roof strata occurs at a substantial distance in front of the face. The model indicates that this takes place at least 10-15 m ahead of the face, and that it extends up to the Corvus Seam (20-25 m above the worked seam). The fractures are pervasive but have no pattern. The expected microseismic characteristics would therefore be many low intensity energy releases, rather than a (periodic) high energy release of lesser frequency.

- Failure of the immediate floor strata occurs at regular intervals.

- The nature of rock failure ahead of the face is shear fracture through intact material, and bedding plane shear.
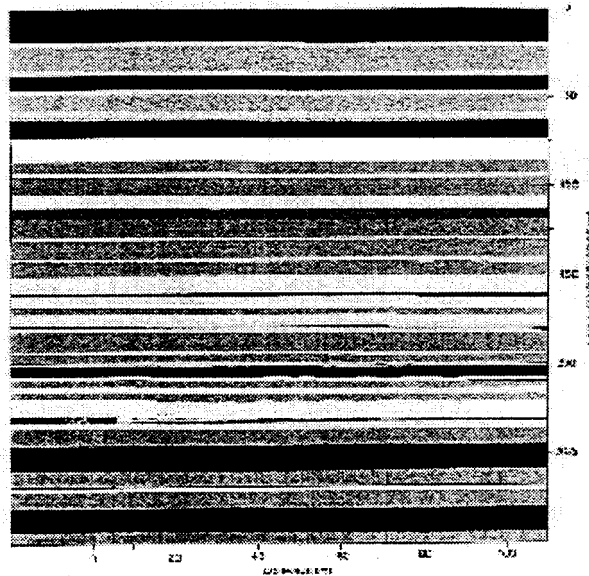
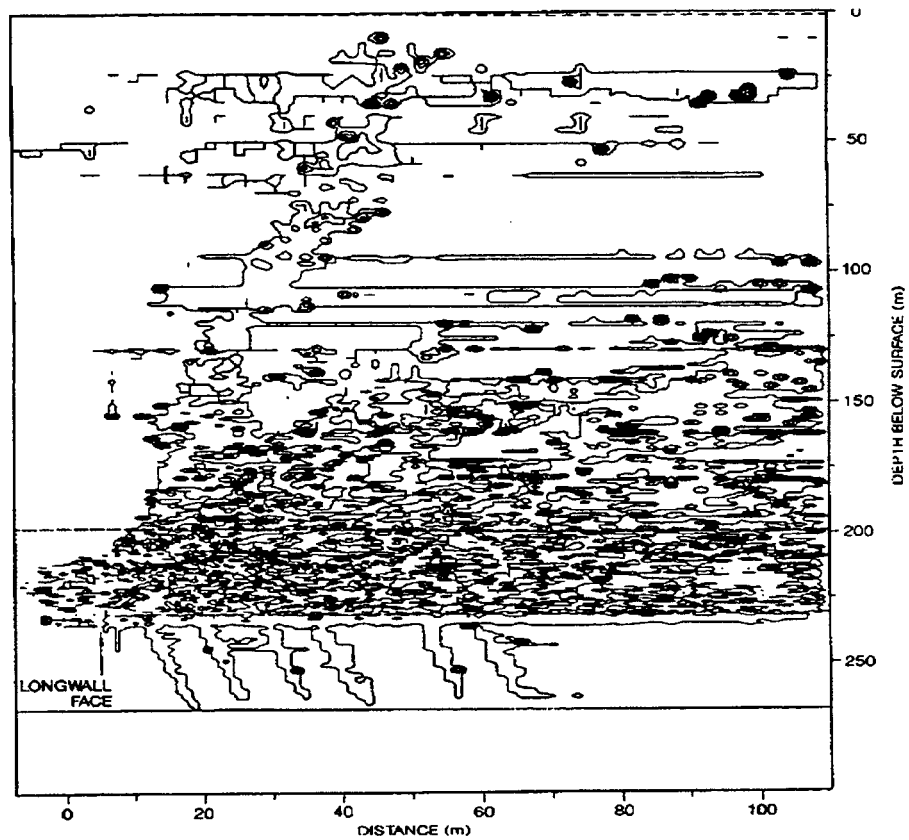Fig. 4 - A section of the Gordonstone geological model

Fig. 5 - Results of modelling showing zones of rock failure - weak roof

This initial simulation does not have coupled fluid pressure as part of the rock failure process as current models now have. As a result, it is probable that shear fractures form even further ahead of the face than indicated from this study. At Gordonstone, the outcomes of subsidence, stress measurement and microseismic data are all consistent with the results of the simulation.

MEDIUM STRONG STRATA STUDIES - RESULTS FROM APPIN COLLIERY

Appin Colliery is located in the Southern Coalfield of the Sydney Basin. The longwall panel at Appin is 200 m wide and extracts the 2.3 m thick Bulli Seam at a depth of about 500 m. The strata below the Bulli seam typically consists of interbedded strong sandstone, coal, carbonaceous material and interlaminated sandstone and shale. A study was made of longwall panel 28a to determine the nature of the fracturing to the underlying Wongawilli seam and to determine whether the fractures extended to the Tongarra seam. These seams are significant potential sources of goaf gas emissions. Within the panel numerous strike slip joint structures intersect the maingate particularly between 5 and 7 cut-throughs.

Microseismic monitoring results

At Appin Colliery 17 triaxial geophones were installed with nine geophones in a borehole drilled from the ground surface to the Bulli Seam and two perpendicular surface strings of four geophones each. The microseismic activity was monitored during August to November 1996 during which time there was 700 m of face retreat. Distinctive seismic events with low and high frequencies were observed.

The microseismic events locations in plan view, Fig. 6, indicate three broad areas of failure (i) cyclic failure of strata from mid face across to the tailgate (ii) reactivation of the strata under the pillars of the previous gateroad and (iii) activation of a strike dip structure in the maingate well outbye of the face position. All of the high frequency events are located in the fault structure zone and activation of the structure started far ahead, more than 300 m, of the face.
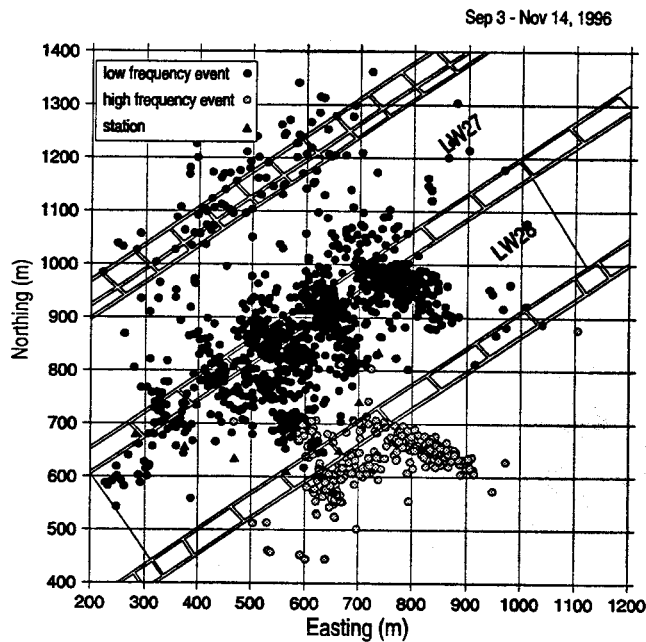

Fig. 6 - Microseismic events loation in plan view - medium strong roof

The event locations in section, Fig. 7, show that the majority of fracturing (the low frequency events) extends to a height of about 50 to 70 m above the Bulli seam and to a depth of 80 to 90 m into the floor, often extending down to the Tongarra

seam. They tend to occur up to 30 - 50 m ahead of the face in cyclic pattern. The events around the previous gateroad pillars may also be up to 300 metres away from the face position.
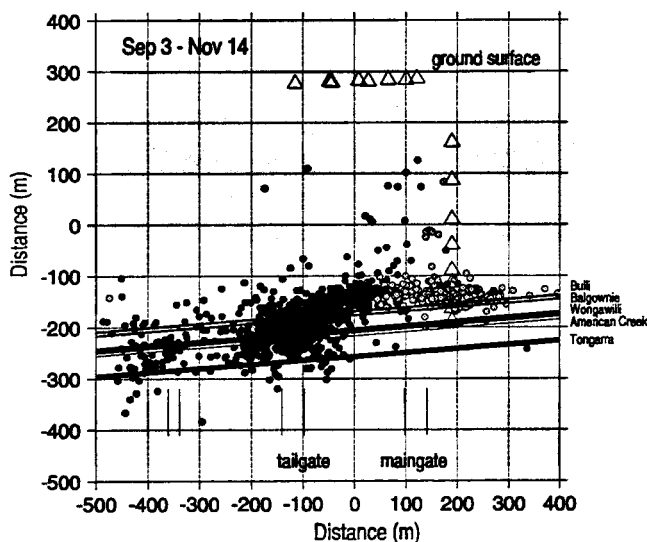

Fig. 7 - Microseismic events locations in cross section

Numerical modelling results

The Appin longwall caving model, Fig. 8, has been developed using the geological and geotechnical data collected from the mine. The section considered for detailed investigations extends from 50 m below the seam to 150 m above the working seam. The model simulations also included coupled fluid pressure as part of the rock failure process. The results of the simulations are presented in Fig. 9. Key features of the results include:

- Cyclic fracturing through to the base of the Wongawilli seam and occasional permeability increase down to the Tongarra seam.

- Bedding plane shear in the Stanwell park claystone unit approximately 100 m above the Bulli seam and extending 50 - 100 m in front of the working face.

The model predictions are consistent with microseismic monitoring measurements with respect to the cyclic loading but do not represent the extraordinary three dimensional nature of failure in this environment.

Face monitoring

In addition to the above studies, face monitoring investigations were conducted at Appin Colliery. The new convergence monitoring system was used in conjunction with support manufacturer's monitoring packages for the monitoring of both leg pressures and convergence. The results agree with those from a conventional potted wire convergence system also used on the face. With the additional information on canopy angle, it is possible to determine whether there is tip loading or goaf loading occurring. The face monitoring data are currently being analysed for comparison with the microseismic and modelling results. Preliminary analyses show a correlation between convergence rate, microseismic events and subsequent gas emissions.
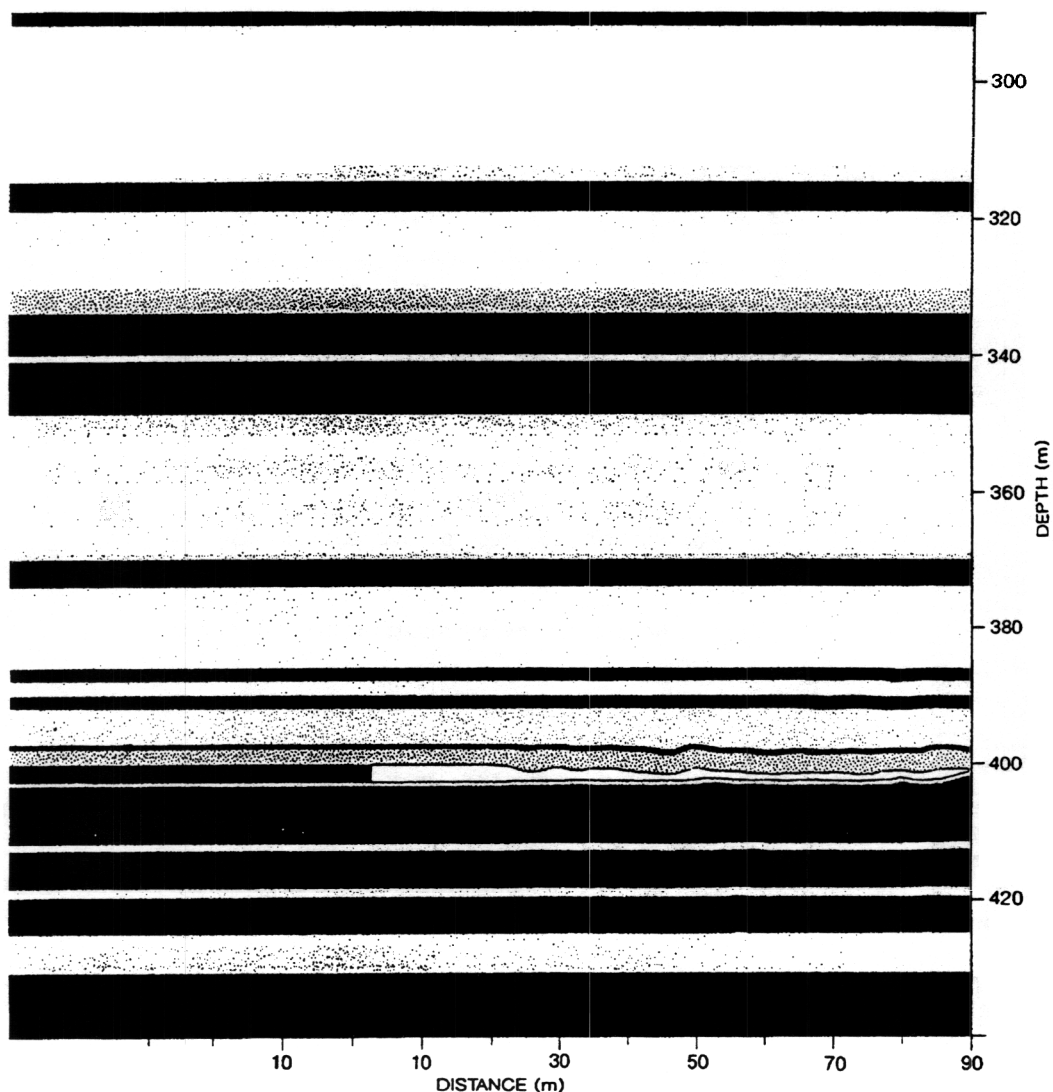
Fig. 8 - A section of the Appin geological model.

NEW INSIGHTS INTO LONGWALL CAVING

As described earlier, most traditional studies while recognising that abutment loads can be detected significant distances away from the longwall, still predict that the maximum abutment loads occur close to the longwall excavation. They further predict that these abutments are 4 to 6 times the overburden pressure. Most studies also predict either explicitly or implicitly that the failure mechanism is tensile. This tensile mechanism is caused by an indirect tensile stress due to an essentially unconfined large abutment load close to the face.
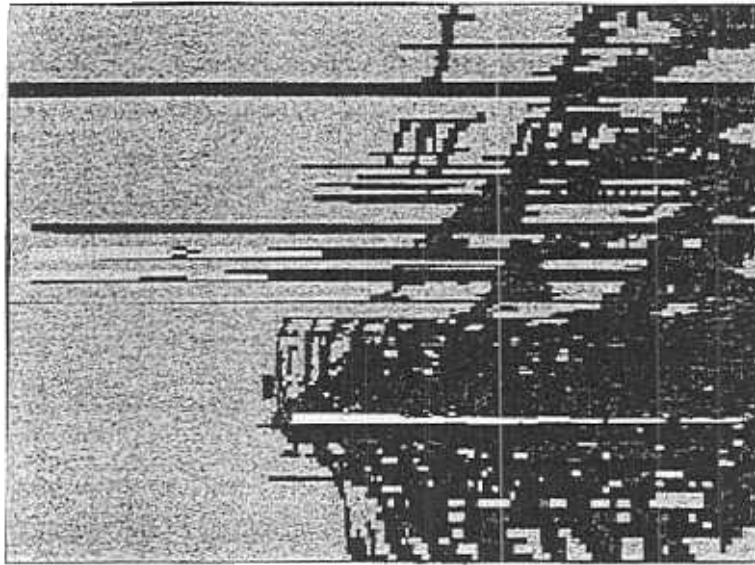
Fig. 9 - Results of modelling showing zones of rock failure - medium strong roof

In contrast, the vertical stress profile, Fig. 10, developed from the simulation, shows that the maximum abutment load is only twice the overburden stress and occurs 10 metres ahead of the face. This difference may be from two main causes:

- Firstly, many Australian mines are in a high horizontal stress regime with the major principal stress being horizontal, and about 2.5 times the overburden stress and typically designed to be parallel to the gateroads. The horizontal relief into the goaf is quite significant and through lateral relaxation will have a decreasing influence on the vertical stress.
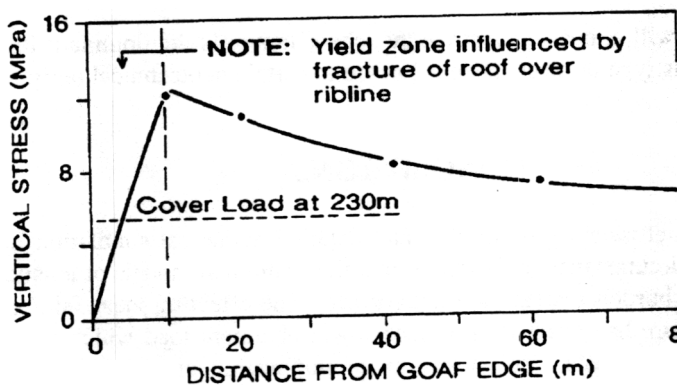

Fig. 10 - Vertical abutment stress relative to the goaf edge developed in the model

- Secondly, bedding plane shear and shear through intact rock will result in a reduction in the load carrying capacity of the rock adjacent to the longwall zone. This will effectively transfer the abutment peak away from the longwall and reduce its magnitude.

The microseismic events at Gordonstone have shown that the initial failure occurs 50-70m ahead of the face and that the dominant failure mechanism of all events is a shear failure with a failure plane orientated at an average angle of 50° to the horizontal thrusting up into the goaf direction. This failure is further validated by piezometric evidence. Our modelling has also indicated that the initial failure occurs a substantial distance ahead of the face with the dominant failure mechanism being shear through intact rock with some bedding plane shear.

The main difference between the model and actual field microseismic measurements are not the modes of failure but the predicted distance ahead of the face where failure occurred, being 15 m for the model and a mean of 30 - 40 m for the field measurements. The roof sequences at Gordonstone have a high moisture content which was not modelled as part of the failure criteria. It is postulated that pore water pressure has an influence on the intact rock failure by reducing the effective stress. This will cause failure to be initiated at lower stress levels and may explain the differences between the model and field measurements.

At Appin, the failure mechanisms recorded were of three main types:

1. A cyclic failure in the Tailgate side of the face with an interval of slightly more than 100 m. These events occurred about 50-60 m ahead of the face and with the majority from 80 m above the seam to 100 m below the seam. These mechanism was expected, although the depth below the seam was surprising. This depth demonstrated consistent breakage of the Tongarra seam for gas release.

2. Failure along a joint-shear in the Maingate/blockside of the face. This joint had been mapped as a minor feature underground. Failure along this joint commenced while the face was still 450 m inbye of it and this mechanism controlled the stress relief along the entire maingate side. It is suspected that this mechanism was a major influence on the reduction of gas release to 25% less than normal total gas make expected. This mechanism is outside all conventional longwall geomechanics theory and was a surprise to both the research team and site staff.

3. Failure of the gateroad pillars between the previous longwalls 26 and 27. Conventional pillar theory revolves around empirical coal strength formula. However the majority of the failure observed in this case occurred from in the surrounding strata, predominantly in the floor below the pillar up to a depth of 130m below the seam. Again this is outside conventional longwall geomechanics theory.

The results from the current project will either demonstrate that shear failure is the dominant failure ahead of a longwall face or otherwise demonstrate that this type of mechanism is limited to certain geotechnical regimes.

CONCLUSIONS

The power of combining accurate microseismic monitoring and detailed numerical simulation has been demonstrated in this study. It has shown that, in the circumstances at Gordonstone, the traditional models of tensile failure mechanisms and abutment loads of 4-6 times the overburden pressure are not correct. The effect of shear failure, reduction of horizontal stresses and perhaps pore fluid pressure has resulted in a much lower abutment load which peaks further away from the longwall face than traditional models indicate. This has a major implication in understanding longwall geomechanics generally and will influence issues of face control, gateroad abutments and fluid flow (both gas and water).

At Appin, the results have been even more dramatic and in contradiction to traditional longwall geomechanics theory. The essence of the 3D nature of failure in medium strength environments has been depicted, especially underlying the effect of minor structure in influencing failure mechanisms and questioning the relevance of conventional pillar design theory which relies principally on empirical coal strength formula. The 3D nature and effect of structure has also been demonstrated at North Goonyella, although that site is still being monitored and results are preliminary at this stage. The value of detailed site studies, especially structural analyses, has been demonstrated at all of the sites.

The effectiveness of the combination of technologies has been the most potent outcome of the work to date. Validation of results through 2, 3, 4 and even 5 independent technologies increases confidence in the findings and dismisses the academic controversies which tend to cloud important new work such as this. This confidence assists implementation into minesites and graphically demonstrates the narrow vision of past assessment methods. The future requires a better understanding of the 3D nature of some of these mechanisms and the development of effective numerical modelling that can translate results into studies of mining alternatives. Also required is the further development of the microseismic monitoring systems. Current analyses, although accurate, are slow and tedious.

Finally, although not discussed throughout the paper, the safety implications of better defining longwall mechanics demands a comment. A better understanding of longwall geomechanics has profound safety implications. Issues such as face control, wind blasts, gateroad support and high level gas emissions can all be better addressed with the knowledge that this project will provide.

ACKNOWLEDGMENTS

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