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Application of Computer Modelling in the Understanding of Caving and Induced Hydraulic Conductivity About Longwall Panels

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ABSTRACT

Computer modelling is being used to simulate rock fracture, caving and stress redistribution about longwall panels with increasing confidence. The models are being assessed against field monitoring and have significantly increased the understanding of caving mechanics within the overburden.

This paper discusses the modelling approach and provides some examples of its application to overburden damage and induced hydraulic conductivity. Computer models used in this study simulate the fracture process in the geological units throughout the overburden. Analysis of the mining induced fracture patterns and *in situ* joint patterns allows an estimation of the hydraulic conductivity within the overburden. The cubic flow relationship has been used in the examples presented.

INTRODUCTION

Computer modelling is being used to simulate rock fracture, caving and stress redistribution about longwall panels with increasing confidence (Gale, Mark and Chen, 2004; Gale, 1998, 2004). The models are being assessed against field monitoring and have significantly increased the understanding of caving mechanics within the overburden.

In general, the models have been intended to assess longwall caving issues, however their application extends to ground subsidence, overburden fracture mode and mining induced hydraulic conductivity of the ground adjacent to mining operations.

The aim of this paper is to discuss the modelling approach and some examples of its application to overburden damage and induced hydraulic conductivity. Analysis of the mining induced fracture patterns and *in situ* joint patterns allows an estimation of the hydraulic conductivity within the overburden. The method also provides an estimation of the conductivity effects at seam level which will impact on the effectiveness of seals placed in roadways subject to abutment related deformation and fracture.

Two examples are presented to provide an overview of the approach and to highlight findings of a current ACARP project undertaking research into induced hydraulic conductivity. The first example is that of the induced conductivity created by longwall extraction and the second is the conductivity issues for seals at the seam level.

COMPUTER MODELLING APPROACH

SCT Operations has been developing the capability to undertake computer simulations of strata caving and the interaction of longwall supports within a site-specific geological setting. This capability has been developed from in-house R&D and from collaboration with CSIRO within three interrelated ACARP Projects researching longwall geomechanics.

The model is two-dimensional and represents a longitudinal slice along the central zone of the longwall panel. 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. Rock failure is based on Mohr-Coulomb criteria relevant to the confining conditions within the ground.

Computer models are developed on the basis of detailed geotechnical testing of pre and post strata failure properties. Detailed models of the geology are necessary to obtain a satisfactory simulation of the rock failure mechanics. The model simulates rock fracture and stores the orientation of the fractures. 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.

The model simulates the mining process by progressively excavating approximately 1 m shears, allowing caving and then excavating the next shear and advancing the face supports. 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. Ground displacements, rock fracture and stress redistributions can be assessed within various rock units and geometries about the extraction panel.

HYDRAULIC CONDUCTIVITY OF *IN SITU* STRATA

The hydraulic conductivity of *in situ* strata is a combination of:

1. The conductivity of the rock (grain) fabric of each rock unit.
2. Joint and fracture planes which cut through the rock strata units. These planes include bedding planes mobilised in previous tectonic movements.

Typically, the conductivity of the rock fabric is low and the greatest potential for flow through the rock mass is via the inherent fracture networks within the strata sections.

A range of typical conductivities measured for rock fabrics and that of joints/fractures is presented in Figure 1. This data is a compilation of borehole tests and rock core fabric tests. The results indicate that the overburden conductivity is generally controlled by the fracture patterns within the ground.

The conductivity of fractures reduces with confining pressure which closes the aperture through which fluid may flow. Laboratory testing of rock fractures has demonstrated a rapid reduction of conductivity with confining stress across the fracture plane. The actual relationship will vary somewhat depending on the fracture surface geometry and the material. The conductivity of the near surface region (<100 m) is typically high and then rapidly reduces as confining pressures reduce the aperture to is 'residual value'.

A relationship based on laboratory and *in situ* testing of targeted fractures is presented in the Figure 1 for a single plane having a spacing of 1 and 5 m. This relationship tends to fit the data reasonably well and examination of roadway cuttings and highwall exposures confirms the likelihood of fracture spacing within this range. In this study, this general relationship has been used to characterise the mass conductivity in terms of fluid flow potential through the ground.

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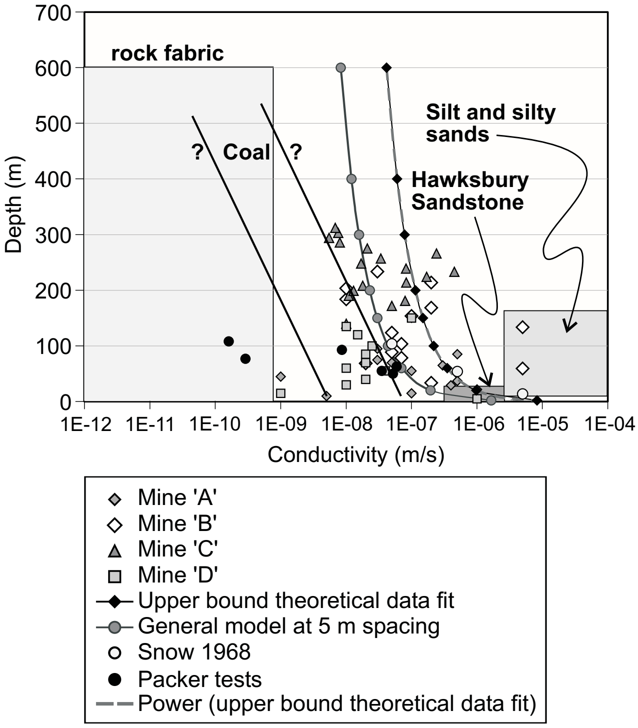


FIG 1 - Conductivity of individual rock fabric and jointed rock mass as measured from borehole testing.

However, it is also noted that structural zones have been intersected which can have larger frequency or greater residual apertures than the 'normal' joint/bedding plane surfaces. Some examples exist in the data, however it should be anticipated that the actual conductivity of such features might well be variable and locally high.

HYDRAULIC CONDUCTIVITY OF INDUCED FRACTURES

The hydraulic conductivity (water flow) of a fracture can be estimated on the basis of:

$$K \approx t^3 * 10^6 \text{ m/s}$$

where:

t = hydraulic aperture of the fracture.

The hydraulic aperture is generally related to the actual fracture dilation with modification due to surface roughness. The effect of surface roughness needs to be assessed for flow calculations however its effect tends to reduce when fracture dilation exceeds approximately 1 mm.

An estimate of the horizontal and vertical conductivity within the strata about longwall panels can be obtained within the large scale models of caving. To obtain this, the dilation and hydraulic aperture of the fractured strata and bedding planes is estimated and the conductivity derived.

In this manner the conductivity distribution above the panels and adjacent to panels can be estimated. The impact on aquifers and water bodies can then be assessed on the basis of the mining induced fracture networks created. The effect of *in situ* fracture conductivity is included in such analyses. The aim of this approach is to provide a better understanding of the fracture distributions and their impact on conductivity within the strata surrounding the longwall panel.

EXAMPLES OF SIMULATIONS

The approach is to develop a model of the strata and then excavate the panel progressively. An example showing the geology and the resultant fracture mode within the overburden for one excavation geometry is presented in Figure 2. Overburden is 190 m. The section is composed of Permian sediments and a 50 - 60 m section of Tertiary sands, clay and basalt.

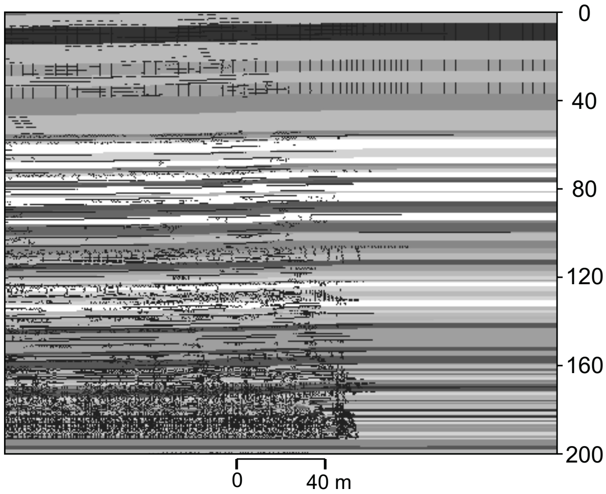


FIG 2 - Example of fracture distribution within strata layers.

The results indicate that fracture through the overburden is extensive and affects the total section to the surface. Surface subsidence is approximately 66 per cent of seam extraction. The subsidence profile obtained is presented in Figure 3 compared to actual monitored data of panels. The results are comparable and indicate that the fracture patterns created in the overburden simulate the actual caving and subsidence characteristics of the section in a realistic manner.

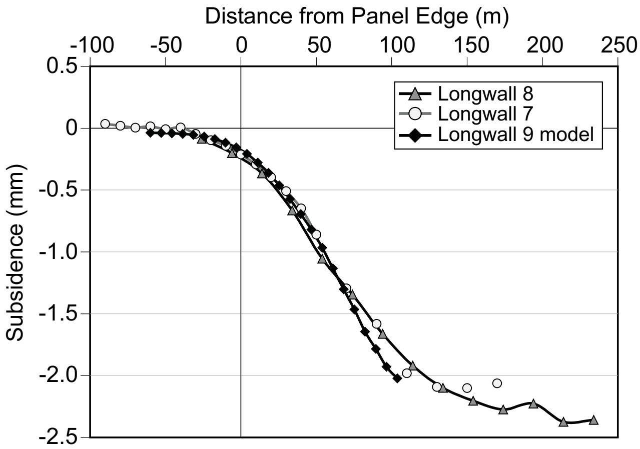


FIG 3 - Correlation of measured and modelled subsidence.

The horizontal conductivity and conductivity as determined from bedding plane dilation (aperture) is presented in Figure 4. The results indicate very high, horizontal conductivity localised along bedding planes throughout the overburden section. Considering the large number of horizontal flow pathways, the vertical fracture conductivity will control the overall connectivity and potential for inflow.

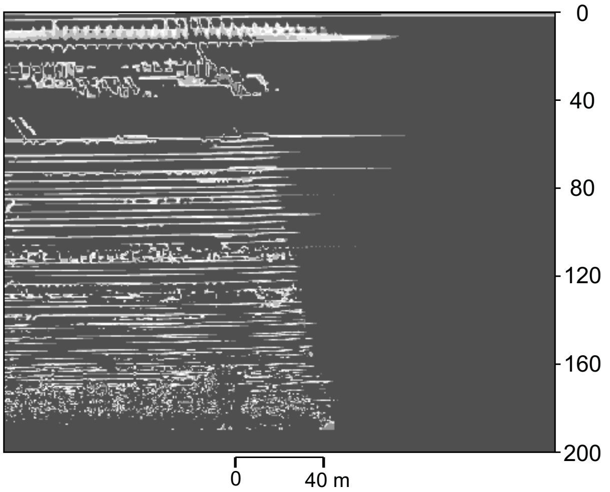


FIG 4 - Areas of elevated horizontal conductivity.

The overall connectivity of the overburden has been investigated by averaging the vertical conductivity in metre thick sections across the extracted panel and creating a vertical profile. In this way an overview of the potential vertical connectivity between layers can be obtained. An example profile for this supercritical model is presented in Figure 5 and indicates:

1. Variable but generally high conductivity created in the geological units within the overburden.
2. Localised zones of low induced conductivity. Jointing in these zones is likely to impact on the pathway.
3. Essentially open flow within the immediate caved zone.

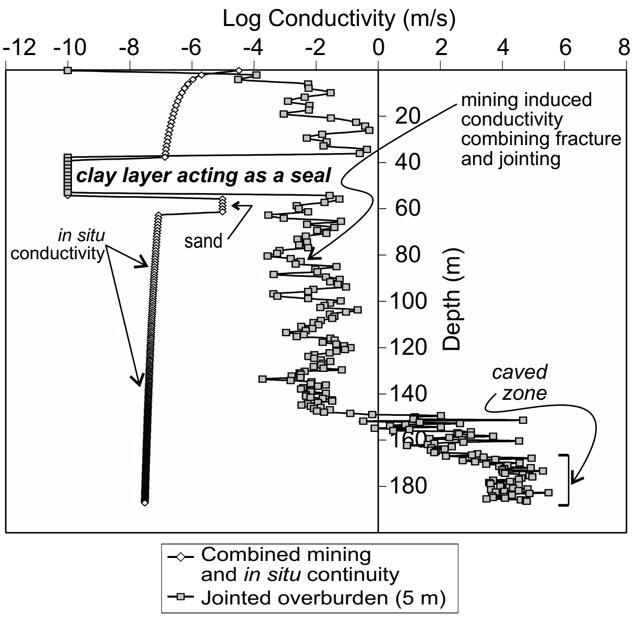


FIG 5 - Combined mining and *in situ* conductivity.

The variable conductivity within the overburden is associated with localised fracture networks created within each layer. Flow will occur through a network of vertical and horizontal pathways created within the various layers of the overburden.

The conductivity within the overburden is consistent with more generalised estimates often applied to subsided panels, however the models have the ability to relate the conductivity to the fracture networks created in the geological units within the overburden.

CONDUCTIVITY ABOUT ROADWAYS AND SEALS

The same relationships as determined above can be applied to the deformation and conductivity about mine roadways. Computer modelling is undertaken to assess the fracture patterns created by mining and the resultant conductivity about the roadway. An example is presented in Figure 6 which relates to a typical thick coal seam in a depth range of 250 - 300 m.

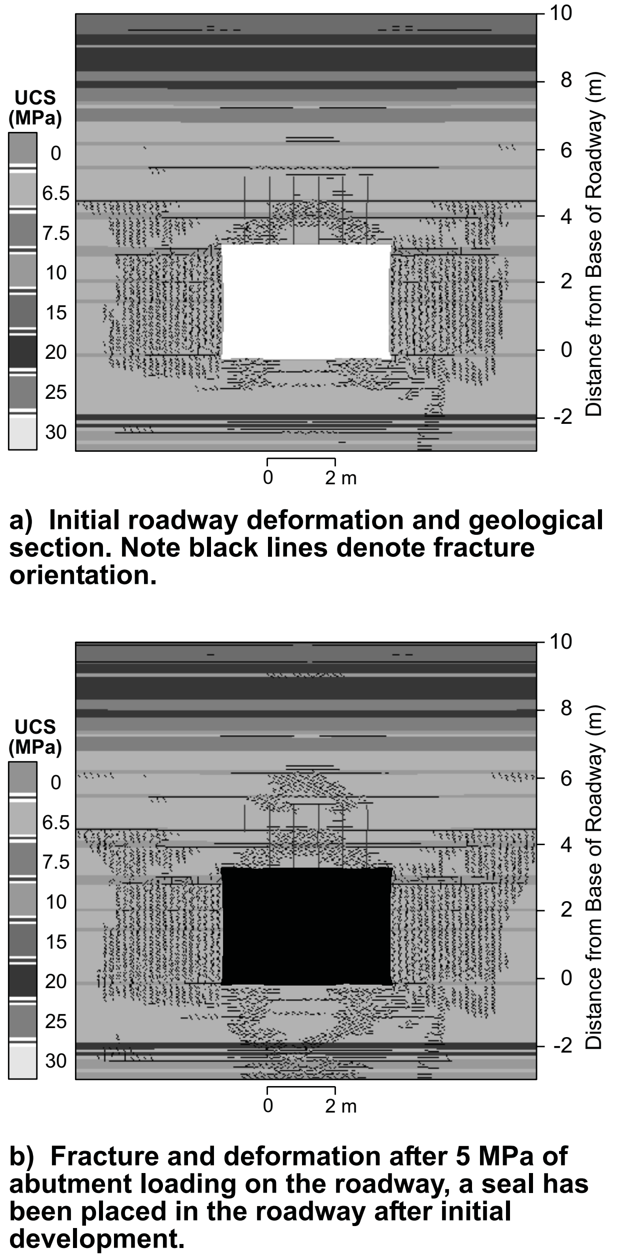
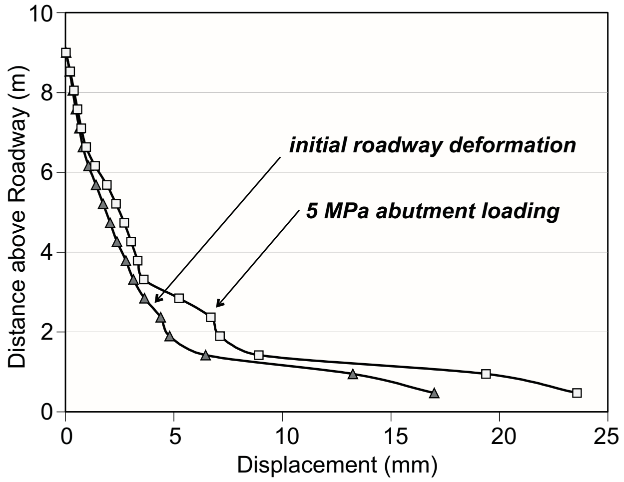
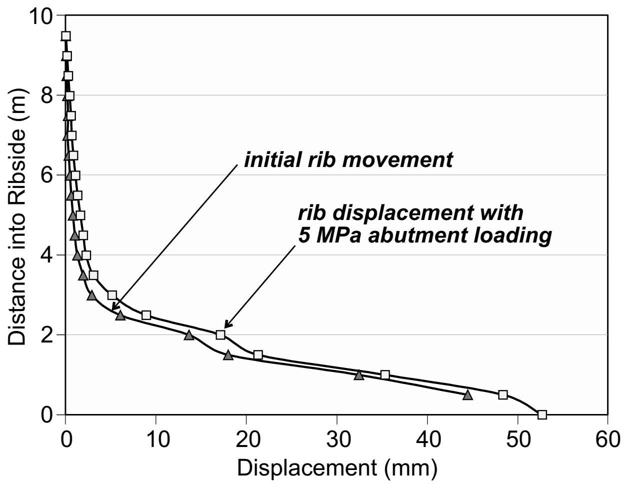


FIG 6 - (**A**) Initial roadway deformation and geological section. Note black lines denote fracture orientation. (**B**) Fracture deformation after 5 MPa of abutment loading on the roadway, a seal has been placed in the roadway after initial development.

The geological section as characterised by UCS of the material is presented in this figure together with the fractures developed as a result of mining. The roof and rib dilation is presented in terms of an extensometer plot in Figure 7. The mining induced conductivity is presented in Figure 8. The results show that at this stage the effective conductivity of the immediate area about the roadway is high and equivalent to that of sands and gravel.

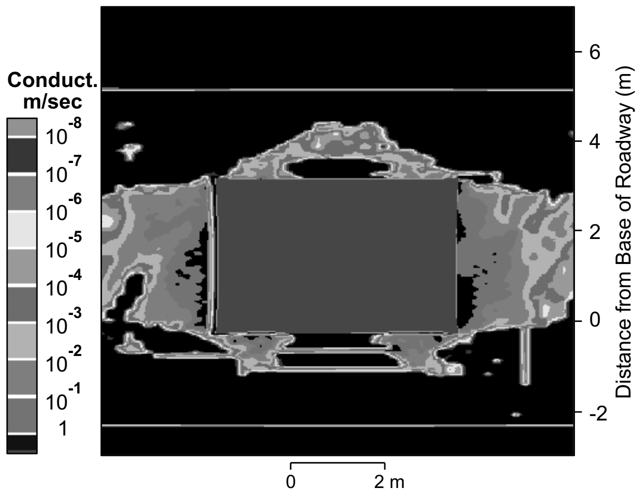


a) Roof dilation as an extensometer plot for initial roadway deformation and abutment loading.

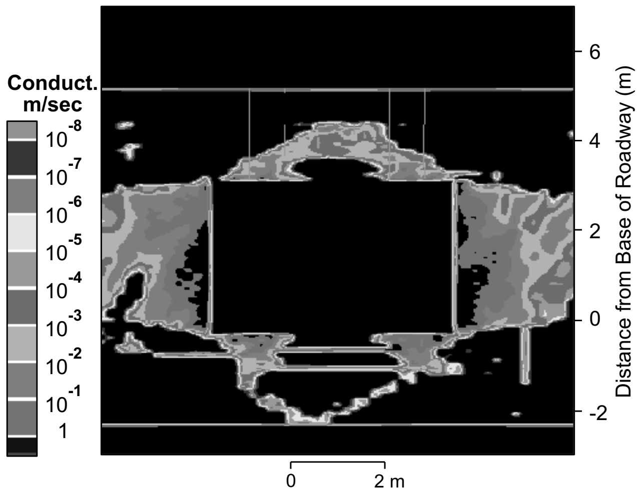


b) Rib dilation as an extensometer plot for initial roadway deformation and abutment loading.

FIG 7 - (**A**) Roof dilation as an extensometer plot for initial roadway deformation and abutment loading. (**B**) Rib dilation as an extensometer plot for initial roadway deformation and abutment loading.



a) Conductivity about the roadway for initial roadway deformation.



b) Conductivity about the roadway after 5 MPa abutment loading.

FIG 8 - (**A**) Conductivity of individual rock fabric and jointed rock mass as measured from borehole testing. (**B**) Conductivity about the roadway after 5 MPa abutment loading.

The effect of increased vertical abutment loading about the roadway was examined with the addition of a low to moderate strength seal. The seal has a stiffness of approximately 10 MPa which relates to a structurally soft or foaming type seal. The seal properties are hypothetical to demonstrate the issues rather than represent any site.

As the abutment load is increased about the roadway, roadway deformation increases and the dilation extends deeper into the strata. The roadway deformation and dilation relative to an extensometer reading is presented in Figures 6 and 7 for the addition of 5 MPa. The conductivity about the roadway is presented in Figure 8 at these load stages. The stress developed in the seal during loading was typically less than 0.5 MPa (50 t/m^2).

The results indicate that whilst the seal itself may remain intact, there is significant potential for bypass flow within the coal and strata surrounding the seal. Even if the ground surrounding the roadway were injected prior to abutment loading, there would still be significant potential for bypass leakage, resulting from the additional dilation and deformation about the roadway.

The resultant conductivity about the roadway can be reduced by a stiffer seal material, which confines the ground and restricts dilation. The design for seals, which are required to restrict bypass leakage as opposed to dynamic pressure events, requires detailed design and monitoring of the system. Further work is required to design such systems in terms of the materials, geometry and surface preparation.

DISCUSSION AND CONCLUSIONS

Stress redistribution about longwall panels, caving and subsidence movements create a fracture network of bedding, shear and tension fracture planes which combine with the *in situ* joints and structures. The mining induced fracture network can extend outside the mined panel. Horizontal conductivity can be significantly enhanced along bedding planes well outside the panel. Also, bedding planes can be mobilised within the near surface overburden as a result of large-scale stress redistributions within the overburden rather than due to induced subsidence movements.

The main control on the connectivity within the fracture networks is typically the vertical (subvertical) fractures connecting horizontal bedding.

A particular application of the modelling is to provide additional information on the fracture networks created about mining panels. This information can be used as part of the mine design process to evaluate the potential impacts of mine extraction geometries on aquifers and surface features.

This approach has been applied to other sites and provides results, which are consistent with the monitored behaviour of aquifers and inflows. The impact of such networks on inflow and aquifer integrity is related in part to the recharge characteristics of the aquifer relative to the outflow into the fracture network. This will vary depending on the nature of each site; however, the modelling has the ability to provide a good understanding of fracture networks created and an estimation of the enhanced conductivity within the overburden created by mining.

This type of analysis applied to flow about seals in roadways indicates the potential for 'time dependent' bypass within the strata and coal ribsides. The design requirements for dynamic events such as explosions are different to those referred to as bypass leakage as discussed in this paper. Design of long-term fluid seals requires further work and monitoring studies.

Research in this project is still continuing over the next six months. Ongoing work is continuing to improve the definition of fracture connectivity within the overburden.

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