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28 February 2007

Joanne Woodhouse
Environmental Scientist - Hunter Valley
ERM Australia Pty Limited
PO Box 71
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Dear Joanne,

GROUNDWATER MONITORING AND MODELLING

As requested, please find herein an overview of the groundwater modelling approach that we propose to use at Integra Coal Operations. This approach has been used at numerous sites and has been found to provide a sound basis for assessing the near-field impacts of longwall mining on groundwater behaviour. The approach is based on using field measurements to validate the model including validation of material properties, deformations and groundwater impacts.

Dr Winton Gale has developed an integrated approach to ground deformation/groundwater modelling using FLAC, a finite difference numerical modelling code. This approach is described in Gale (2004), a copy of which is attached for reference purposes.

The approach is based on characterisation of the overburden strata using a range of geophysical and other testing techniques. The *in situ* stresses are typically determined from borehole breakout measurements in exploration holes and overcoring stress measurements conducted underground where available. Ground deformations are typically confirmed using surface extensometers located over the centre of longwall panels to determine the height and nature of fracturing as the longwall approaches and passes under the extensometer. Multiple piezometer strings installed into exploration boreholes have proved useful for determining the impact of longwall mining on groundwater behaviour.

The numerical modelling code that has been developed provides a basis for integrating the various field measurements into a cohesive model which allows the impacts of various mining geometries to be assessed and evaluated. The technique has been found to be very successful and would be recommended for use at Integra Coal Operations.

It is noted that conventional ground water modelling codes do not easily integrate the ground deformations that are recognised to occur as a result of longwall mining and which are known to impact on groundwater behaviour.

The results provided by the model and field validation results are typically used by hydrogeologists to better assess the potential impacts of mining on regional groundwater models.

The various stages of investigation and numerical modelling work can be undertaken in the overburden strata above and ahead of existing longwall operations. It would be proposed to undertake the investigations prior to mining Longwall 10.

If you have any questions or require further clarification of any of these issues, please do not hesitate to give me a call.

Regards

Ken Mills
Senior Geotechnical Engineer

Reference:

Gale, W.J. 2004, 'Application of computer modelling in the understanding of caving and induced hydraulic conductivity about longwall panels', in proceedings of Mine Subsidence Technological Society 6th Triennial Conference on Subsidence Management Issues (MSTS 2004), 31 October-2 November 2004, Maitland, NSW, pp. 101-106.

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

W.J. Gale, Managing Director, SCT Operations Pty Ltd

Summary

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.

The aim of this paper is to discuss the modelling approach and 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 examples presented.

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 about longwall panels. The examples relate to the “end member” situations of a super critical shallow operations and a deep single, sub critical panel.

1. Introduction

Computer modelling is being used to simulate rock fracture, caving and stress redistribution about longwall panels with increasing confidence (Gale et al. 2004, Gale 2004, Gale 1998). 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 conductivity.

The aim of this paper is to discuss the modelling approach and some examples of its application to overburden damage and induced hydraulic conductivity. 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 about longwall panels. The examples relate to “end member” situations of a shallow supercritical panel in the Bowen Basin and a deep sub critical panel in the Southern Coalfield.

2. 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. 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. 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 1m 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. 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.

3. 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 1mm.

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 initial jointing can also be 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.

4. Examples Of Simulations

The approach is to develop a model of the strata and then excavate the panel progressively.

4.1 Supercritical Panel: Bowen Basin

An example showing the geology and the resultant fracture mode within the overburden for one excavation geometry is presented in Figure 1. Overburden is 190m.

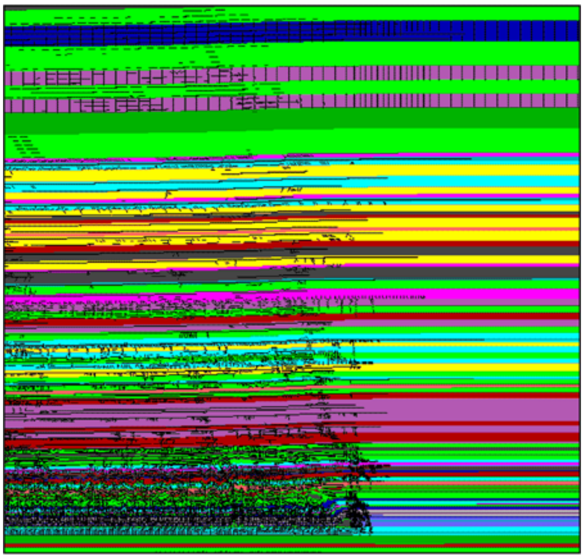


Figure 1: Example of fracture distribution within strata layers.

The section is composed of Permian sediments and a 50-60 m section of Tertiary sands, clay, and basalt.

The results indicate that fracture through the overburden is extensive and affects the total section to the surface. Surface subsidence is approximately 66 percent of seam extraction. The subsidence profile obtained is presented in Figure 2 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.

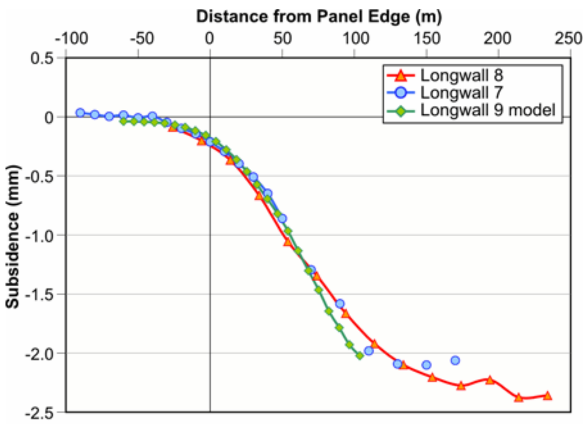


Figure 2: Correlation of measured and modelled subsidence.

The horizontal conductivity and conductivity as determined from bedding stone dilation (aperture) is presented in Figure 3. 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.

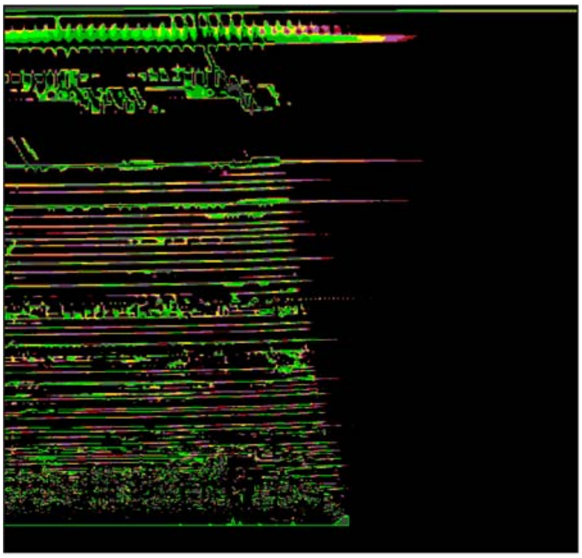


Figure 3: Areas of elevated horizontal conductivity.

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 4 and indicates:

i. Variable but generally high conductivity created in the geological units within the overburden.

ii. Localised zones of low induced conductivity. Jointing in these zones is likely to impact on the pathway.

iii. Essentially open flow within the immediate caved zone.

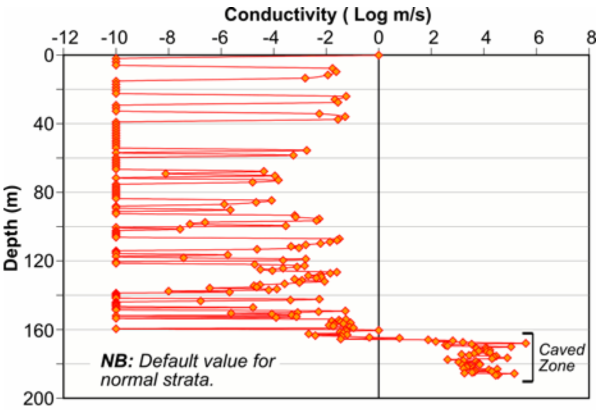


Figure 4: Profile of average vertical conductivity over panel edge zone.
Note: Regional jointing not included

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.

5. Example of Conductivity and Caving about a Deep Longwall Panel

Extraction of a longwall within the Bulli Seam at approximately 520m depth was simulated to assess the height of caving, overburden fracture effect and induced hydraulic conductivity. The panel was 250m wide and model geology is presented in Figure 5.

The fracture mode within the overburden for a single and multiple panel example is presented in Figure 6 and indicates that bedding plane shear is extensive throughout the overburden and near surface.

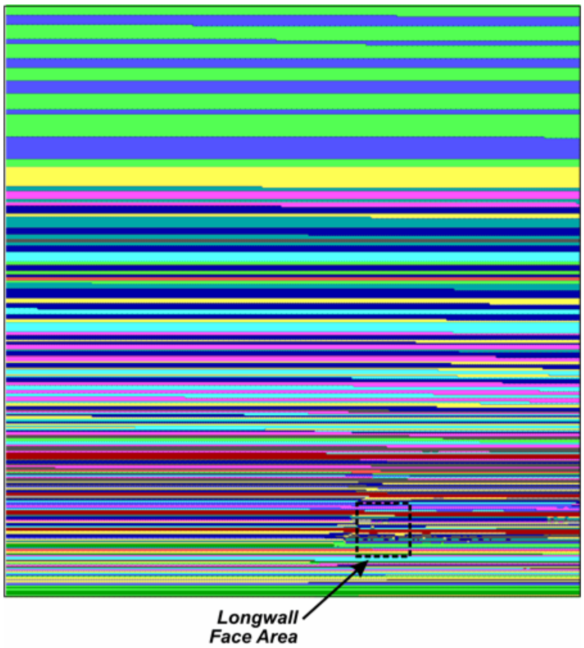
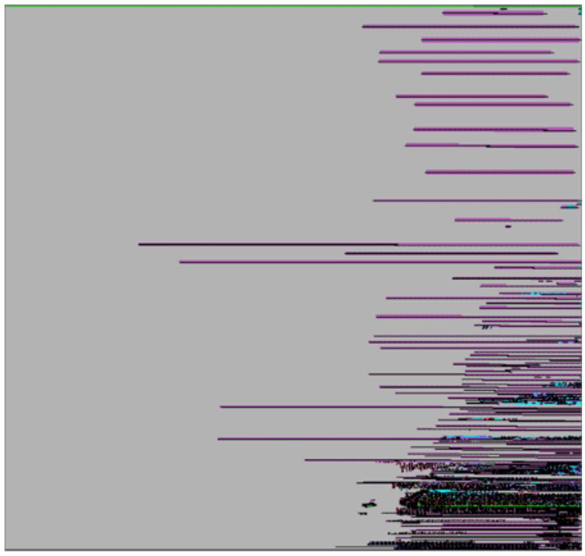
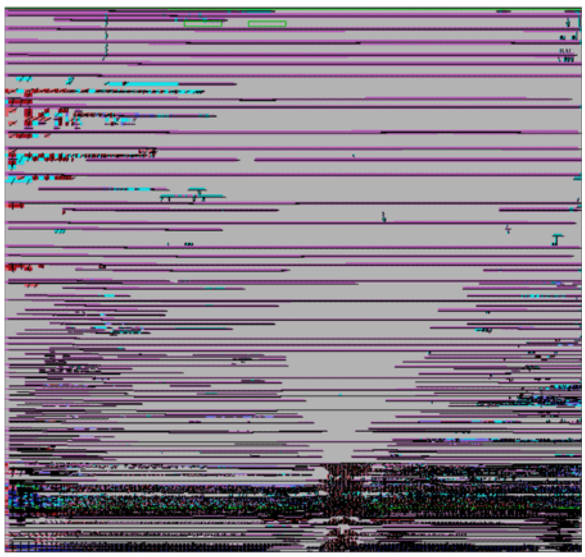


Figure 5: Computer model and strata section.



Single Panel



Multiple Panel

Figure 6: Fracture distribution for single and multiple panels for Bulli Seam example.

Bedding plane shear may extend well outside the extraction area. The bedding plane shear results from large scale stress redistributions about the panel. These fractures allow horizontal movements to occur which are not directly related to the subsidence process as traditionally considered (vis angle of draw).

The vertical strata movement over the panel is presented in Figure 7 as a surface extensometer plot.

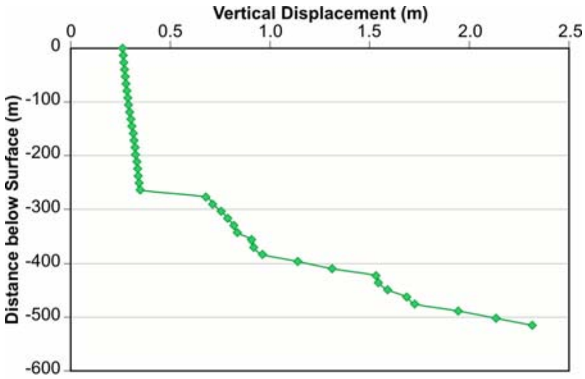


Figure 7: Ground displacement profile down the centre line of a single panel.

The zone of significant strata dilation for the single panel sub critical case extends to approximately 260m above the seam. Strata fracture extends up to the surface in the form of bedding plane shear.

The horizontal conductivity is presented in Figure 8 and shows very high conductivity within the caved zone and localised conductivity about sheared bedding planes throughout the overburden. It also shows an elevated horizontal and vertical conductivity in the surface region.

However the key issue for inflow assessment is the potential for vertical flow and vertical connectivity between the high horizontal conductivity zones. Vertical conductivity will control the overall flow within the fracture network.

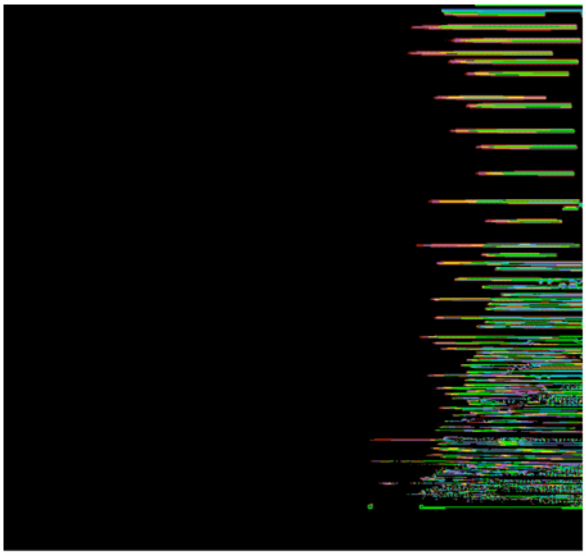


Figure 8: Zones of elevated horizontal conductivity about a single panel.

The vertical conductivity within the overburden presented in Figure 9 as a vertical profile of average vertical conductivity for 1m slices across the panel. This provides an estimation of the conductivity and the potential for connected vertical flow within the overburden. The conductivity related to the mining induced fracture network and that which would be developed by dilation of existing joints is presented. In this example a joint spacing of 10m was used.

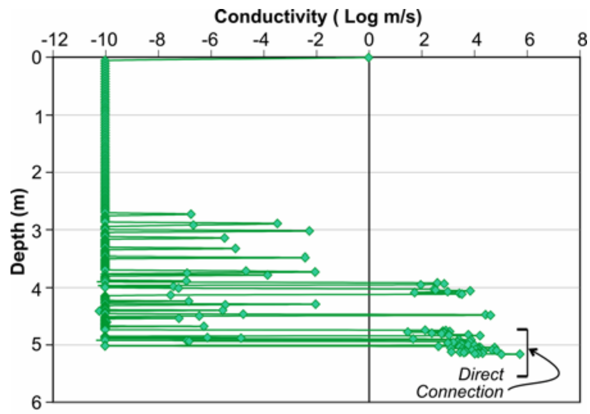


Figure 9: Profile of average vertical conductivity over a single longwall panel.

The overall result indicates very high conductivity within the caved zone and low conductivity higher into the overburden.

The results indicate that the immediate goaf zone up to approximately 20-30m has direct free flow connectivity, however the zone up to the top of the caving zone (at approximately 260m above the seam, has a tortuous interconnection of fractures, joint and bedding planes. Above this the conductivity is low until the near surface zone is created.

There has been no analysis of flow and secondary fluid pressure effects on the strata behaviour in this example.

6. DISCUSSION AND CONCLUSIONS

Stress redistribution about longwall panels, caving and subsidence movements create a fracture network of bedding, shear and tension fracture planes. The 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 (sub vertical) fractures connecting horizontal bedding.

A particular application of the modelling is to provide additional information of 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 potential mine extraction geometries on aquifers and surface features.

Modelling is viewed as a powerful tool to be used in conjunction with other approaches, however ongoing monitoring and validation is an essential part of the process to ensure that the ground behaviour is being simulated in a realistic manner.

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 fracture networks created and an estimation of the enhanced conductivity within the overburden created by mining.

Research in this project is still continuing over the next 12 months. Ongoing work is continuing to improve the definition of fracture connectivity within the overburden.

5. REFERENCES

Gale W.J. 2004, 'Rock fracture, caving and interaction of face supports under different geological environments. Experience from Australian coal mines', in proceedings 23rd International Conference on Ground Control in Mining, 3-5 August 2004, Morgantown WV, USA, pp. 11-19.

Gale W.J., Mark C. & Chen J. 2004, 'Computer simulation of ground behaviour and rock bolt interaction at Emerald Mine', in proceedings 23rd International Conference on Ground Control in Mining, 3-5 August 2004, Morgantown WV, USA, pp. 27-34.

Gale W.J. 1998, ‘Experience in computer simulation of caving, rock fracture and fluid flow in longwall panels’, in 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.