Review and Estimation of the Hydraulic Conductivity of the Overburden Above Longwall Panels. Experience From Australia

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ABSTRACT

The aim of this paper is to summarise the results and conclusions of Australian Coal Association Research Project (ACARP) Report C13013 which relate to water inflows into a mine which occur through the overburden above and adjacent to longwall panels. The study assessed available data of inflows into underground coal mines and utilised computer simulation of water flow through fracture networks. The study concluded that flow into mines is typically via an interconnected network of pre existing and mining induced fractures. The height above the coal seam that mining induced fractures extend is typically related to the width of the panel. However the potential for those fractures to form a connected network which can facilitate flow, is related to the amount of subsidence and the depth of mining. The study compares model simulations with measured data and provides guidelines to estimate the average hydraulic conductivity of the overburden above extracted longwall panels in Australia.

INTRODUCTION

Water inflow into coal mines has been a design issue for many years. Guidelines as to the potential for water inflow have been developed in many countries based on local experience and the form of mining being undertaken. In most instances, the guidelines relate to inflows which would endanger underground personnel and operations.

In more recent times, water inflow criteria for mines has been widened to include lesser inflows which may not impact on mine safety or operations, but have the potential to reduce water flow within streams and surface aquifers. For the purpose of this paper the larger inflows which are readily measured in a mine or may impact on mining safety are defined as *mine inflow* and the lesser inflow relating to aquifer water loss as *environmental inflow*.

The water losses referred to are those which enter the mine from the surface or from near surface aquifers.

The empirical relationships developed as mine design guidelines or regulations typically relate to high flow (mine inflow) situations and in this paper, these have been reviewed as to their application to environmental inflow. In many cases environmental inflows were unlikely to have been noted or recorded in many mining operations in the past.

The aim of this paper is to summarise the results and conclusions of Australian Coal Association Research Project (ACARP) Report C13013 which relate to water both mine and environmental inflows into a mine which occur through the overburden above and adjacent to longwall panels.

The study assessed available data of inflows into underground coal mines and utilised computer simulation of water flow through fracture networks. In order to study flow associated with underground mines, both flow within in situ strata and that within strata impacted by mining needs to be assessed.

FLOW IN THE ROCK MASS AND THE IMPACT OF MINING

Fluid flow within sedimentary strata occurs within the rock fabric (grain or matrix fabric) and within fractures that cut through the strata units. Flow within the rock matrix or fabric commonly occurs in coal and poorly consolidated rocks having connected void space. Otherwise, water and gas flow within the consolidated strata primarily occurs via fracture networks rather than through the rock fabric. These fracture networks consist of interconnected joints, faults and bedding planes which have been fractured by geological events. The large scale conductivity of the overburden is related to the conductivity of the individual fractures and the degree of connectivity or networking of those fractures within the strata.

The hydraulic conductivity is defined as the rate (m/second) that water flows through the rock fabric or the fracture system over a unit distance (say 1 m (3.3 ft)) for a unit pressure gradient (say 1 m (3.3 ft) head) acting to induce flow over that unit distance.

K (m/s) = Velocity (m/s) / pressure gradient (m water head differential/m length)

The most frequently used method to measure the hydraulic conductivity of the rock mass is by the use of packer testing within boreholes. The method injects water into an isolated section of the borehole and the volume of water injected relative to the injection pressure of the water provides a measure of the conductivity of the rock mass which intersects the borehole. In most cases this is a combination of rock fabric and geological fracture planes. The value obtained is the overall net flow into the borehole, however, no directional properties of where the flow has gone into the rock mass can be obtained from the test.

Examples of packer testing done in the Permian strata of the Sydney and Bowen Basins is presented in Figure 1. The conductivity of the fabric for the typical strata is also presented. The results show a wide range of responses from intact rock fabric to highly conductive fractured ground. In general, the data indicates that most measurements are consistent with flow within fractures and demonstrates that the major flow systems in the rock mass are via joint, fault and bedding planes. Local variation to that occurs in highly conductive materials such as coal and poorly consolidated strata.

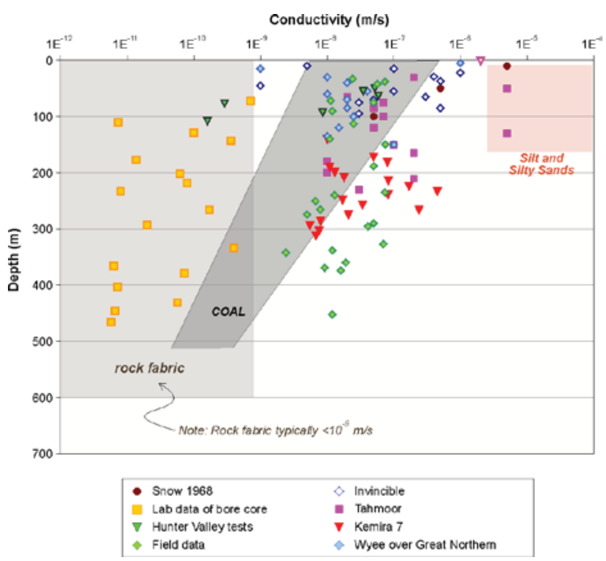

Figure 1. Examples of field measurements of hydraulic conductivity of strata.

Longwall mining creates additional fractures and changes the conductivity of pre-existing fractures by increasing (or decreasing) the apertures of pre-existing geologic structures.

Extraction of coal via longwall methods is the most common method currently used in Australia. Extracted coal thickness typically ranges from 2-4.5 m (7-15 ft) for conventional systems and may be higher for top coal caving systems. Longwall panels are typically 200-400 m (656-1,213 ft) wide and 1-3 km (0.6 to 1.9 mi) long. They are, therefore, essentially long rectangular panels. As a result of this simple geometry, the overburden caving and subsidence behaviour is largely controlled by the panel width (shortest dimension). The panel length has no major impact on the overall result, other than at the panel start and finish line area. This simple geometry allows much of the overburden caving characteristics to be analysed as a two dimensional problem, related to panel width.

The extraction of coal causes stresses in the ground to be redistributed around the panel during mining. This stress distribution may result in overstressing of the strata and creation of new fractures. The location and extent of such fractures depends on the strata and depth of mining. Extraction of the coal also causes caving of the immediate roof (5-20 m (16-66 ft) depending on the strata types) behind the supports to form a goaf. Above this goaf zone, the strata tend to part along particular bedding planes and form “beams or plates”. These subside onto the goaf as an interlocked but fractured network of bedding planes, pre-existing joints, mining induced fractures and bending related fractures within the beams.

Tensile fracturing and dilation of existing jointing occurs in the upper zones of the overburden as a result of bending strains. The development of these zones is dependent on panel geometry and depth.

Caving and cracked beam subsidence movements tend to occur up to a height of 1-1.7 times the panel width. Examples of this have been monitored by surface to seam extensometers (Mills and O’Grady, 1998; Holla and Armstrong, 1986; Holla and Buizen, 1991; Guo et al., 2005; Hatherley et al., 2003) and predicted to occur from computer models (Gale, 2006). This indicates that cracking and deflection related to such caving and cracked beam subsidence could extend to the surface for panel widths greater than 0.75-1 times depth.

The creation of caving related fractures alone does not necessarily imply that a significant or direct hydraulic connection exists through this zone. In order for mine inflow to occur, the fractures created must form a vertically connected and conductive network to allow significant volumes of inflow.

A review of mine inflow in the UK found that potentially unsafe volumes of water inflow in the UK occur for longwall mines having a rockhead less than 105 m (344 ft) to the water source and theoretical tensile strains above 10 mm/m (0.12 in/ft). Rock head is defined as the thickness of non weathered rock above the extracted coal seam. Longwall faces tended to be dry for strains on the strata at the water source less than 4 mm/m (0.05 in/ft). It was found that longwall faces were typically wet with strains at 6 mm/m (0.8 in/ft) and high inflows may occur at strains greater than 10 mm/m (0.12 in/ft).

Water inflow experience in Australia was consistent with this experience, albeit with some variance related to the existence of clay bearing strata of Tertiay and Quaternary age underlying water bodies.

Examples of water inflow experience in Australia at Oaky Creek, Southern and Central Collieries in the Bowen Basin were documented by Klenowski (2000). He presents data to show that a significant inflow occurs with rockhead between 70-175 m (230-574 ft) in these cases. Subsidence was typically in the range of 1.2-1 6 m (4-5 ft).

Experience under Lake Macquarie NSW has been reported by Li et al. (2006), whereby longwall panels of 150 m (492 ft) width were successfully extracted under a lake with 160 m (525 ft) depth of cover. Subsidence in this case was estimated to be less than 0.6 m (2 ft).

Experience in the Hunter Valley NSW (Wollombi Creek) Li (2004) indicates that stream flow was lost when it was undermined at a depth of approximately 90 m (295 ft) but not for depths greater than 120 m (394 ft). Subsidence was estimated to be approximately 1.4-1.6 m (4.6-5.2 ft).

The impact of geology was apparent at Crinum Mine whereby a pervasive clay layer acted as an aquiclude between fractured strata above a longwall panel and saturated basalt. The clay layer was typically up to 10 m (33 ft) thick. In this case, the clay created a barrier to flow to the cracked strata below. In situations where the clay barrier was breached, high water inflow occurred (Seedsman, 2006). Subsidence at this site is typically in the range of 2-2.5 m (6.6-8.2 ft).

The cases reported in the study are presented within Figure 2 relative to subsidence and rock head.

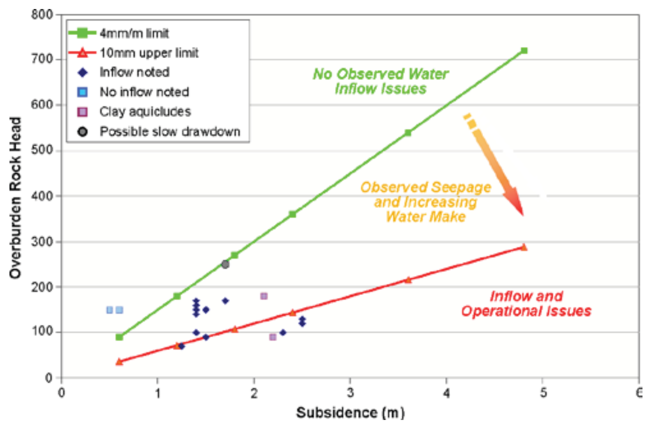

Figure 2. Inflow experience from Australia plotted relative to subsidence values and rockhead.

Overall, the data suggest that mine inflows can occur for theoretical strain values above approximately 6 mm/m (0.08 in/ft), and that the severity of inflow increases as the strain increases. Strains above approximately 10 mm/m (0.12 in/ft) are likely to be associated with significant inflow. Clearly, the impact of geological effects (i.e., clay layers) can impact the overall result.

The empirical relationship outlined above provides a broad qualitative overview of the likelihood for mine inflow. In order to obtain a better understanding of environmental inflow, quantification of the potential flow rates is necessary. This was achieved by estimating the hydraulic characteristics of the overburden above longwall panels over a wide range of subsidence values.

This was done utilising computer modelling of the overburden caving and subsidence behaviour for a range of depths and panel geometries. Back analysis of site data was also used and provided validation for the modelling outcomes.

Simulation of the fracture distribution and resultant hydraulic conductivity of the overburden was conducted to assess the impacts both above and adjacent to longwall panels. The impact of various levels of subsidence on the conductivity of the overburden and on the water profiles which may be maintained above the longwall panels was evaluated. Geological sections from the Hunter Valley and the Bowen Basin were modelled.

The model applied is two-dimensional and represents a cross section across the longwall panel. Element sizes used in this study were typically 1 m (3.3 ft) square.

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 developed by SCT Operations to represent the rock fracture mechanics in detail. Rock failure is based on Mohr-Coulomb criteria relevant to the confining conditions within the ground. Post-failure strength properties of the fractured rock are defined and are primarily related to confining pressure. The rock properties are derived from testing of core samples in multi stage triaxial tests and direct shear tests of bedding planes.

A detailed verification study of such computer modelling applied to overburden conductivity and water inflow was presented in Guy et al. (2006). In this study computer modelling and field investigations were used to assess water inflow into a pillar extraction mine in New Zealand.

The in situ overburden conductivity is modelled on the basis of an average conductivity over a 1-m (3.3-ft) interval.

The conductivity is enhanced by the creation of mining induced fractures and dilation of pre-existing fractures. Quantification of the fracture induced conductivity is estimated within the model on the basis of the equivalent material conductivity calculated from aperture flow within a fracture. The conductivity (k) estimated from the flow quantity through a 1 m^2 (10.8 ft^2) area with unit pressure gradient. This then simplifies to solve k as approximately equal to:

$$k = e^3 \times 10^{6} \text{ m/s}$$

where: e is the hydraulic aperture (m).

The aperture of the fractures will vary depending on confining pressure such that conductivity reduces in areas of increased stress normal to the fracture and vice versa.

Once rock fracture occurs due to mining, the dilation of the strata is considered to be related to fracture dilation. This is calculated in each element on the basis of change in length once material stiffness effects have been taken into account. It has been assumed that there is 1 fracture per element in the model and that the aperture is equal to the average dilation.

This provides an estimate of the fracture conductivity distribution within the ground and gives the capability to assess flow characteristics within the overburden for different mine geometries, subsidence and geological sections.

The model represents coupled fluid flow and strata deformation and as such, the short term fluid pressures in the system need to be equilibrated. The short term pore pressure effects relate to ground relaxation during mining. These are useful for gas flow modelling and effective stress criteria for rock failure, but are not of significance to long term inflow issues. Therefore for long term issues it has been found that the best method to assess the flow characteristics of a particular strata and fracture network is to input a hydraulic gradient into the overburden above the goaf and let the flow networks establish in the system. A constant head can be placed at the level of the initial water table to assess the recharge effect on the flow.

The benefit of this approach is that fractures which exist in the strata but do not connect into other fractures will not contribute to the overall flow network. In this way, any estimate of the equivalent conductivity within a layer will filter out those fractures which exist but do not contribute to the flow network.

An example of the results is presented below for a site within the Bowen Basin Qld.

The UCS profile modelled for this study is presented in Figure 3. The panel width was 250 m (820 ft) and the rockhead to the base of alluvial sands was 200 m (656 ft). The seam extraction thickness modelled was 2 and 4 m (6.6 and 13 ft). The subsidence for the two cases was 1.2 and 2.4 m (4 and 8 ft), respectively. The subsidence profiles are presented in Figure 4.

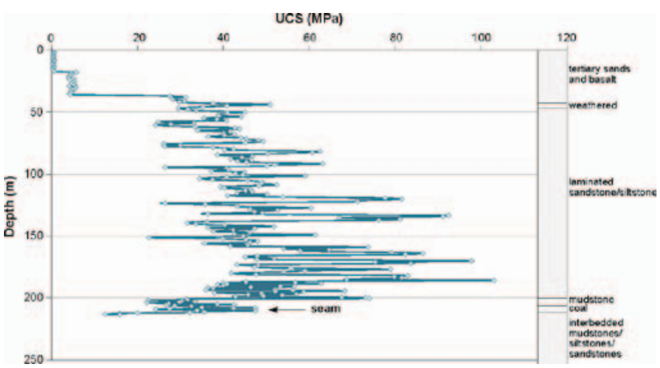

Figure 3. UCS profile modelled for Rangal coal measures.

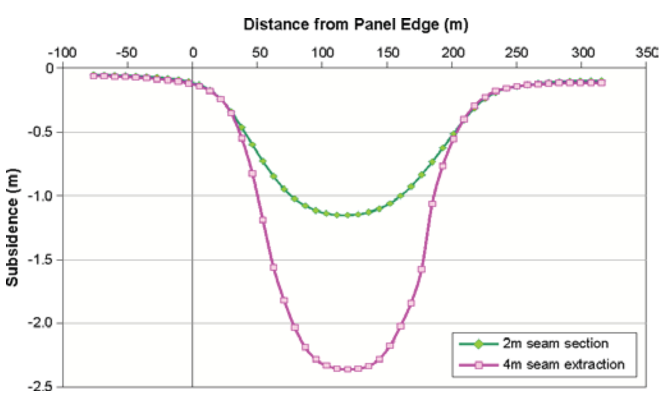

Figure 4. Subsidence profile for the modelled cases.

The rock fracture distribution for the two cases is presented in Figure 5 together with the resultant flow networks developed.

It is clear that increasing subsidence is coincident with the development of highly connected conductive fracture zones formed adjacent to the panel edges.

The conductivity profiles for the two cases is presented in Figure 6 and an average overburden vertical conductivity of $10^{-6.5}$ m/s was found for 1.2 m (4 ft) of subsidence and 10^{-3} m/s when 2.4 m (79 ft) of subsidence was developed.

This case demonstrates the impact of increased subsidence on the flow networks and overall connectivity within the overburden. The results demonstrate that irrespective of the height of fractures, the fractures must have formed a connected network to allow observable volumes of inflow. It is considered that the frequency, networking and aperture of those fractures increases with increasing overburden strain and subsidence. Therefore, whilst panel width typically controls the height of fracturing, the network connectivity and conductivity of fractures is controlled by the magnitude of strain and subsidence. Panel width, depth and seam thickness influence strain and subsidence. Therefore, there are a number of inter related factors which can influence the result.

The computer models of the various sites have given a range of conductivities depending on the thickness of overburden, magnitude of subsidence and the nature of the strata.

The results have been plotted relative to the overburden and subsidence in Figure 7. The average vertical conductivity from the top of the caved zone to the rock head is plotted.

The strain boundary lines (4 and 10 mm/m) (0.05-0.12 in/ft) from the empirical data are also presented. It is clear that the modelled results fit well with the empirical and the Australian data. The conductivity increases from near virgin conditions at the 4 mm/m (0.5 in/ft) line to very high values near the 10 mm/m (0.12 in/ft) line. There is an indication from the results that the degree of fracture networking appears marginally greater for the stiffer strata of the Bowen Basin than that of the Hunter Valley.

At a number of sites, Helium injection has provided estimates of the conductivity of the overburden (Heritage and Gale, 2009). These sites are from the Hunter Valley NSW. The water inflow from Southern and Oaky Creek (Sandy Creek Diversion) also provide data for comparison. These data points are placed on the modelled results in Figure 8 and provide a very close comparison. This comparison covers a wide range of conductivities from 10^{-1} to 10^{-6} m/s. This indicates that the process and outcome of the modelling is consistent with measured data from sites within the Hunter Valley and the Bowen Basin.

Overall, the results indicate that the overburden above panels having theoretical tensile strains of 4 mm/m (0.05 in/ft) has flow networks close to the in situ conductivity. This, therefore, provides a reasonable estimate for the onset of enhanced conductivity of the overburden.

It was noted that a hydraulic profile was maintained in the upper strata where the average conductivity was less than approximately 10^{-6} m/s. This indicates that flow in strata with an average conductivity less than 10^{-6} m/s is tortuous and may support a water table under the appropriate site conditions.

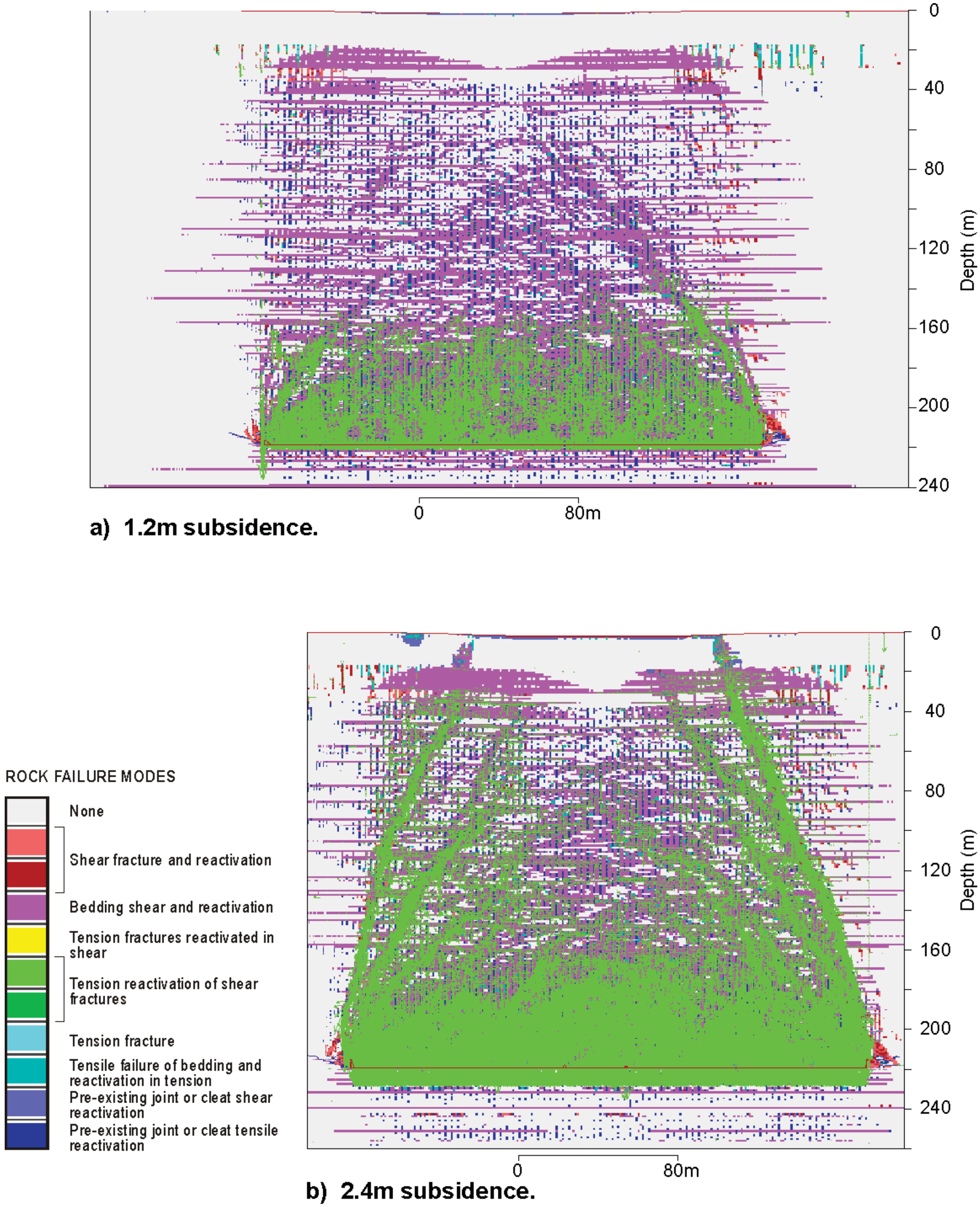

Figure 5. Flow networks developed for the cases.

A hydraulic profile was not typically maintained where the average conductivity was greater than approximately 10^{-5} m/s. The overburden only supported localised perched water above the goaf in these cases.

As the subsidence increases the conductivity increases to the point of a highly conductive fractured mass. Average conductivity

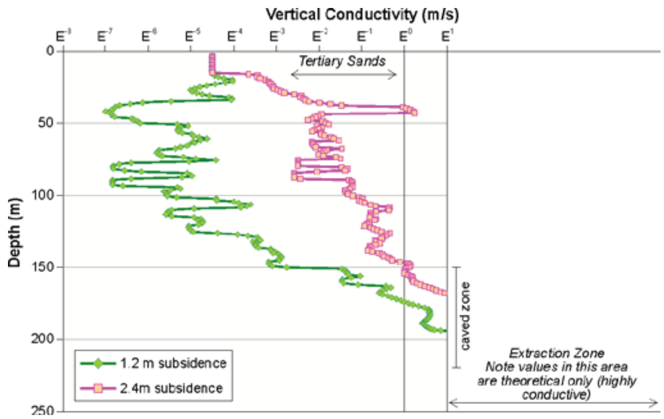

Figure 6. Conductivity profiles developed for the cases.

If a highly conductive fracture system above a longwall panel intersects saturated regolith, then the inflow rate of the system is typically controlled by the lesser resultant conductivity of the regolith and the rock units within the overburden. If the fractures intersect open flowing water, then the full capacity of the fracture system will be utilised.

CONCLUSIONS

Longwall mining creates additional fractures and changes the conductivity of pre-existing fractures. However, the creation of these fractures alone does not necessarily imply that a direct hydraulic connection exists through this zone. In order for mine inflow to occur, the fractures created must form a connected and conductive network to allow significant volumes of inflow.

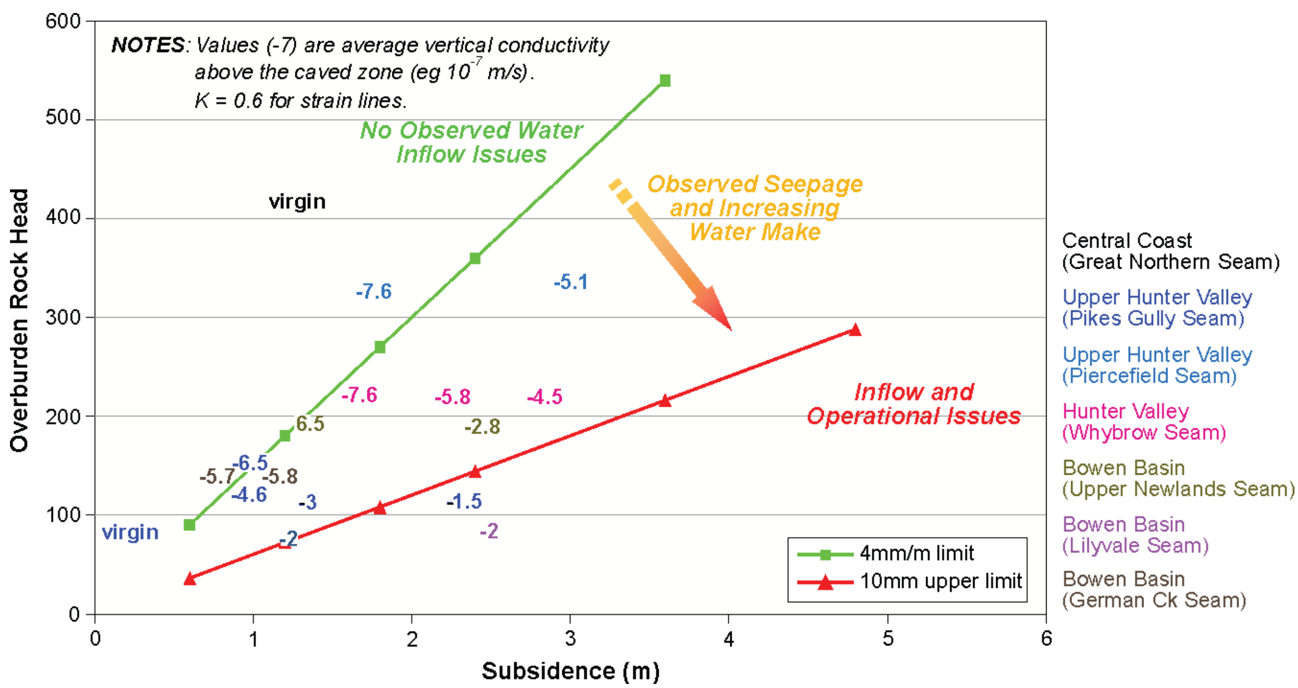

Figure 7. Comparison of computer modelling results relative to the empirical range.

overburden for panels having a theoretical strain of 10 mm/m (0.12 in/ft) is typically in the 10^{-2} to 10^{-3} m/s range.

Conductivity of 10^{-1} to 10^{-2} m/s was noted for strain values greater than 10 mm/m. Inflow for the highly conductive cases close to and greater than 10 mm/m (0.4 in/ft) would be largely controlled by the aquifer properties.

In order to evaluate the potential inflow it is essential to assess the surface or aquifer conditions which would provide input into the fractured network as the nature of soils and surface topography may impact on the location and rate at which surface water may connect with the mining fractures. It has been noted that weathered zones and clay layers can form aquitards which restrict connectivity of the regolith to the fractured rock material below.

It was concluded that the frequency, networking and aperture of fractures increases with increasing overburden strain and subsidence. Therefore, whilst panel width typically controls the height of fracturing, the network connectivity and conductivity of fractures is controlled by the magnitude of strain and subsidence. Panel width, depth and seam thickness influence strain and subsidence.

Geological factors also have an impact in terms of the nature of the fracturing and subsidence movements. Other geological variations were noted where a significant thickness of clay material occurs. In this case the clay may have the effect of constraining the fracture network either due to the fact that it can strain without fracturing or it is able to heal fractures by expansion of the clay. The nature of this is likely to be site specific and dependent on the clay material.

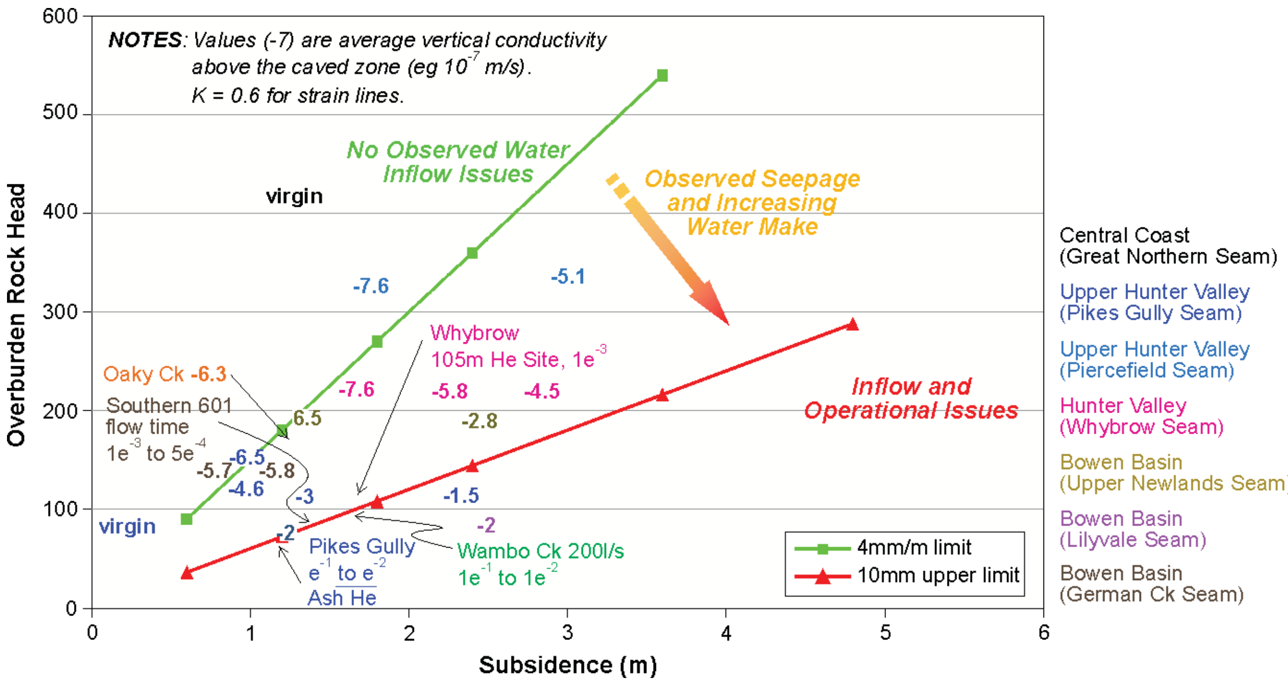

Figure 8. Comparison of modelled data with calculated average conductivity from Helium and inflow data.

The estimated average hydraulic conductivity presented (from top of caving to top of "solid" rockhead) is related primarily to the fracture enhanced conductivity of the rock mass. This is additive to the primary conductivity of the material fabric of the strata units.

The aim of this work has been to provide an overview of the hydraulic conductivity and connection above longwall panels. These results are based on single panels and as such, the results may vary for more complex mine layouts.

The actual inflow which may result is dependent on the nature of the boundary conditions between the aquifer and the rockhead. This will depend on site conditions and the hydraulic properties of the aquifer, soils and weathered strata.

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