ESTIMATION OF THE HYDRAULIC CONDUCTIVITY OF THE OVERBURDEN ABOVE LONGWALL PANELS IN COAL MINES

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Abstract

The aim of this paper is to summarise and update the results 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 and the thickness of the coal extracted. 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 relating to 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 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 update 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. This project was undertaken in 2008 and additional results and overview have been included in this paper.

In order to study water flow into 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 and within fractures which cut through the strata units. Flow within the rock fabric commonly occurs in coal and poorly consolidated rocks having connected void space. Flow within fractures is dependent on the confining stress across the fracture, whereby under high confining stress the fracture aperture closes and flow tends to diminish to that related to the rock fabric.

The 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 most frequently used method to measure the hydraulic conductivity of the rock mass is by the use of packer testing within boreholes. The method measures the conductivity of the rock mass which intersects the borehole. In most cases this is a combination of rock fabric and geological fracture planes, however no clear directional properties can be obtained.

Examples of packer testing done in the Permian strata of the Sydney Basin (Australia) is presented in Figure 1. The stress environment is one where the major principal stress is horizontal and the minor principal stress is vertical. The intermediate principal stress is typically marginally greater than vertical. Therefore fracture flow is likely to be biased to bedding partings and joints oriented close to the major principal stress direction.

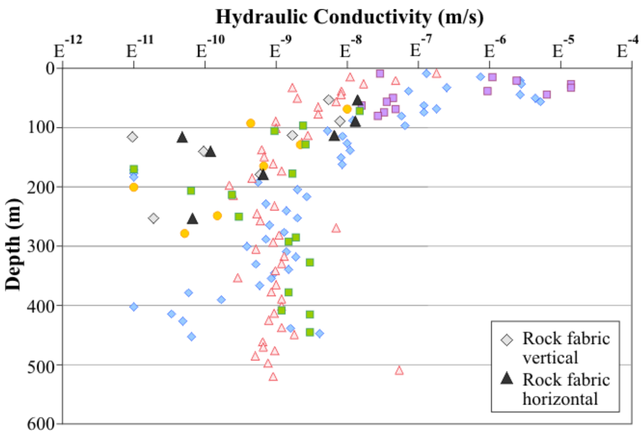


Figure 1. Examples of field measurements of hydraulic conductivity of strata and laboratory tests.

The results show a wide range of response from intact rock fabric to highly conductive fractured ground. In general, the data indicates that flow is typically within fractures and bedding partings within the upper 150-200m of the strata.

Below 200m, flow appears to be less influenced by the fracture and bedding parting fabric due to closure of the aperture to a residual value. Conductivity of the rock fabric increases in relevance at these depths.

Local variation to that occurs in highly conductive materials such as coal and poorly consolidated strata. Also, variation occurs for larger structural features which have a greater effective aperture than the "normal" joints and bedding partings.

Longwall mining creates additional fractures, changes the confining stress distribution across fractures and therefore modifies the conductivity of pre-existing fractures.

Extraction of coal via longwall methods is the most common method currently used in Australia. Extracted coal thickness typically ranges from 2-4.5m for conventional systems and may be higher for top coal caving systems. Longwall panels are typically 200-400m wide and 1-4km 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 (5-20m 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 0'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 experience the UK found that significant water inflow can occur for longwall mines having a rockhead less than 105m to the water source and theoretical tensile strains above 10mm/m. Longwall faces tended to be dry for strains on the strata at the water source less than 4mm/m. It was found that longwall faces were typically wet with strains at 6mm/m and high inflows may occur at strains greater than 10mm/m.

Water inflow experience in Australia was consistent with this experience, albeit with some variance related to geology.

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 70-175m in these cases. Subsidence was typically in the range of 1.2-1 6m.

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

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 90m but not for depths greater than 120m. Subsidence was estimated to be approximately 1.4-1.6m.

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. 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 2-2.5m.

These results are presented within Figure 2 relative to subsidence and rockhead.

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

The empirical relationship outlined above provides a broad qualitative overview of the likelihood for mine inflow. However, 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.

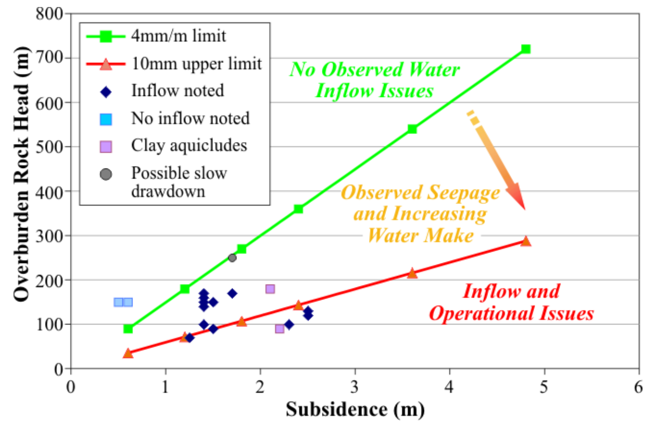


Figure 2. Inflow experience from Australia plotted relative to subsidence values and rockhead.

This was undertaken utilising computer modelling of the overburden caving and subsidence behaviour for a range of depths and panel geometries. Back analysis of site data over at least 10 years (e.g. Gale, 2011) has provided validation for the modelling process and provides confidence that the resultant ground deformation can be analysed to estimate the hydraulic characteristics of pre-existing fractures and those created within the strata due to longwall extraction. This general approach has been undertaken by other workers in the past.

In the ACARP study, and others subsequent, the 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 in Australia were modelled.

The model applied is two-dimensional and represents either a cross section across the longwall panel. Element sizes used in this study were typically 1m 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 models typically have element sizes of 1m or less in the area of interest.

A verification study of this form of 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 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 $1m^2$ area with unit pressure gradient. This then simplifies to solve k as approximately equal to:

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

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. It has been assumed that there is 1 fracture per element in the model and that the aperture modified by the displacement components which occur post fracture formation.

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 is 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.

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 or block 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, Queensland.

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

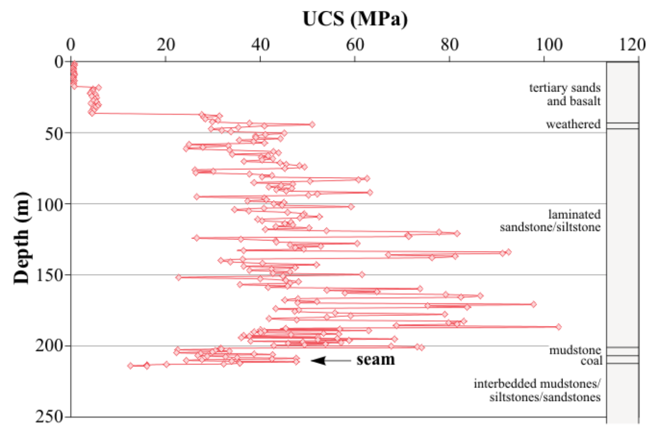


Figure 3. UCS profile modelled for Rangal coal measures.

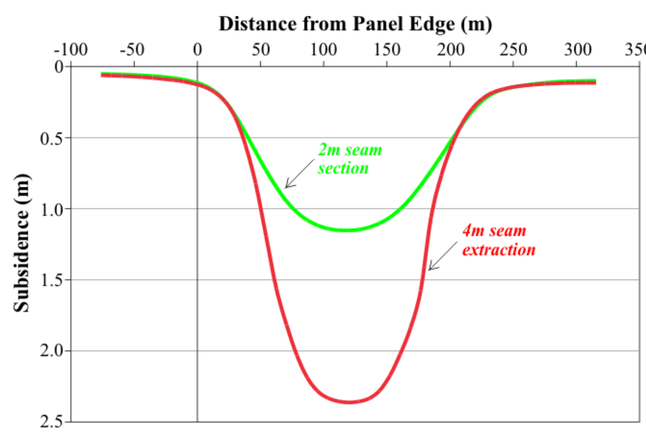
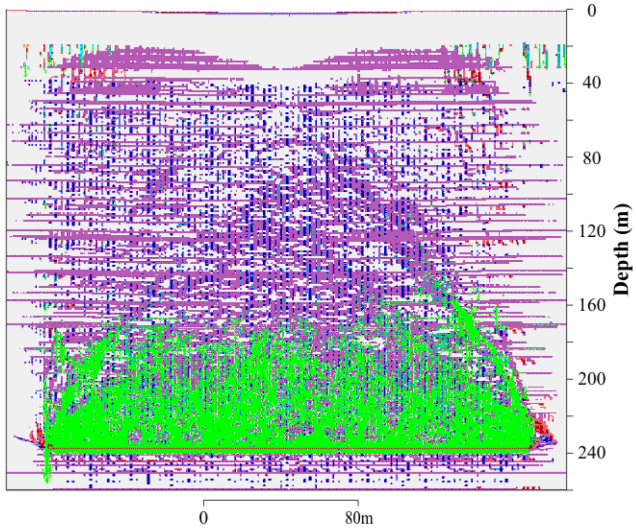
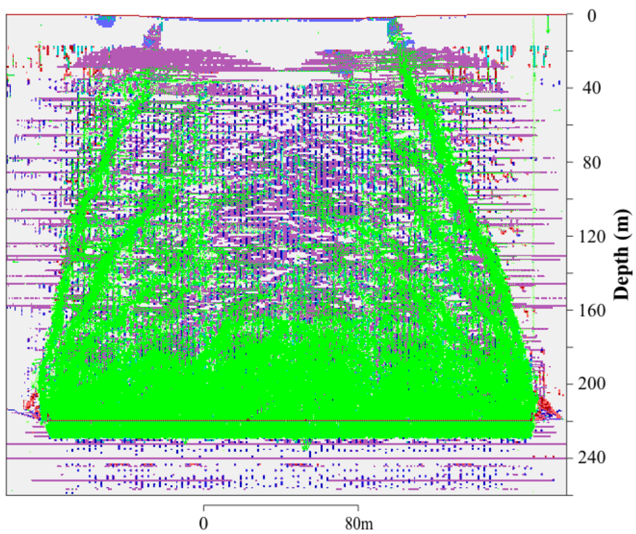


Figure 4. Subsidence profile for the modelled cases.

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



a) 1.2m subsidence.



b) 2.4m subsidence.

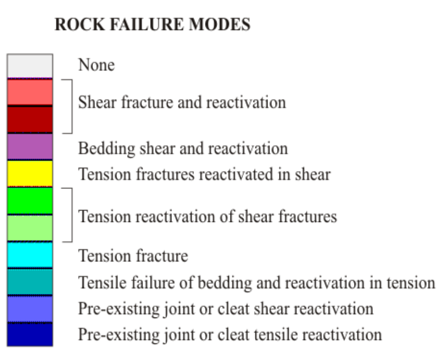


Figure 5. Flow networks developed for the cases.

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}m/s was found for 1.2m of subsidence and 10^{-3}m/s when 2.4m of subsidence was developed.

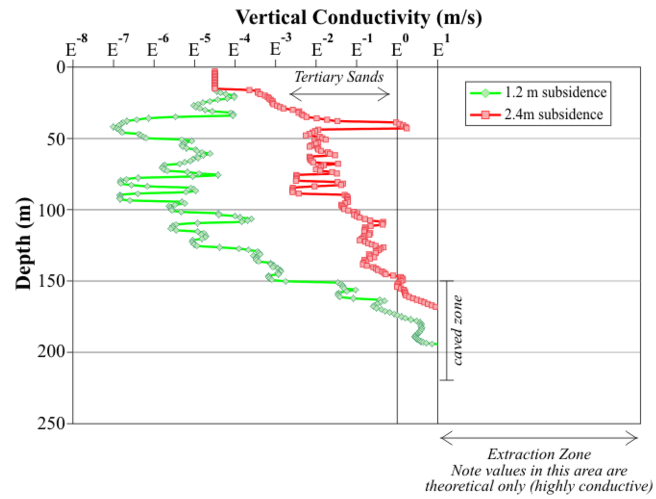
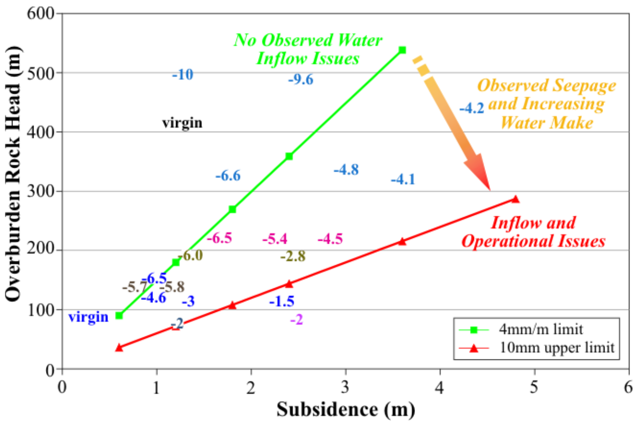


Figure 6. Conductivity profiles developed for the cases.

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.

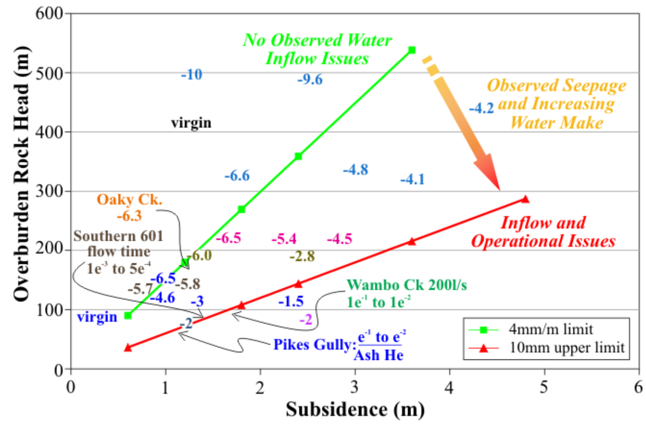
The computer models of the various sites have given a range of conductivities depending on the thickness of overburden, magnitude of subsidence and the nature of the strata.

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



NOTES: Values (-7) are average vertical conductivity above the caved zone (eg 10^{-7} m/s). K = 0.6 for strain lines.

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



NOTES: Values (-7) are average vertical conductivity above the caved zone (eg 10^{-7} m/s). K = 0.6 for strain lines.

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

The strain boundary lines (4 and 10mm/m) 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 4mm/m line to very high values near the 10mm/m 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 into, and above, longwall panels has provided estimates of the conductivity of the strata above the extracted coal (Heritage and Gale, 2009). These sites are from the Hunter Valley, NSW. The water inflow from Southern and Oaky Creek (Sandy Creek Diversion) also provides 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 less than 3-4mm/m have an average vertical conductivity from the surface to the mine, close to the in situ conductivity. This, therefore, provides a reasonable estimate for the onset of enhanced conductivity of the overburden.

As the subsidence increases, the conductivity increases to the point of a highly conductive fractured mass. Average conductivity overburden for panels having a theoretical strain of 10mm/m 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 10mm/m. Inflow for the highly conductive cases close to and greater than 10mm/m 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. Similarly, clays, silts and soils having low conductivity can restrict the inflow into a fractured rock mass.

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.

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.

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.

It is interesting to note that the results are consistent with a two dimensional analysis of the transverse section across the longwall panels. The impact of displacement and fracture related flow appears to be less significant in the longitudinal dimension. This is understandable when considering that most of the major flow paths (e.g. subsidence cracks) concentrate on the panel edges where the long term tensile strains develop. Lateral strains in the longitudinal direction are transitory and may become compressive. Therefore, a two dimensional transverse analysis appears to capture the key ground movements and flow pathways. These pathways are likely to be orders of magnitude greater than those associated with longitudinal strain in the central areas of the panels.

Acknowledgment

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