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CONNECTIVITY OF MINING INDUCED FRACTURES BELOW LONGWALL PANELS: A MODELLING APPROACH

Yvette Heritage¹, Winton Gale and Adrian Rippon

ABSTRACT: Gas make into active longwall panels is an important issue in ventilation and gas drainage design. A method of simulating the mining induced fracture network and associated increase in hydraulic conductivity is a necessity for improved mine design, hazard management planning and gas drainage efficiency. This paper identifies and illustrates the key components in determining the connectivity of lower gas sources to an active goaf. Computer modelling identifies the formation of cyclic fractures that form below the longwall face and extend down back below the goaf. These cyclic fractures form when the stress conditions are high enough and the strata properties allow for shear failure to extend down through the strata. The mining induced fracture formation and stress redistribution creates increased hydraulic conductivity of the floor strata below the active goaf. The stress redistribution and fracture volume also reduce the pore pressure below the goaf, allowing gas desorption to occur from lower seams. The combination of gas desorption and increased hydraulic conductivity allows gas connectivity from gas sources below the seam to the active goaf. A monitoring program at a NSW mine as part of ACARP Project C23009 allowed for preliminary validation of the concepts illustrated from the computer modelling. Preliminary field gas flow measurements are within the range of connectivity expectations based on rock failure modelling of longwall extraction. This report presents the first validation results for the modelling approach presented in this paper. Further results from ACARP Project C23009 on optimisation of gas drainage will follow in future publications.

INTRODUCTION

Gas make into coal mines is an increasingly important issue with the increasing depth of coal mines. Together with the longwall method of extraction and with increasingly wider panels, an understanding of gas make into the actively mined seam from adjacent seams is necessary. Coal mine safety and regulations require adequate gas management plans incorporated into the mine design and operations. Coal mine gas is generally controlled through mine ventilation and gas drainage. To optimise ventilation and gas drainage design, an understanding of the volume and rate of gas make into the mine is the key element.

There are robust methods for measuring gas content, volume and desorption characteristics in coal, however there are less robust methods of estimating the volume of gas that makes its way into the mine ventilation system from adjacent seams. This paper investigates the connectivity of mining induced fractures that form below longwall panels and their potential to facilitate gas make into the active goaf from coal seams below.

Computer modelling software, FLAC 2D, was used to simulate fracture formation below longwall panels. These models illustrate the concept and nature of mining induced fracture formation that facilitates gas flow from lower seams to the active goaf. The computer models are also used to assess connectivity between the lower seams and the active goaf by providing vertical hydraulic conductivity estimates for gas drainage and ventilation assessments. FLAC 3D was also used to simulate gas make and gas drainage in simplified three dimensional models.

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Previous studies have shown good correlation of the SCT modelling approach using FLAC2D for rock failure and overburden caving about longwall panels, in particular in Gale *et al.* (2004) and Gale and Tarrant (1997). This paper is the initial validation for computer modelling of gas connectivity to lower seams using SCT's approach.

Preliminary results from a recent field monitoring program are included in this report to provide an initial validation of the modelling concept for gas connectivity to lower coal seams. The field monitoring program was part of ACARP project C23009 (Gale and Rippon, 2016) and was conducted at NSW mine.

MINING INDUCED FRACTURING BELOW A LONGWALL PANEL

Often in gassy mines the recorded gas make is more than the volume of gas that the operational seam can produce. This alone indicates that there must be an alternative gas source from surrounding seams. Although increased mine gas volumes can occur from interaction with overlying strata, the underlying seam interconnection is assessed in this study.

Fracturing below the longwall panel can be distinct and highly connective or may not form vertical connective fractures at all. Parametric studies conducted using computer simulation of longwall extraction show that the mining induced fractures below a longwall panel vary in nature depending on depth/vertical stress, horizontal stress, lithology, geotechnical properties and the presence of low cohesion units.

The models show the connective mining induced fractures forming at the face and extending down back underneath the goaf. These fractures are cyclic in nature and occur about every 5 m. The length and conductivity of these fractures depends on the factors mentioned in the points above.

Some scenarios are such that the stresses aren't high enough to produce distinct cyclic fractures, or failure is focussed on shear failure of weak planes, and the fractures don't extend through the weak unit. In other scenarios the presence of weak units or bedding planes increases the deformation and associated connectivity within the floor. Alternatively in other scenarios the fractures form, however the strain, dilation or stress transfer through the fractures is such that the connectivity through the fractures is near *in situ*.

Figure 1 shows a model of a Queensland coal seam example at 300 m depth showing the cyclic nature of the mining induced fractures. Figure 1a shows the mode of failure as a mixture of bedding plane shear failure, shear failure of intact rock, and reactivation of cleat or joints. The mixture of the different modes of failure creates the shear fracture that extends down below the longwall goaf.

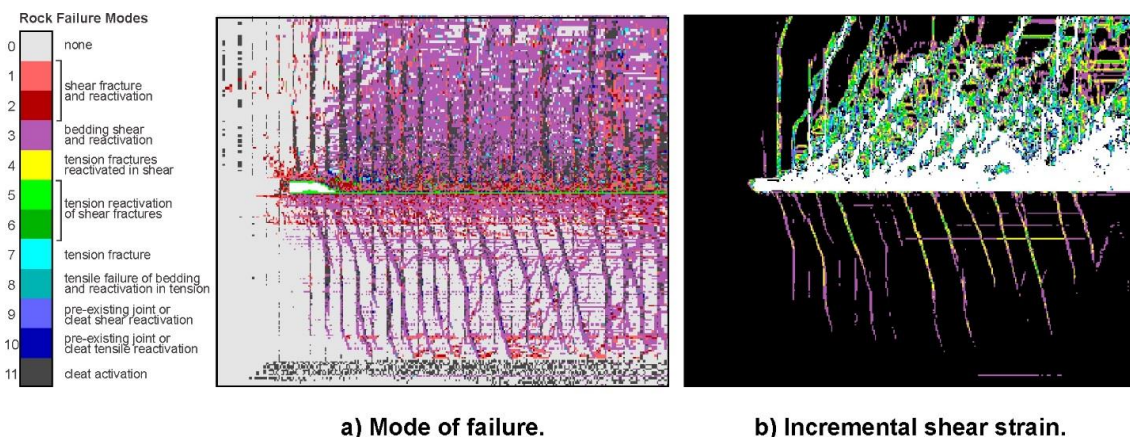


Figure 1: Computer model of cyclic floor fractures below a longwall panel.

Figure 1b shows the incremental shear strain, which highlights movement on the fracture in addition to the initial rock failure. The movement and dilation of these shear fractures would potentially increase their aperture and connectivity. Likewise, fractures with no to little shear strain are not likely to have large apertures and associated higher conductivity.

The two dimensional longitudinal cross section model presents the fractures as they would form under the stress conditions in the centre of the longwall panel. A cross section model across the panel width shows mining induced fractures extending from the panel edge down below the goaf. Figure 2 illustrates the modelled panel edge fractures below the extracted longwall panel.

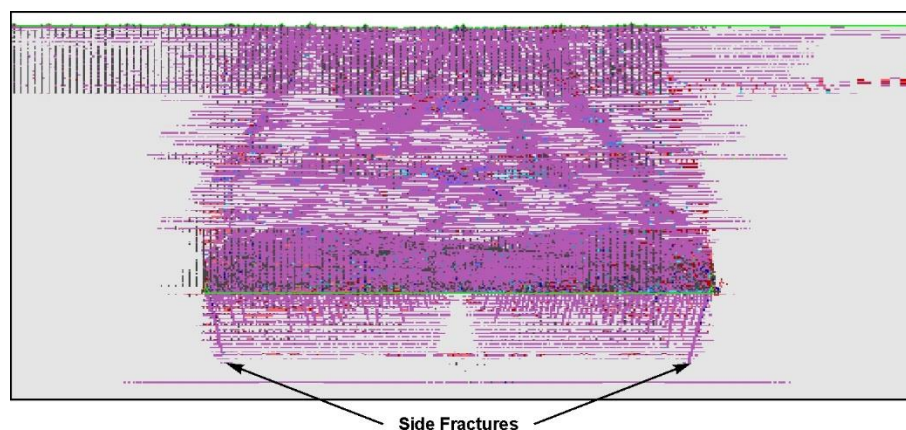


Figure 2: Computer model of panel width cross section showing panel edge floor fractures.

The three dimensional concept of the mining induced fracture system that forms below a longwall block is presented in Figure 3. In the centre of the panel there are cyclic fractures forming approximately every 5 m. A long fracture forms along the length of the panel by interconnection of panel edge floor fractures and cyclic fractures.

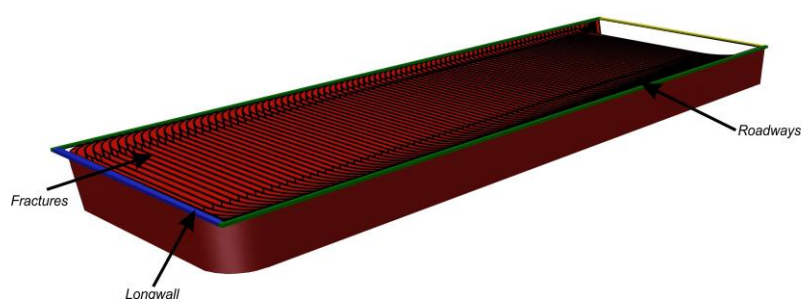


Figure 3: Model interpretation of mining induced floor fractures.

The concept consists of a panel edge fracture that forms on the panel edge and extends below the goaf at approximately 5 degrees from vertical. These panel edge fractures are observed in the panel width cross sectional models as observed in Figure 2. The cyclic fractures that form in the dynamic longitudinal models, observed in Figure 1, are repeated along the length of the panel and join up with the panel edge fractures.

A plan view concept of how both of these two dimensional model observations would manifest in three dimensions is presented in Figure 4. This concept shows how the cyclic face fractures are

envisaged to curve around and form the panel edge fractures. The curvature of the face fractures to form the panel side fractures is similar to what is observed on the surface where subsidence cracks form in a cyclic nature in the dynamic high strain zone at the face. These subsidence cracks then curve around to meet the panel edge high strain zone cracks.

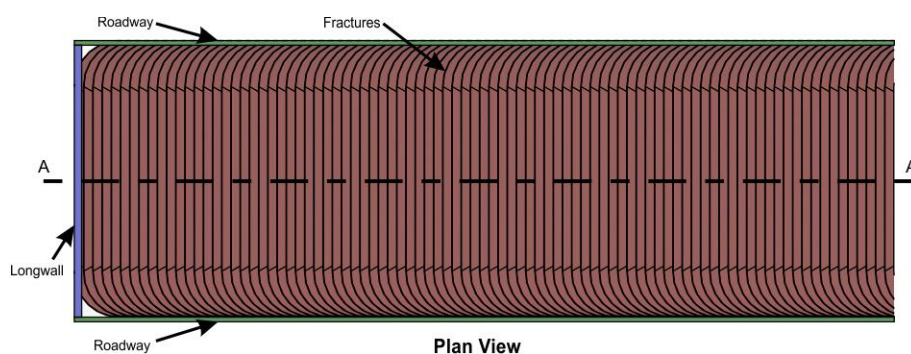


Figure 4: Plan view of cyclic floor fractures below panel.

FACTORS INFLUENCING FRACTURE CONNECTIVITY AND GAS MAKE

Although the mining induced floor fractures may have formed below an active panel, there are a number of factors that contribute to the floor fractures facilitating gas flow from the lower seams to the active goaf. These factors consist of fracture geometry and dilation, stress, pore pressure/gas desorption, gas volume and goaf loading.

The physical aperture and connectivity of the fractures plays a key role in the overall hydraulic conductivity of the fracture system. Fractures that form along the high strain zone from the face to down under the goaf may not have enough strain to dilate and increase the fracture aperture. This is dependent on the stress and rock properties described earlier. Generally higher stress environments would be expected to produce increased deformation and increase the effective fracture aperture.

Additionally, individual fractures that form along these shear strain zones may not connect together to form a continuous fracture plane. The mode of failure model in Figure 1 shows that the shear fracture zone is made up of many bedding fractures, joints or cleat or shear of intact rock. For low strains, these individual fractures may not connect to form a continuous fracture plane as depicted in the concept model.

The physical attributes of the cyclic floor fractures can however be assessed through analysis of computer models for the site specific scenarios to determine the mining induced fracture network. This mining induced fracture system is then hydraulically stressed to determine the hydraulic conductivity of the seam floor fractures.

Stress plays a significant role in both the conductivity of the mining induced fractures and the pore pressure of underlying seams.

Longwall extraction significantly changes the stress environment with stress redistribution occurring about the excavation, caved overburden and fractured floor strata. Figure 5 shows the modelled vertical stress redistribution about a longwall face. Key features of this stress redistribution are:

- Increased abutment stress at the face – also contributing to cyclic shear fractures in the floor strata;
- Reduction in stress behind the face – this area creates low stress transfer across fractures, causing increased conductivity, and also reducing pore pressure in underlying seams causing gas desorption;

- Increased vertical stress at some distance behind the face – goaf reloading increases vertical stress in the centre of the panel increasing pore pressure and reducing horizontal conductivity.

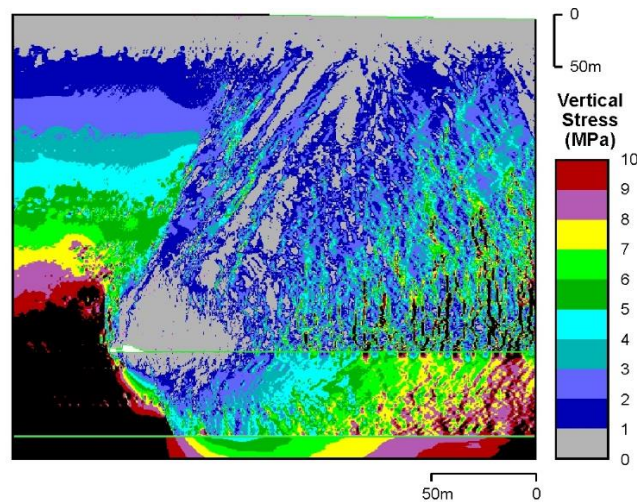


Figure 5: Modelled vertical stress distribution about a longwall face.

A reduction in vertical load below the longwall panel is often enough to reduce the pore pressure of close underlying seams to below desorption pressure, thus making gas available for migration. Figure 6 shows an example of depressurisation below a longwall panel, where the fractures are observed to directly reduce the pore pressure for 50-80 m below the seam. This includes the reduction in pore pressure of an underlying seam at approximately 60 m below the operational seam.

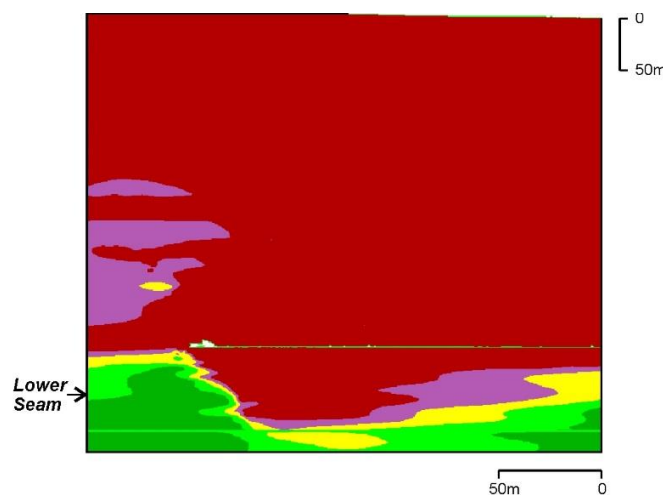


Figure 6: Modelled pore pressure about a longwall face.

The pore pressure contours in Figure 6 also show an increase in pore pressure due to goaf loading at approximately 80-100 m behind the face for this example. This increase in loading could increase the pore pressure to above gas desorption pressure to limit gas supply. If the pore pressure is increased to a pressure below desorption pressure, the gas flow would be expected to be reduced below the goaf due to the reduction in pressure gradient.

The volume of gas in the coal directly influences the volume of gas that has the potential to make its way to the active goaf.

Goaf loading reduces hydraulic conductivity in the horizontal plane, with little impact on the vertical conductivity. A significant increase in horizontal stress would be required to reduce the vertical

conductivity. The reduction in conductivity of the horizontal planes reduces the area from which vertical fractures can source gas volumes.

COMPUTER MODELLING ASSESSMENT OF CONCEPTS

The computer models have proposed a concept that suggests the mechanism for gas flow from lower seams to the active goaf via a network of existing fractures and mining induced fractures. The models have also identified stress redistribution about the longwall panels and its impact on pore pressure and fracture conductivity.

Further manipulation of the computer models provides assessment of the connectivity of the fracture system below the active panel through assessment of vertical hydraulic conductivity. The models also provide a means to assess different sensitivities that are expected to influence the conductivity and gas flow. Specific elements assessed to further understand the connectivity concept include:

1. Hydraulic conductivity of the fracture system in the floor
2. Impact of goaf loading on horizontal and vertical conductivity
3. Gas flow from fractured strata without drainage boreholes
4. Gas flow from fractured strata with drainage boreholes

Assessment of these elements is presented for a case study at a NSW mine. The field program of work was designed as part of ACARP project C23009 where assessment of the gas connectivity concept through measurement of pore pressure and gas flow in cross measure gas drainage wells was conducted. The working seam has cross measure gas drainage holes intersecting four lower seams. The actual gas flows and calculated average hydraulic conductivity are discussed in the following section. The site specific characteristics from the case study are used in this section to address the different key elements of the connectivity concept.

The hydraulic conductivity of the floor fracture system is determined by modelling flow through the fracture network as a result of a hydraulically stressed model. The vertical conductivity is a result of flow through horizontal and vertical fractures that form the fracture network. The result of this is a detailed vertical hydraulic conductivity section through the model fracture network. Figure 7a shows the vertical conductivity of the case study model where the conductivity of the cyclic fractures is in the order of 5×10^{-6} m/s. For practical purposes, the conductivity is best presented as an average conductivity in order to estimate average gas flows for a given area, where the average vertical conductivity for the 50 m behind the face is $1 \times 10^{-7 \text{ to } -8}$ m/s.

An important factor in understanding connectivity is to understand the impact of goaf reloading on the conductivity and resulting gas flow. The horizontal and vertical conductivity for the case study have been teased apart to address this element of connectivity. Figure 7 shows a comparison of modelled vertical and horizontal conductivity for the area of stress relaxation behind the face and the area experiencing goaf reloading.

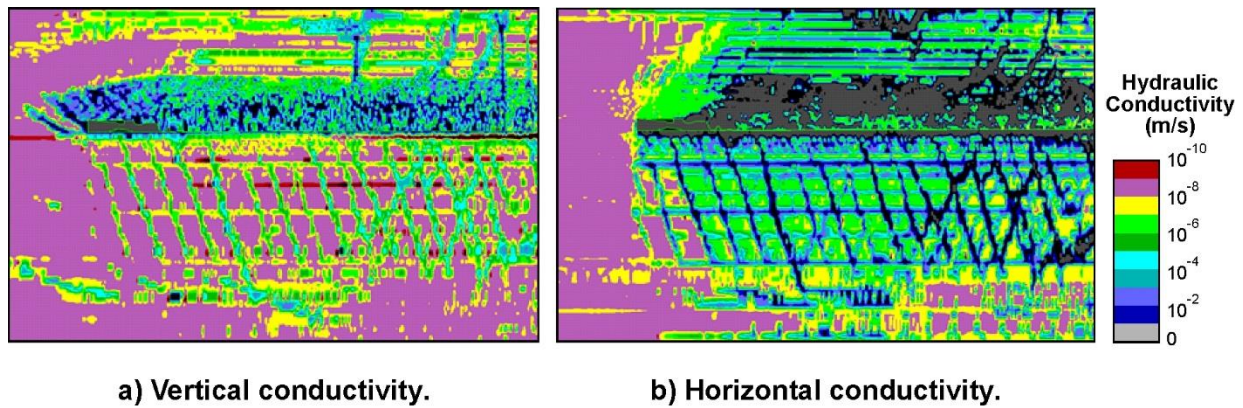


Figure 7: Modelled conductivity results for the case study mine.

The horizontal conductivity shows a significant reduction from 1×10^{-2} m/s to 1×10^{-6} m/s due to the additional vertical goaf load, however the vertical conductivity remains relatively unchanged at approximately 1×10^{-7} to 10^{-8} m/s due to low variation in horizontal stress. This implies that although the vertical conductivity is similar, the gas source may be reduced due to the reduction in lateral connection and surface area to the gas source. In the same way that goaf reloading occurs at a distance behind the face, the goaf loading in the panel width section is only in the panel centre, leaving a stress relaxation zone at the panel edges. Figure 8 shows the vertical stress distribution across two adjacent panels showing the goaf loading effects in a zone in the panel centre with relaxed zones either side.

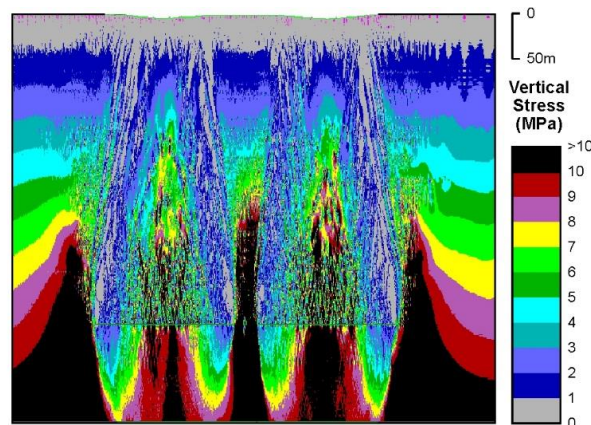


Figure 8: Vertical stress distribution across panel widths.

A simpler equivalent mass model based on the fracture characteristics of the rock failure models was created in FLAC 3D to assess gas flow from the thickest underlying seam into the active goaf. Scenarios were modelled without goaf drainage wells and with wells at 20 m and 100 m spacing. Model variables also included wells intersecting one or two horizontal fractures, and different down hole well pressures to determine the range and characteristics of expected gas flows. The coal desorption pressure was modelled at 1.5 MPa and the drainage holes had a diameter of 45 mm.

The results show that for the scenario without drainage holes, flow is predominantly on the horizontal partings in the coal, before intersecting with the sub vertical mining induced fractures. The results for the flow model without gas drainage wells are presented in Figure 9a. The trend in Figure 9a represents the total gas flow volume for a 50 m x 50 m area of gas make into the goaf.

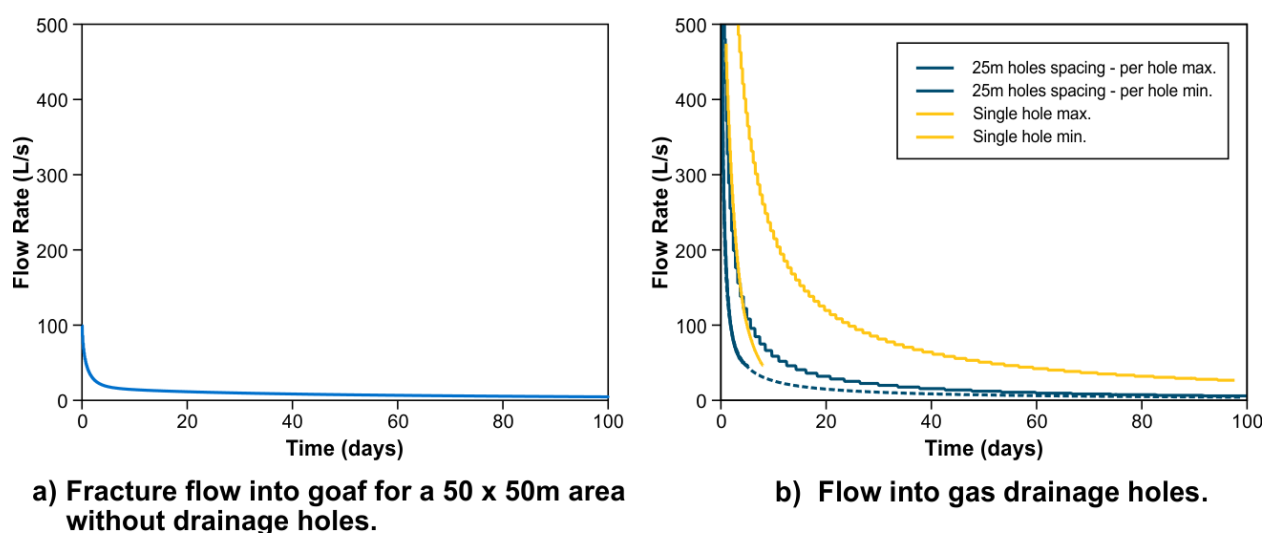


Figure 9: Modelled gas make for the case study mine.

For the models with gas drainage wells, flow is concentrated along horizontal partings and sub vertical mining induced fractures, until the drainage well is intersected. For boreholes that intersect the lower coal seams, direct flow from the seam is also observed from the borehole.

The flow outputs from the drainage wells for different model scenarios are presented in Figure 9b. The modelled scenarios include the flow for expected end members for a single hole over a 50 m x 50 m area and, per hole, for three holes draining the same volume. Both scenarios are run for a maximum and minimum downhole pressure of 600 kPa and zero back pressure.

The peak drainage well flows were modelled to be in the order of 500 L/s, where the flows then quickly reduced in an exponential manner and were mostly reduced by approximately 20-60 days from the onset of drainage. The rapid decrease in flow rate is due to:

1. A reduction in pressure gradient caused by a reduction in gas volume and pore pressure due to gas being drained from the seam
2. A reduction in pressure gradient due to gas drainage from a farther distance from the drainage well.

These preliminary models do not include goaf loading. The models indicate the range and trend of anticipated gas flow into a gas drainage well. The models indicate that for the case study longwall extraction, peak flows of up to 50 L/s would be anticipated, with flows quickly reducing to low flows of less than 100 L/s in 2-25 days.

MODEL VALIDATION WITH EARLY FIELD MEASUREMENT RESULTS

A large field monitoring program for the case study has captured a significant amount of information to investigate gas drainage and borehole efficiency. The field program of work is far more involved than the results discussed in this paper, however this paper shows the preliminary results that illustrate initial validation of the fracture system and connectivity concepts presented in this paper. The case study field trial monitored cross measure gas drainage wells and found that the peak flows varied depending on the measures that the boreholes intersected. Figure 10 shows the flows measured in the boreholes that drilled through the different horizons at various stages of retreat and in relation to the number of days the wells were on line.

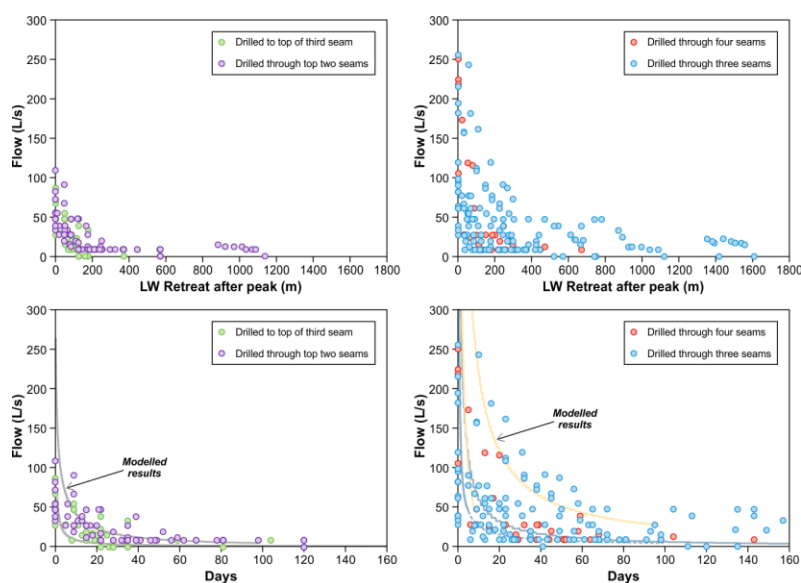


Figure 10: Gas drainage well flow monitoring from case study mine

Boreholes that intersected the upper two seams had peak flows up to approximately 100 L/s, while drainage holes that were drilled through the four seams showed peak flows up to 250 L/s. The increase in flow volumes is generally consistent with the increase of volume of gas available for desorption.

The peak flows were measured to be less than the anticipated maximum 500 L/s. It is however noted that if the initial flow in a drainage well is not observed, and the first flow measurement is taken even a couple of days later, then the peak flows would not have been recorded. The actual initial peak flows on onset of drainage are expected to be greater than the measured peak flows.

The modelled trends for single hole and 25 m hole spacing are plotted on Figure 10 for models where the hole intersects only the two upper seams and where the hole intersects all four seams. The data is generally in the range of the modelled results and follows similar trends of reduction over time. The modelled hydraulic conductivity estimates have therefore produced flows within the order of magnitude of measured flows.

The gas flow from the drainage wells shows a trend of reducing flow exponentially over time. The time at which the flow significantly reduces in all holes varies between 20 and 60 days. This is consistent with the modelled flow reduction trends.

The flows from the gas drainage holes presented in Figure 10 show a rapid reduction in flow within 100 m of longwall retreat and significantly reduced flows after 200-300 m of extraction. The rapid reduction in flow at 100 m of retreat suggests that goaf loading may play a role in reducing the area of high horizontal conductivity, thus reducing the gas source for the borehole. This is consistent with the modelling results showing a reduction in horizontal conductivity from goaf loading.

Both the magnitude of peak flows and timing of flow reduction measured in the case study are within the range of modelled expectations. This indicates that the model concept of fracture formation, estimated hydraulic conductivity and flow reduction over time is consistent with the measured results.

The modelling of gas flow for different well spacing provides an interesting insight into interpretation of effective drainage wells. On initial assessment, the drainage holes with lower flows may appear to be compromised holes with less effective drainage, however the model results indicate the opposite.

The modelling results show that a number of adjacent effective drainage wells can produce lower flows than drainage wells acting as a single well due to compromised adjacent wells. A high flowing

well may indicate adjacent compromised wells. This leads to further work in understanding the optimal spacing of drainage wells.

FORWARD WORK PROGRAM

This paper presents the preliminary results as part of a much larger program of work for ACARP Project C23009. Further results from ACARP Project C23009 on optimisation of gas drainage will follow in future publications. The ACARP study intended to form a basic understanding of gas make into active goafs and gas drainage wells in order to optimise gas drainage. A number of key areas for further work include:

1. Investigate the impact of turbulent flow on gas flow rates
2. Investigate the impact of gas desorption rates on gas drainage flow rates
3. Assess gas drainage borehole efficiency in regards to optimal spacing

CONCLUSION

Gas make into active longwall panels is an important issue in ventilation and gas drainage design. A method of simulating the mining induced fracture network and associated increase in hydraulic conductivity is a necessity for improved mine design, hazard management planning and gas drainage efficiency. Computer modelling illustrates the formation of mining induced fractures below a longwall block and their connectivity for gas make into an active goaf. A number of elements have been identified as key factors in the connectivity of lower seam gas to the active seam.

1. Cyclic mining induced fracture formation below longwall panels
2. Stress redistribution
3. Pore pressure reduction
4. Vertical hydraulic conductivity

Preliminary field gas flow measurements measured at the case study mine are within the range of connectivity expectations based on rock failure modelling of longwall extraction. This report presents the first validation results for vertical conductivity estimates for the modelling approach presented in this paper.

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