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Effect of Grouting on Longwall Mining Through Faults

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EFFECT OF GROUTING ON LONGWALL MINING THROUGH FAULTS

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ABSTRACT: The demand for increased production, safety and resource recovery has put pressure on the coal industry to find methods to mine through fault zones. One of the processes used to reduce the likelihood of face instability is to consolidate the strata around the fault using grouting techniques. Since grouting techniques are being used more frequently in practice, the industry requires a greater understanding of the effect of fault consolidation on ground improvement and associated strata response during mining.

This paper presents the results of a recent ACARP research project aimed to assess faulted areas to determine the need or otherwise for grouting and their likely impact on mining performance. A review of past fault consolidation projects was undertaken to determine their "success" in longwall operations and to identify factors that influence longwall ground control.

This paper includes a comparative analysis of grouting results from several mines. The outcomes will provide guidance to assist operators in understanding when fault grouting is required, how it might be implemented and expected outcomes of the grouting program.

INTRODUCTION

A risk assessment of longwall retreat through a fault zone will quickly identify potential financial losses or personal injury due to strata failure as major risks. Smith (2006) suggests that major causes and contributing factors of strata failure and/or poor longwall operating conditions are commonly:

- Poor horizon control
- Poor face alignment
- Incorrect setting of shields
- Stopping or inconsistent face retreat
- Breakdowns or failure of equipment to perform
- Crews cutting inconsistently or with low morale
- Poor cutting sequence
- Inability to react to problems
- Mining into ground that is outside the capability of the equipment or people

A fault management strategy that includes the following critical controls provides the greatest likelihood of a safe and consistent longwall retreat through a fault zone:

- Accurate and precise geological knowledge of the nature of the faulting and lithology
- Knowledge of the geomechanical behaviour of the strata, including any likely beam effects, particularly with a coal roof
- Adherence to basic longwall operating standards, including horizon control, cutting sequence, creep control and shield setting
- A proactive maintenance regime targeting the section of the face likely to be most affected by the fault zone
- An effective water management strategy
- An effective circle of communication between geologists, geotechnical engineers, the longwall department and underground crews, with an agreed plan of attack

Often in good ground conditions, the absence of one or more of these controls may be tolerated with little effect on production. However, during retreat in faulted ground, the likelihood of a significant interruption to face operations is greatly increased. It is therefore essential that, when mining into faulted areas, all of these controls are in place and any of the root causes of strata failure or poor operating conditions are addressed.

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A research project funded by the Australian Coal Association Research Program (ACARP) was initiated to investigate issues associated with mining through faults (ACARP C13015, 2006). This project focused on a detailed monitoring program of mining through a fault at an Australian longwall mine. Analysis of the fault pre-consolidation program including comment on grout takes, pressures and penetration was. Longwall support monitoring and face stability analysis was also used to examine overall strata-support interaction processes.

Following the detailed study, a review of past fault consolidation projects from various mines was undertaken. The aim of the review was to devise a means to assess faulted areas to determine the need or otherwise for consolidation and their likely impact on mining performance.

FAULT CONSOLIDATION USING GROUTING

Current Grouting Practices

The civil engineering industry has developed several techniques for permeation grouting and grout design for use in dam construction, civil works and tunnel sealing. The coal mining industry has adopted many of these methods and attempted to apply them to fault consolidation on longwall mines.

The conventional method of grouting has been substantially developed over the last 40 years from empirical results obtained from different grouting activities. Houlsby (1990) has extensive experience in the area and has reported his findings in a practical and applicable manner.

After drilling the grout holes and water testing to determine the permeability, a decision on the grout type, initial water:grout ratio and maximum grouting pressure is made. The initial water:grout ratio is guided by the results obtained from the water tests starting with a thin grout mix and slowly increasing the grout water cement (w/c) ratio throughout the grouting process.

A review of different mine sites shows the most common grouting method involves drilling grout holes at a given spacing to intersect the fault whilst minimizing the drill lengths and maximizing the drill angle. The grout is then pumped into the total length of the grout hole until significant increases in pressures are achieved. If the grouting pressures don't increase over time the grout mix is thickened and the thicker grout is pumped into the grout hole. The backpressure is monitored using a bleeder hole, which can also be used to pump grout into should any blockages in the grout hole occur.

The selection of grout can be wide and varied depending on the application and the results required from the grouting project. The grout type chosen for the task is primarily a function of the aperture of the joints in the fault and the associated costs. Water cement ratios can vary from about 0.3:1 by weight to around 10:1, however research by Houlsby (1990) and Weaver (1991) have shown grout mixtures with w:c greater than 5:1 have little strength and durability. Grout mixtures have also become more sophisticated in recent years by using complex admixtures and microfine cements. Modifiers such as superplasticers allow enhanced grout strengths by providing greater penetrability at lower w:c ratios.

Drill Holes, Spacing and Layout

Boreholes can be drilled inseam or from the surface depending on the depth of mining, the ground conditions and the available equipment. Both methods are used in Australia for fault consolidation work. The general consensus for sealing rock in the grouting industry recommends borehole spacings of 1 to 3 m and row spacings of 1.5 to 2.5 m (Kutzner, 1996).

For inseam holes, borehole spacing is typically between 2.5 m and 4 m. The drill patterns commonly adopted generally aim to target the first 1 m to 2 m of immediate roof above the longwall face. Figure 1 shows a plan view of a typical inseam drill pattern. For surface holes, a 5 m x 5 m grid pattern up to a 5 m x 10 m grid pattern is typically used around the proposed fault location.

Grout Injection Pressures

Injection pressures within the grouting industry can vary significantly, ranging from 1 bar to 50 bar depending on the application and the pumping equipment available. In general the extent of grout spread is proportional to the grouting pressure, the extent of fractures, and inversely proportional to the cohesion of the fluid grout. Even though little evidence is available to give a standard grout pressure range, particularly in coal mining, the easiest method to determine the maximum grouting pressure is to keep the grouting pressure below the cracking pressure (Kutzner, 1996).

The cracking pressure is dependent on the rock conditions, however a simple calculation for the maximum grout pressure is based on the unit weight of the overburden relative to depth. A more detailed approach considers the potential for borehole fracture based on the in-situ stress state and rock properties. In general terms, hydrofrac stress measurements indicate that the magnitude of minimum horizontal stress is equal to the shut-in pressure, or the minimum pressure needed to keep a fracture open after pumping has been stopped. A review of hydrofrac stress data in the Bowen and Sydney basins indicate that the minimum total stress in coal seams generally varies between 50% and 85% of overburden pressure at typical mining depths (Enever et al, 1999).

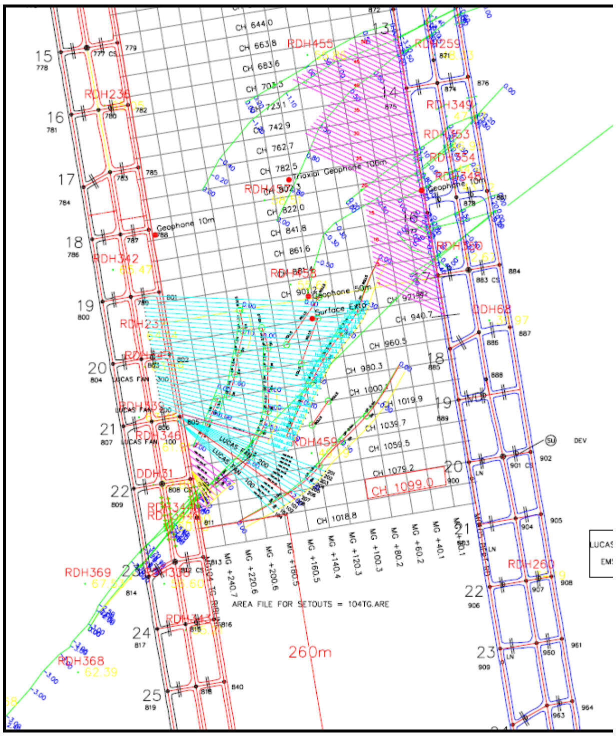

Figure 1 - Typical drill hole layout into LW block

Measuring Grouting Outcomes

Grouting has traditionally been used for seepage reduction in tunnelling and the dam construction industry and collectively this work forms the basis for measuring grouting success. In general, a reduction in permeability or Lugeon value (1 Lugeon unit = 1 litre/metre/minute at 1000 kpa) to less than 2 is often considered successful as a maximum leakage criterion. The cost of grouting to reduce the Lugeon values below 2 is often considered uneconomical.

A method for measuring grouting success for longwall operations is less evident since the primary purpose is to consolidate the faulted rock mass. In general, the characteristics of the fault(s) and surrounding strata govern longwall face stability. However, methods of measuring the pre- and post-mining effects of ground improvement are difficult to quantify.

Faults that intersect one or two longwall supports do cause significant delays. Therefore one measure is that if the fault consolidation could confine instabilities to one or two supports then it could be considered sufficient for consolidation, having reduced delays to an acceptable level (ACARP C10019, 2003). Similarly, if the influence of grouting can be related to the level of ground improvement, eg via permeability testing, this may provide another means of measuring grouting success.

One approach is to simply maximize the volume of grout injected in to the fault(s). This is the current fallback position used by the industry given the lack of alternative approaches. A database that contains records of the volume of grout injected, hole location, the type of faulting encountered, mining performance and related test data should provide a starting point to quantify the influence of grouting.

FAULT TYPES AND GROUND CONDITIONS

Fault Stability Criteria

In general, major structures present a high level of risk if they are orientated at less than 20 degrees to the longwall retreat line. This is due to the alignment with goaf cracks and mining induced fractures, and the length of the longwall face that is exposed to poor ground conditions at any one time.

Using simple mechanics, the most unfavourable orientation of a shear plane in relation to the major stress direction is about 30°. Faults dipping at 60° to 90° towards the longwall face would therefore generally present the greatest risk of instability when subjected to vertical abutment loads, as shown in Figure 2. Similarly, faults oriented 30° to the longwall panel would generally be most prone to instability as a result of horizontal abutment loads, as shown in Figure 3.

Lee (1966) outlines a number of factors likely to cause fault reactivation and subsidence based on U.K. experience as a result of longwall mining:

- The fault must dip over the panel and toward the panel centre with the panel in the footwall of the faults, i.e. towards the longwall face
- The fault surface expression must be about 0.2 times the depth towards the goaf from the gateroads.
- A longer fault is more prone to reactivation than a shorter fault. Also a fault that does not completely cross a panel and extend well beyond its limits, is less prone to reactivation.

The first point highlights that shown in Figure 3, in which fault reactivation is more likely when the overlying material is able to "slide" towards the goaf. This can be further exacerbated by the presence of multiple structures, which can often form wedges. Wedge failure can be particularly damaging if low angle (thrust) structures are present.

The second point suggests that the fault must be in the maximum tensile strain area of the subsidence trough between the gateroads and the trough centre. The third point provides that the fault completely crosses the panel. This is logical because the end of the fault provides a restraint against reactivation by the unfaulted strata, requiring shearing through unaffected strata to continue lateral fault movement.

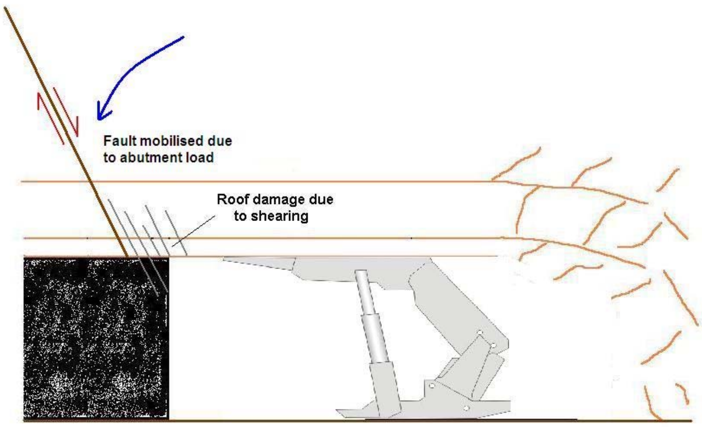

Figure 2 - Potential for roof damage due to vertical abutment loading

From a mining standpoint it is generally preferred to first intercept the fault in the tailgate. This is preferred over the alternative, in which first interception at the maingate would result in sustained tailgate damage as mining progresses. Similarly, faults oriented near parallel to the face present an extreme risk of instability and therefore need to be approached at a compromised angle (say 30°) to minimise face exposure at any given time whilst limiting the overall length of retreat in the fault system.

The potential for fault movements in the "high risk" zones is overprinted by the local fault characteristics, for example an open, soft structure versus a tight structure. The combination of open voids and potentially elevated abutment loads in a high risk zone can therefore present a challenging set of conditions for longwall mining. Unfortunately, longwall operating and production requirements necessitate mining through faults at angles that are generally the most unfavourable from a fault stability standpoint. This is why the correct choice of mining horizon is so important and needs to be coordinated with accurate determination of fault characteristics and targeting of stabilisation measures.

Water Pressure Testing

Water pressure testing is perhaps the simplest and certainly most widely used method for assessing the need for grouting. Houlsby (1990) recommends that while conducting a water pressure test the pressure should be held constant at one bar for 15 minutes with the water take measured in 5 minute intervals. This is recommended to get a representative set of data for the WPT. Analysis of the water pressure test data can give an indication of the

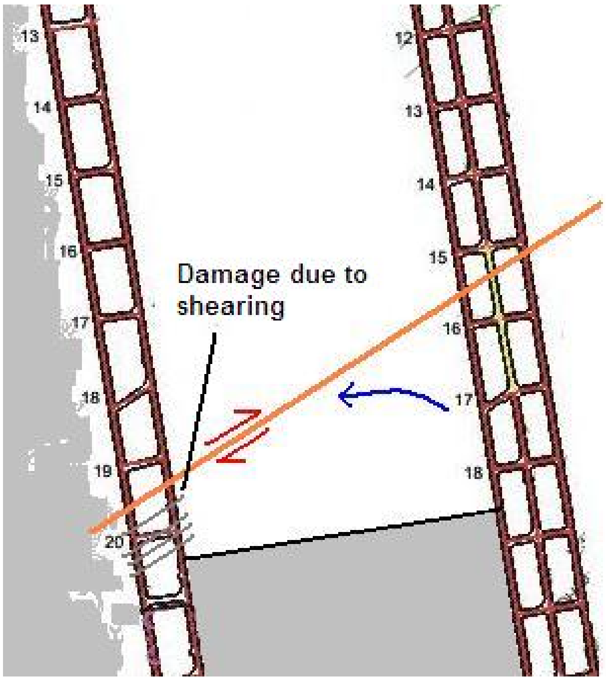

Figure 3 - Potential for damage due to horizontal abutment loading

permeability but also the characteristics of the fault. Decreasing Lugeon values indicate voids being filled whereas increasing Lugeon values indicate either void creation by washing out the hole or under certain conditions or hydrofracing of the borehole.

As discussed previously, grouting has traditionally been used for seepage reduction in tunnelling and the dam construction industry and thus seepage mitigation is the basis for measuring grouting success. The current study has provided evidence that permeability testing can provide a good indication of fault conditions and the need for grouting. The grouting industry has developed a guide to grouting requirements on the basis of rock mass permeability. For example,

- 1 Lugeon unit is the type of permeability where grouting is hardly necessary.
- 10 Lugeons warrants grouting for most seepage reduction jobs.
- 100 Lugeons occurs in heavily jointed sites with relatively open joints or in sparsely cracked foundations where joints are very wide open.

Analysis of permeability test data suggests similar limits apply to longwall mining. In general, faults with a hydraulic conductivity in excess of 10 Lugeons are likely to take significant amounts of grout and will benefit from a grouting program. For tighter structures, there is some evidence to suggest that grouting may be less influential on longwall face stability depending on the fault orientation and panel loading influences, particularly for Lugeon values less than about 2.

Lugeon tests should be carried out over a standard length to ensure consistency of results. The location of packers and subsequent calculation of Lugeon values can dramatically influence estimate values. In particular, mine operators should ensure that a good standard of testing is undertaken and directly targets the fault structure(s). The tests should also be supported by good drilling records that provide as much detail of the fault structure as possible. In general, where a large length of borehole is pressured, the Lugeon value provides a measure of the mean permeability of the formation. For short test lengths, there is likely to be a much closer correlation between Lugeon values and the real permeability of the formation, particularly for faults.

Influence of Grout

It is generally accepted that pre-grouting can improve the quality of the rock mass. Barton et al (2001) states the reasons for increased rock mass quality and easier excavation are due to any or all of the following:

- Filling of joints and voids
- Closing of secondary joints
- Glueing and strengthening of the parts of the rock mass
- Reduction of water flow

If any or all of the above factors are achieved, an inherent outcome of the grouting process is an increase in stiffness of the rock mass. This is a very important but often overlooked result for fault pre-consolidation activities in longwall mining. For example, void filling using grout injection would only provide a minor strength increase in the fault (binding effect) but can increase the stiffness of the fault by an order of magnitude. Following the mechanisms shown in Figures 2 and 3, it can assumed that if the fault is stiffened to a level similar to the surrounding strata then stress transfer through the fault system will be improved thereby minimising stress concentrations in critical areas.

Soft structures such as fault zones are often low stress zones and are unable to transfer stress both in both the vertical and horizontal. Stress is redistributed, which means that elevated stress magnitudes (can be 20 % higher) and localised changes in orientation can develop, typically 10 – 20 m either side of the fault(s). Under elevated stress conditions the strata support interaction characteristics can change significantly. An additional 20 % abutment load can equate to an additional 50 m depth of cover. This can change the roof damage profile considerably. Figure 4 shows a potential roof damage profile under high stress and soft roof conditions.

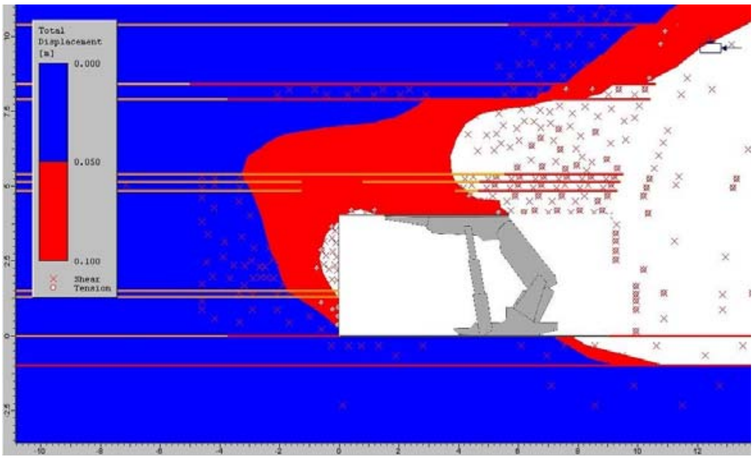

Figure 4 - Typical strata damage profile under 'soft' conditions

In general, two approaches can be taken for grout injection depending on the size, style and orientation of faulting. These are:

- Specific targeting and grouting/reinforcing of the fault zone itself, or
- Grout injection and reinforcing of the fault and overlying roof beam

Specific targeting of the fault zone can be achieved with either in-seam or surface holes and would generally be expected to provide similar results in softer 'unconfined' fault systems, eg normal fault with large throw and broken infill. A general indication of grout coverage is shown in Figure 5.

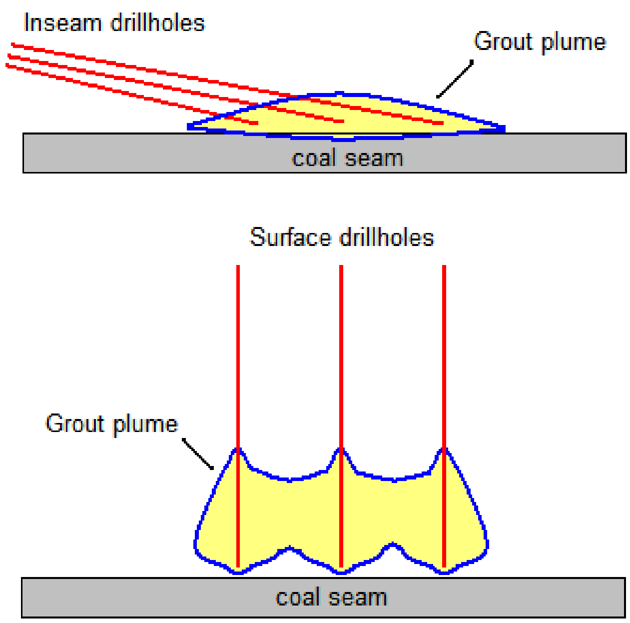

Figure 5 - Typical grout coverage from surface and inseam holes

The stiffness and competency of the immediate roof strata adjacent to the fault(s) is also important, as is the properties of the fault planes. The softer or more broken the surrounding strata, the more likely benefit to be gained from grout injection. Conversely, grout injected into a clean normal fault that intersects a series of strong sandstones for example, is likely to provide minimal impact on stability.

The stiffer the fault system, the less effective grout injection is likely to be. A typical stiff fault system might be a more complex array of small conjugate faults that produce a blocky rock mass. Under these conditions reinforcing of the fault and overlying roof beam would be the preferable option as it also helps to minimise wedge type failures. The use of grout injection from surface based drilling will generally provide a greater spread of grout higher into the strata than would be achieved from in seam drilling. This former is the best method for developing a thicker 'reinforced' roof beam.

The correct choice of mining horizon is the most critical factor in managing face stability. This requires a balance between choosing a stable roof profile and maintaining practical longwall operating tolerances. In general, the bearing pressure of longwall support canopies is diminished 1 m or more into the roof (Medhurst, 2005). It is therefore important when choosing a mining horizon to minimize the thickness of weak roof strata and/or ensure that the pre-consolidation effort has been directed to provide at least a 2 m thick competent roof beam.

ANALYSIS OF FAULT GROUTING

Grout Volumes and Pressures

Thirteen cases of fault pre-consolidation grouting in underground longwall mines were analysed. Where possible, data was collected that included fault characteristics, water test data, grout volumes, grout pressures, drilling patterns, spiling and observations during mining. Total injected grout volumes ranged from 4,000 litres up to 60,000 litres for the various cases.

Various grout mixes were used, however all cases in the database can be regarded as microfine or ultrafine products. Particle size for the grouts varied with a maximum of 40 microns, but most report a maximum size of 12 microns. Similarly, drilling method and hole size varied across the dataset, some drilled from surface, others in-seam intersecting the fault(s) and inseam drilled sub-parallel to the fault(s).

Volumes of grout take were calculated to measure the effectiveness of grouting. To calculate the grout takes the volume of drill hole void space and spiles was subtracted from each grout volume for the corresponding grout hole.

A broad correlation between grout pressure and grout take could be observed across the entire grout database, shown in Figure 6. Given that a "grouting to refusal" approach was used, the maximum pressure was used in the analysis. Significant grout take occurs when injection pressures exceed about 2500 to 3000 kPa. This suggests that perhaps at these pressures, hole fracturing of the strata during injection may begin to develop, which facilitates the increase in grout take.

Clearly, the "tightness" of the fault(s), the hole spacing, grout mix and injection pressure will all contribute to the overall grout take. Simple correlation between grout takes and pressures do not consider the characteristics of the strata or fault system that is being treated. Detailed analysis indicated that grout takes appeared to be greater in the larger throw faults than the smaller faults.

Geological Controls on Grout Take

A comparison between grout take and maximum fault throw is shown in Figure 7. All of the grouted structures are segments of larger normal faults, which have moderate to steep dips. Some faults are part of more complex horst or graben structures, and three examples were related to step-over zones. Fault throws range from 1 m to 7.8 m.

The data shows that grout take increases for faults with greater than 4 m throw. However, changes in grout injection pressure can also account for this increase. Therefore, an attempt was made to estimate the overall trace length of the fault system intersected by the drill pattern. From this estimate, a simple measure of maximum grout take along the faults could also be made for comparative purposes, Figure 8. This assumes that all available grout is taken up in the fault system.

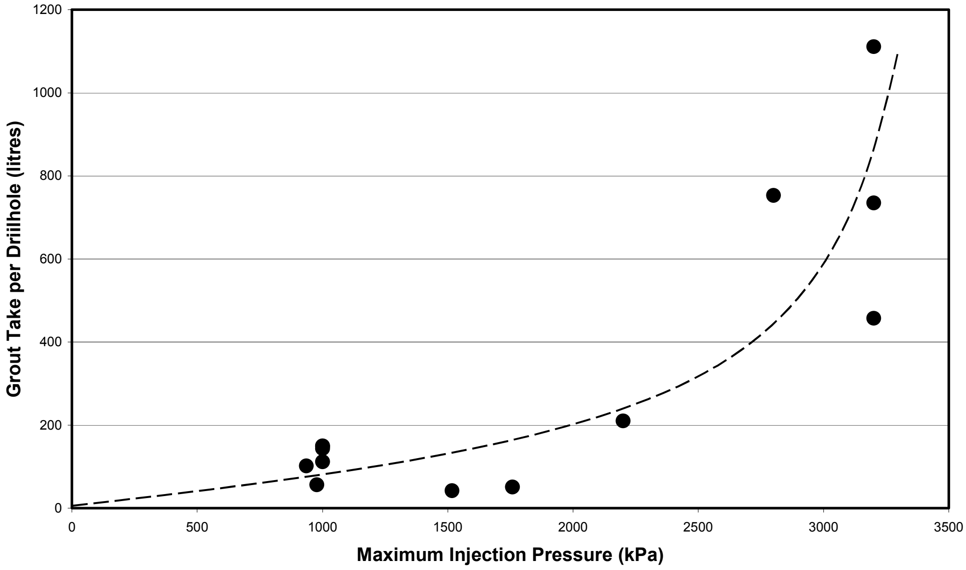

Figure 6 - Relationship between grout pressure and grout take

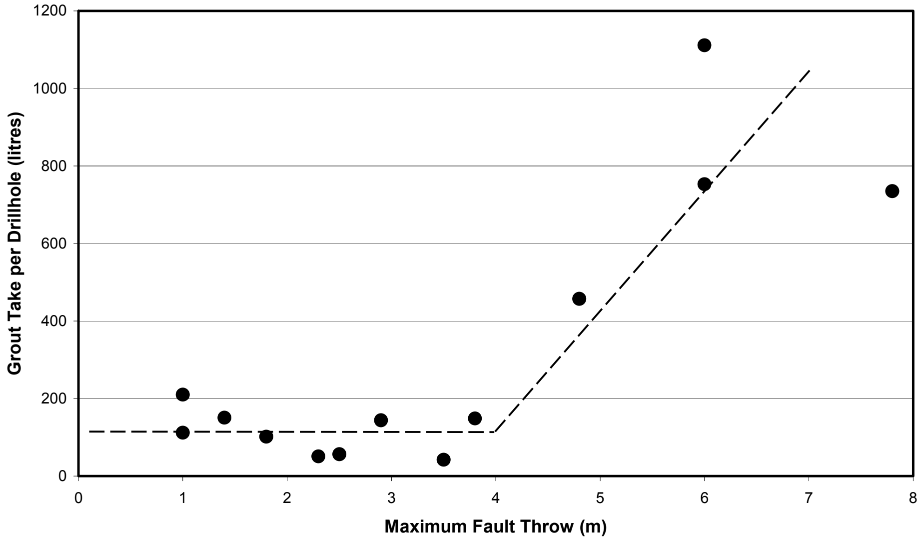

Figure 7 - Comparison of grout take and maximum fault throws

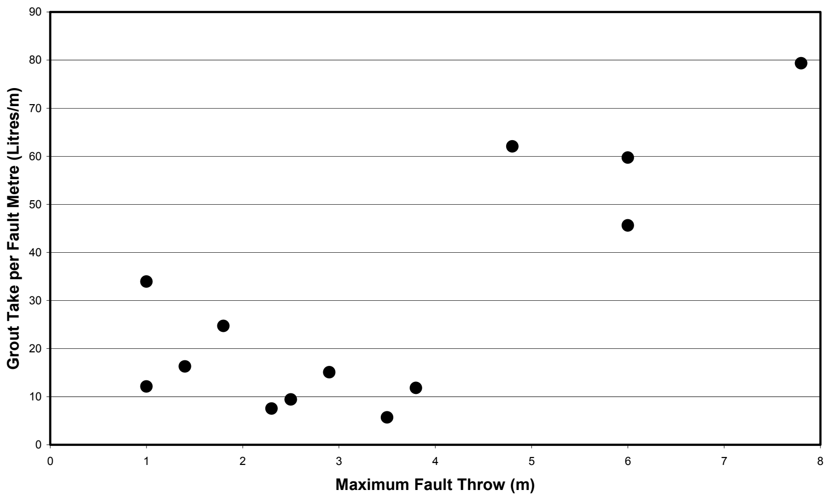

Figure 8 - Comparison between fault throw and grout take in fault

The data shows a general increase in grout takes with the maximum throw of the fault. A similar trend also prevails in terms of injection pressure, Figure 9. The general conclusion is that the main controls on grout take are influenced by the style of faulting and the injection pressure used during grouting. In particular, the larger throw faults were also likely to be subjected to some later reactivation, which is thought to have contributed to the amount of grout take. Although data is limited, permeability test data for these cases also suggested that these faults were more 'open' than the smaller throw examples.

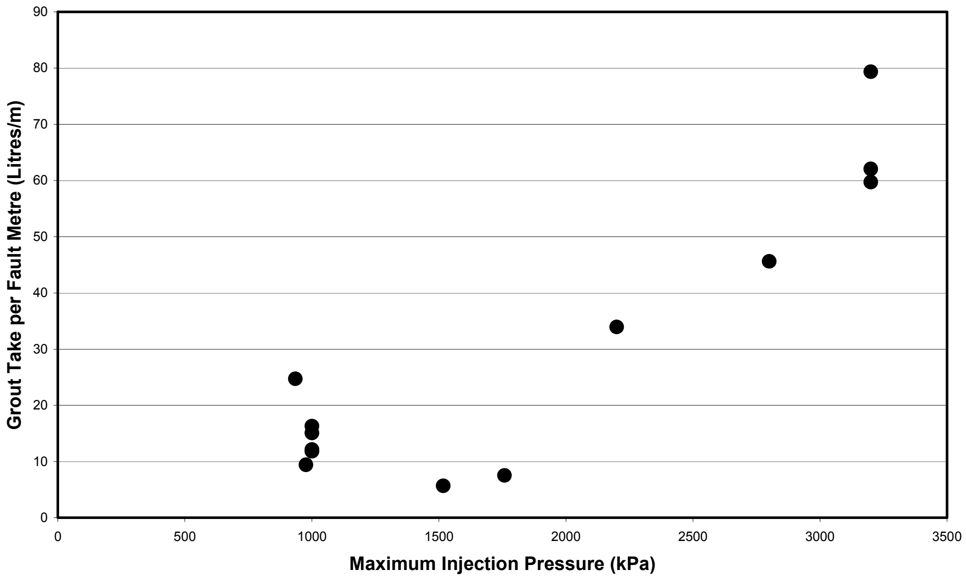

Figure 9 - Relationship between injection pressure and grout take in fault

APPROACH TO GROUTING FAULTS

Drill Program and Testing

The aim of the drill hole grout pattern is to intersect as many joints and bedded planes in the fault as possible while minimising the drill lengths and maximising the intersection angle. This implies a compromise between the costs associated with drilling and the effectiveness of grouting based on the drill hole angle and frequency of intersections with the fault. Since several mines have reported different levels of success using different drilling patterns and techniques, there is no hard rule about which drill design is the best. Drill hole design in reality is site specific and involves many factors that are controlled by the geological features of the fault such as location, size, orientation and depth of cover.

Along with the initial exploration drilling, the first assessments are usually based on seismic profiling and can often provide a broad measure of fault throw. Based on the available data, if fault throw is greater than 4 m, it is likely that roof and longwall face stability would benefit from a drilling, grouting and spiling program. Often the need for such measures however is less obvious, and in this case it is recommended that targeted drilling and permeability testing program be undertaken to investigate fault characteristics.

Water testing will provide a measure of the 'openness' of the fault(s) as well as provide some measure of potential grouting requirements. It is also important to note that water testing over short lengths (less than 5 m) will provide a more representative measure of fault permeability than if undertaken over long hole lengths. Current data suggests that in areas where Lugeon values are less than about 1 or 2 ground conditions may permit longwall mining. An example of the relationship between grout take and permeability is shown in Figure 10.

Estimation of Grouting Requirements

The conventional approach of "grout till refusal" is governed by the grout mix properties and the applied pressure during grouting. Moreover, it is generally thought that the selection of grout parameters can greatly influence the amount of grout take, and is reliant on operator skill. Interestingly, despite the importance of the grout mix, a wide variation in the reporting of grout mix parameters was found. In some cases, grout volumes were reported in kilograms of cement, while others in litres of grout pumped.

Clearly both the volume of grout pumped and the proportion/amount of cement need to be reported as a means to determine effective grout strength/quality. The final cement content in the overall grout volume shows a general trend of a 2:1 mix design across the database, Figure 11. In general, provided the grouting contractor can demonstrate good quality control procedures and adhere to the design controls, our review of case studies suggests that grout takes are more influenced by fault characteristics and injection pressures rather than small differences in grouting parameters.

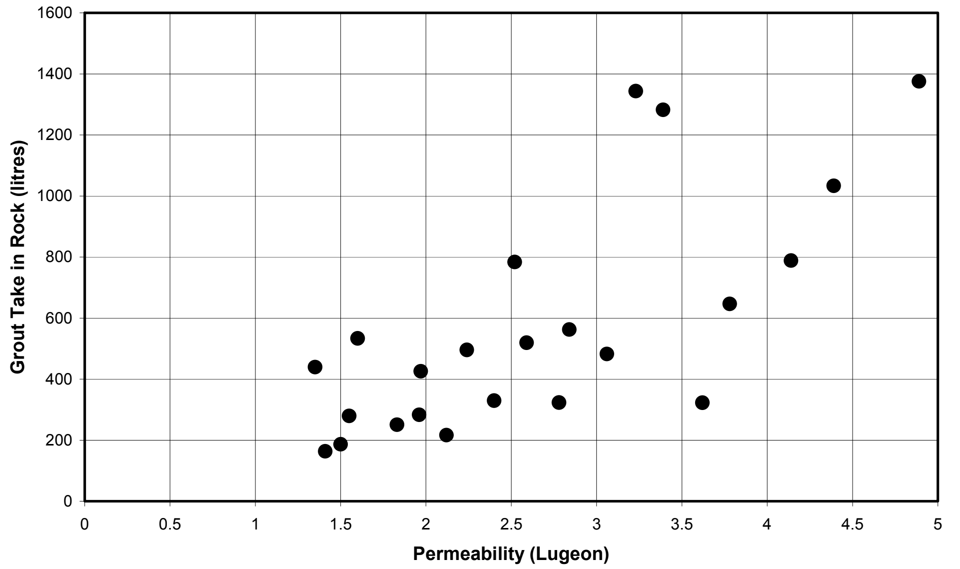

Figure 10 - Typical relationship between permeability and grout take

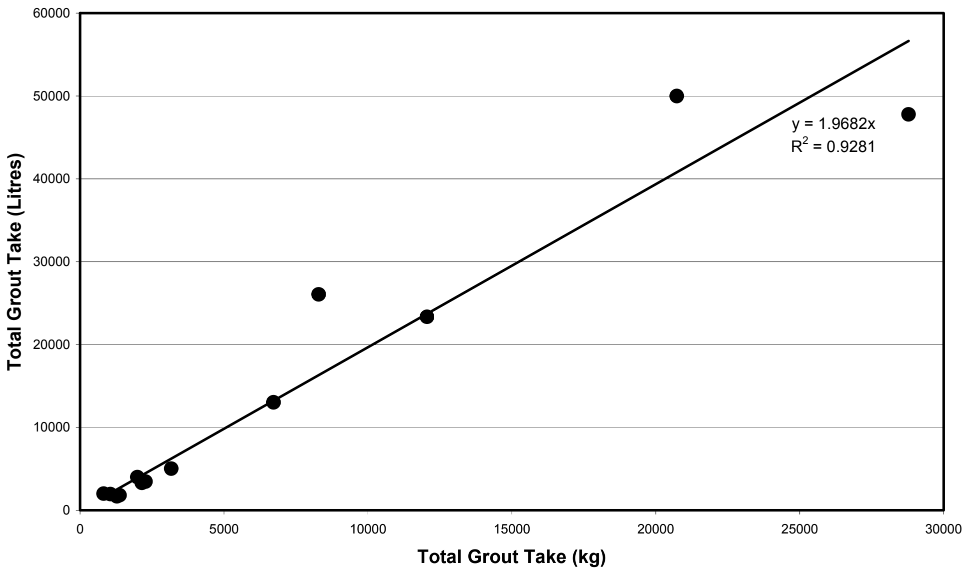

Figure 11 - Comparison between grout volume and cement used

In general, the gate-ends and the last third of the face towards the tailgate are the most critical areas for ground improvement. In large throw faults, stability is likely to be improved using pre-consolidation measures. In other cases, a focus on stabilising gate-ends and other high tensile zones along the face may be sufficient. A summary of general grouting requirements is provided in Table 1.

In rare cases very difficult ground control problems have been encountered whilst longwall mining through faults. in hind-site it may have preferable to relocate the longwall around the fault. These cases usually have possessed three main characteristics:

1. Faults oriented 30° or less to the longwall panel, and
2. Faults dipping at 60° to 90° towards the longwall face, and
3. Fault is first intercepted at gate-end in high stress zone.

As previously discussed, it is generally preferred to first intercept the fault in the tailgate. This is preferred over the alternative, in which first interception at the maingate would result in sustained tailgate damage as mining progresses. The problem can be further exacerbated if longwall panels are oriented such that a stress concentration develops along the maingate side.

Table 1 - Minimum suggested requirements for fault grouting in longwall mining

Fault System Description	Fracture Frequency	Permeability	Stabilization Requirements
Complex fault system oriented near parallel (<30°) to and dipping (60° to 90°) towards longwall face	N/A	N/A	Review potential for severe mining conditions based on detailed study of fault characteristics
Complex fault system with at least 2 faults and maximum throw greater than 4 m. Some minor thrusts suggesting reactivation.	N/A	N/A	Comprehensive pre-consolidation and reinforcement program
Complex step-over zone in normal fault system with maximum throw greater than 4 m.	< 5 m	> 2 Lugeons	Comprehensive pre-consolidation and reinforcement program
Complex step-over zone in normal fault system with maximum throw greater than 4 m.	> 5 m	N/A	Target grouting at gate-ends, high tensile zones and high permeability (> 2 Lugeons) zones
Complex fault system with at least 2 faults and maximum throw less than 4 m.	< 5 m	> 2 Lugeons	Comprehensive pre-consolidation and reinforcement program
Complex fault system with at least 2 faults and maximum throw less than 4 m.	> 5 m	N/A	Target grouting at gate-ends, high tensile zones and high permeability (> 2 Lugeons) zones
Complex step-over zone in normal fault system with maximum throw less than 4 m.	< 5 m	> 2 Lugeons	Comprehensive pre-consolidation and reinforcement program
Complex step-over zone in normal fault system with maximum throw less than 4 m.	> 5 m	N/A	Target grouting at gate-ends, high tensile zones and high permeability (> 2 Lugeons) zones
Single normal fault with maximum throw greater than 4 m and continuous across panel	N/A	> 2 Lugeons	Comprehensive pre-consolidation and reinforcement program
Single normal fault with maximum throw greater than 4 m and terminates in panel	N/A	N/A	Target grouting at gate-ends, high tensile zones and high permeability (> 2 Lugeons) zones
Single normal fault with maximum throw less than 4 m and continuous across panel	N/A	> 2 Lugeons	Target grouting at gate-ends, high tensile zones and high permeability (> 2 Lugeons) zones
Single normal fault with maximum throw less than 4 m and terminates in panel	N/A	> 2 Lugeons	Target grouting at gate-ends, high tensile zones and high permeability (> 2 Lugeons) zones
Single normal fault with maximum throw less than 4 m and continuous across panel	N/A	< 2 Lugeons	Stabilize gate-ends using PUR and additional roof/rib support. Stabilize unstable longwall face during mining.
Single normal fault with maximum throw less than 4 m and terminates in panel	N/A	< 2 Lugeons	Target poor rib areas using PUR and additional roof/rib support. Stabilize unstable longwall face during mining.

CONCLUSION

Thirteen cases of fault pre-consolidation grouting in underground mines were analysed. A strong correlation between grout takes and injection pressure was found across all sites. A simple measure of maximum grout take along the faults was also made for comparative purposes. By estimating the overall trace length of the fault system intersected by the drill pattern, the volume of grout take per metre length of fault could be calculated. The data shows a general increase in grout takes with the maximum throw of the fault and that the overall grout take increases significantly for faults with greater than 4 m throw.

The influence of grout type and mix design parameters is often quoted as a most critical parameter in successful grouting. However, the grout mixes used in the case studies were generally similar.

Overall, it was found that the main benefits of grouting were void filling, producing an increase in stiffness of the rock mass. If a fault is stiffened to a level similar to the surrounding strata then stress transfer through the fault system will be improved thereby minimising stress concentrations (and failure) in critical areas. The stiffness and competency of the immediate roof strata adjacent to the fault(s) is also important. It follows that the softer or more broken the surrounding strata, the more likely benefit will be gained from grout injection.

The correct choice of mining horizon is the most critical factor in managing face stability. This requires a balance between choosing a stable roof profile and maintaining practical longwall operating tolerances. It is therefore important when choosing a mining horizon to minimize the thickness of weak roof strata and/or ensure that the pre-consolidation effort has been directed to provide at least a 2 m thick competent roof beam.

The orientation of fault zones in relation to the direction of longwall retreat plays a significant role in determining grade control, and the sections of the face that will be affected by faulting. In general, major structures present a high level of risk if they are orientated at less than 30° to longwall retreat. Faults dipping at 60° to 90° towards the longwall face would also generally present the greatest risk of instability when subjected to face abutment loads.

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REFERENCES

Australian Coal Association Research Program, 2003. *Project C10019, Cost effective use of PUR and optimising large-scale injected strata reinforcement*.

Australian Coal Association Research Program, 2006. *Project C13015, Monitoring systems and geological structure assessment Leading to Improved Management of mining conditions*.

Barton, N, Buen, B and Stoald, S, 2001. Strengthening the case for grouting, *Tunnels and Tunnelling International*, December 2001 – January 2002.

Enever, J, Casey, D and M. Bocking, M, 1999. The role of stress in coalbed methane exploration, *Coalbed Methane: Scientific, Environmental and Economic Evaluation*, pp297-299 (Kluwer Academic Publishers: Dordrecht).

Houlsby, A C, 1990. *Construction and design of cement gouting*, (John Wiley and Sons Inc: New York).

Kutzner, C, 1996. *Grouting of Rock and Soil*, (Balkema: Rotterdam).

Lee, A J, 1996. The effect of faulting on mine subsidence, *The Mining Engineer*, Vol. 125, p 735-743.

Medhurst, T P, 2005. Practical considerations of longwall support behaviour and ground response, *Coal 2005 – 6th Australasian Coal Operators Conference*, pp49-57, (AusIMM: Melbourne).

Smith, G, 2006. Management strategies for longwall retreat through major fault systems – risks, controls and systems likely to cause instability, Unpublished report for ACARP project C13015.

Weaver, K D, 1991. *Dam Foundation Grouting*, (ASCE Press: Reston).