Proceedings of the Third International Underground Coal Conference, *Managing Production Continuity,* Vol 1, June 12-15, Manly, NSW.

Applications of Hydraulic Fracturing To Control Caving Events in Coal Mines – The Moonee Experience

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ABSTRACT

Hydraulic fracturing involves the injection of high pressure fluid into a rock mass to form one or more fractures. Fractures are oriented perpendicular to the lowest principal stress acting at the time of injection. Hydraulic fractures can be extended considerable distances from one or more boreholes oriented in any convenient direction. The technique offers a method to control caving related phenomena such as inducement of caving, control of periodic weighting, initiation of first goaf fall, and preconditioning of longwall takeoff areas. This paper describes the successful application of hydraulic fracturing to control windblast hazard at Moonee Colliery and opportunities that emerge for other applications.

Moonee Colliery extracts the lower 3m of the Great Northern seam using a 100m wide longwall panel. A 35m thick conglomerate strata immediately overlying the seam is able to temporarily bridge across the panel so that the goaf does not immediately cave. When the conglomerate strata does eventually fall, the bottom 10-15m collapses more or less as a single mass over an area 50-300m long by the full 100m panel width. The windblasts generated by these events present a very significant hazard to men working on the longwall face.

Hydraulic fracturing has been successfully introduced at Moonee Colliery as a method to induce caving events “on demand”. The men are evacuated from the longwall face area prior to commencement of the hydraulic fracture treatment. After a treatment typically lasting 15 minutes to 2 hours, a goaf fall event is usually initiated and mining can be recommenced with the windblast hazard eliminated.

The work at Moonee is believed to be the first successful use of hydraulic fracturing to induce caving events in Australia. Infusing water to weaken rock and small-scale hydraulic fracturing, ahead of or over longwall panels, has been tried previously in Australia and South Africa. Infusion is currently being used in China. Hydraulic fracturing has also been used in Poland to condition the roof over new panels and to modify the stiffness of rock around mine openings to reduce rock burst hazards. The application of hydraulic fracturing, described in this paper, to control the timing of caving events has not been used before.

The technique also offers the potential to control periodic weighting events, induce caving at longwall startup, precondition pre-driven longwall take-off roads and take control of caving in other situations where it would be desirable to induce the goaf to cave.

INTRODUCTION

Moonee Colliery is located in New South Wales, 30 km south of Newcastle. The colliery longwall mines the lower 3-3.5m of the Great Northern Seam. A plan of the mine layout is shown in Figure 1. The longwall panels are 100m wide and separated from each other by 35m wide chain pillars, sized primarily for subsidence control purposes. The depth of overburden ranges from 90m in the north to 170m in the south.

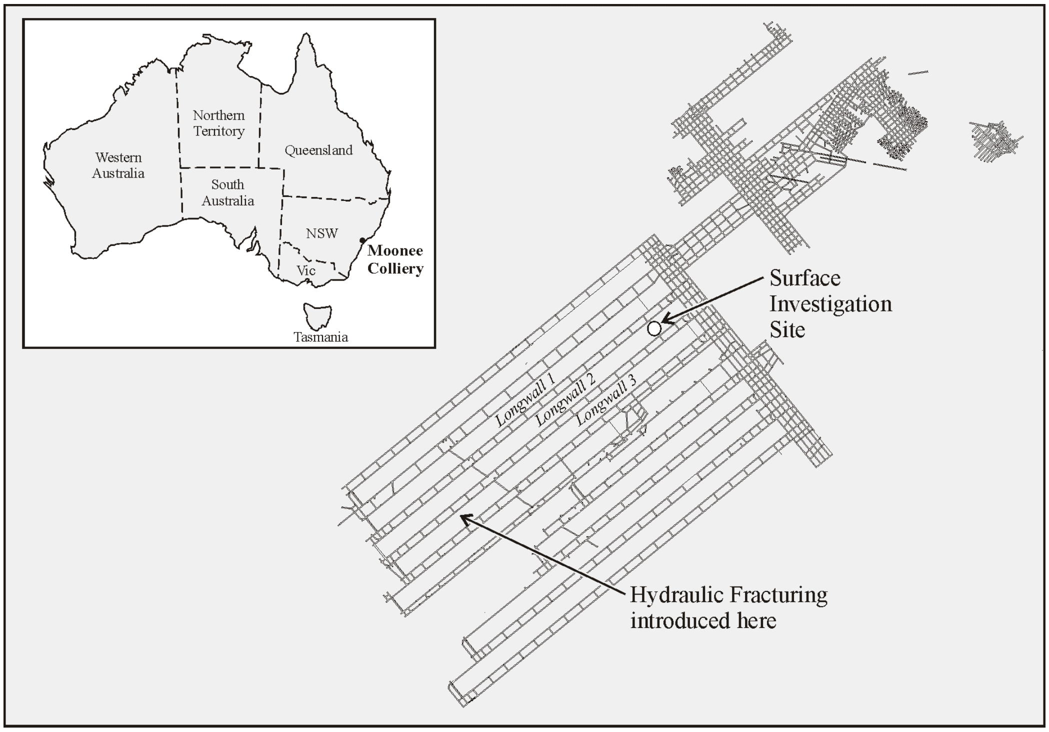


Figure 1 Site plan showing layout of Moonee Colliery.

The immediate roof comprises 1.5-1.8m of coal and claystone material that caves directly behind the longwall supports. The Teralba Conglomerate that overlies the Great Northern Seam is 30-35m thick and is able to temporarily span across the longwall goaf. When the conglomerate does cave, the collapse occurs suddenly, more or less as a single mass over an area between 50m long and 300 m long, typically across the full 100m width of the panel. The collapse results in a stable arched roof across the width of the panel that reaches a height of 10 to15 m above the base of the conglomerate at the centre of the panel.

The first goaf fall occurred when Longwall 1 had retreated approximately 200m. It resulted in a massive windblast (fortunately on a weekend) in January 1998. The geometry of the fallen material is shown in Figure 2. Above this fallen material, the conglomerate strata continues to bridge across the panel leaving a 2-3m high air gap

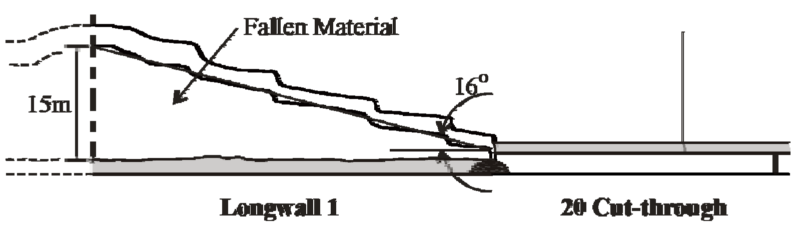


Figure 2 Goaf cross section observed from 20 Cut-through, Maingate 1.

This windblast destroyed many ventilation appliances in the longwall area, blew down some 10 rows of water barriers in the panel, and projected items like computer keypads in the maingate some 30m outbye. The next three goaf falls were much smaller events and there was a hope at that point that the goaf would continue to fall behind the supports and follow the longwall as it retreated.

However the fifth goaf fall in the panel, which occurred at 10am on Thursday 22 January 1998, resulted in a windblast that knocked over and injured 6 of 19 crew who were engaged on regular maintenance. It also destroyed several ventilation appliances. The injuries to the personnel were relatively minor in physical nature with the worst injury being a broken rib but the psychological damage done to the mine personnel as a result was extensive. The publicity received by the organisation was extensive and negative. This was the first of a number of windblast crises that the mine faced in the next 12 months before the event that precipitated the introduction of hydraulic fracturing.

Figure 3 shows an example of the wind velocities measured in the first goaf fall of Longwall 3 (Fowler & Sharma 2000). There is the initial windblast followed by subsequent "suck back" after 3-4 seconds. For reference, a wind velocity of 20m/s roughly coincides with the maximum constant velocity against which a human being can remain upright. This is roughly equivalent to a Beaufort scale of 10, which is a strong gale with 10m waves that could remove tiles from roofs of houses. The peak velocities measured in the roadways at Moonee are considerably higher.

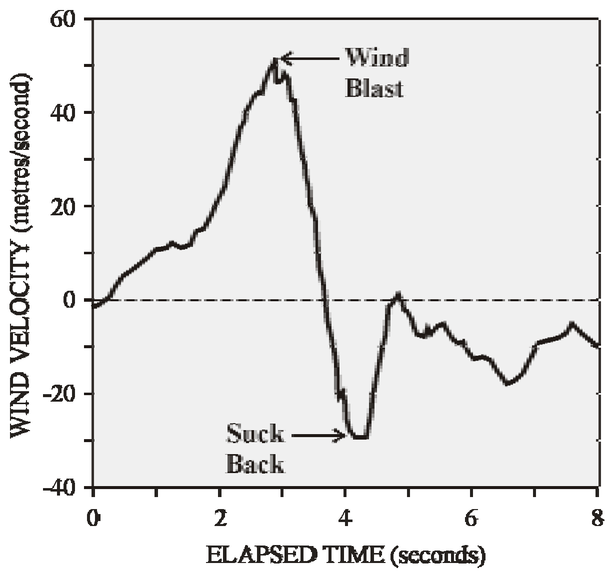


Figure 3 Example of windblast velocities.
(Fowler and Sharma, 2000).

Micro-seismic monitoring was introduced soon after the initial goaf falls as a means to predict, from the signature and frequency of micro-seismic events, the onset of caving with enough warning to allow men working on the longwall face to seek refuge prior to a windblast event (Edwards 1998). This technique proved successful as a means of providing warning to men on the face for two complete longwall panels and continues to be an integral part of the windblast management plan at Moonee Colliery.

However a windblast that occurred on April 30 1999 became the catalyst for a change in approach. A crew leader, who was very experienced in windblast conditions, was speaking on the telephone at No. 4 Support and 2 other technicians were located in the maingate. Unusually, there was no audible warning of impending roof fall and no microseismic warning of the event. The crew leader was blown approximately 3m bodily against the No. 2 Support and suffered multiple compound fractures of the left arm. This event prompted the Department of Mineral Resources to put a halt to mining until a means of controlling caving was implemented.

After consideration of a range of options, hydraulic fracturing was considered as a method to take control of the timing of caving events. The control of caving provided by implementing the mehtod means that the longwall face area is completely evacuated during the period of the treatment and, although a windblast still occurs when the goaf falls, the risk of injury is eliminated.

The concept of generating a fall "on demand" using hydraulic fracturing is fundamentally different to the concept of pre-conditioning the strata ahead of mining to promote caving. When the strata is pre-conditioned by hydraulic infusion, hydraulic fracturing, or any other means, it may be induced to cave more readily but unless caving occurs continuously and immediately after the supports advance there is still no control of the timing of the caving events and a windblast hazard can persist.

BACKGROUND TO HYDRAULIC FRACTURING

Hydraulic fracturing is a technique that is widely used in the petroleum industry to stimulate oil and gas production from underground reservoirs. In the petroleum industry, the technique typically involves generating fractures that enhance the effectiveness of each well (borehole) for draining the reservoir. At Moonee, hydraulic fracturing is used to create a fracture applying the same fundamental principles, but for the different purpose of inducing the goaf to cave.

Figure 4 shows the principles of the technique as used at Moonee Colliery. Water is injected into a short section of borehole at sufficient pressure to overcome the stresses acting around the borehole and the tensile strength of the rock. Once the fluid pressure rises high enough to overcome the forces holding the rock together, a fracture, initially only a fraction of a millimetre wide, is initiated in the rock. The fluid injected into the hole enters this fracture, pressurising and opening it. As injection continues, the fracture spreads laterally away from the hole and aligns itself, as it continues to grow, in a direction perpendicular to the lowest principal stress.

The fluid pressures and flow rates required to keep the fracture growing are typically well within the range of readily available pumping technology. The pressure is mainly a function of the minimum stress in the ground – higher pressure is required for higher minimum stress. The flow rate to keep the fracture growing is mainly a function of the strata permeability and the rate at which the fracture is required to grow – more permeable strata requires more flow to maintain a given rate of fracture growth.

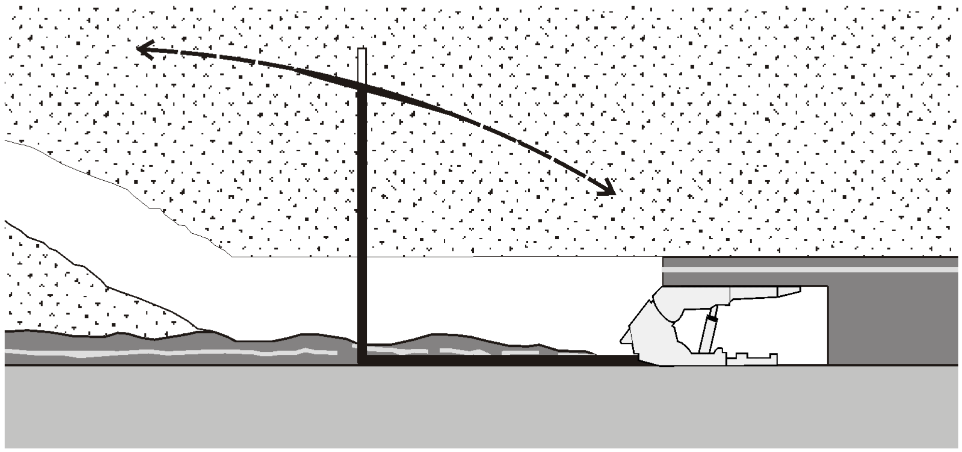


Figure 4 Routine treatment strategy used at Moonee Colliery.

The application of hydraulic fracture technology to actively promote caving within a specific timeframe is new to coal mining in Australia. Hydraulic infusion had been undertaken a decade earlier at Newstan Colliery (Holt 1989) on a trial basis to "soften" massive sandstone ahead of longwall mining but this was discontinued after the first trial. Hydraulic fracturing was part of the Newstan trial, but was seen as a means of introducing the water into a volume of rock rather than as the primary means of conditioning the rock for caving. In the metalliferous mining industry, hydraulic fracturing had been used successfully to promote caving of ore at Northparkes gold and copper mine (van As and Jeffrey, 2000) where caving typically occurs some days or weeks after treatment.

Overseas experience of water infusion in China reported by Pan et al (1983) and in South Africa by Summers & Wevell (1985) appears successful for promoting caving but does not offer a way to take control of the timing of caving events. Konopko et al. (1997) report success in Poland using hydraulic fracturing to reduce rock burst potential and improve the condition of the roof over new panels. Haramy et al. (1995) describe the potential for using hydraulic fracturing to modify strata behaviour and encourage caving in the United States.

At Moonee, hydraulic fracturing is attractive as a method to control caving because the minimum stress in the conglomerate above the goaf follows a trajectory that is approximately the same shape as the stable geometry of the fallen goaf. By initiating the fracture at a point close to the top of the final stable arch profile, a fracture that is essentially circular in plan can be extended outward from the injection point to approximate the shape of the final stable arch.

The radially expanding fracture has the effect of artificially removing the tensile strength of the rock over a larger and larger area (typically greater than 25 to 30m in radius) while at the same time applying a fluid pressure down on top of the uncaved strata. Jeffrey and Mills (2000) discuss the mechanics of hydraulic fracture growth at Moonee in more detail. As long as the fracture continues to grow, instability of the strata below the fracture horizon is inevitable. Once a critical point is reached, the lever arm generated by gravitational forces acting on the detached strata continues to propagate the fracture independently of the hydraulic fracture process and a goaf fall occurs shortly after.

The main limitation to the fracture continuing to grow is from loss of water from the hydraulic fracture into the formation or out through pre-existing fractures in the rock to the goaf. Loss of fluid to the open void of the mined goaf, the already fallen goaf, or into natural joints of high permeability, have the potential to retard or stop the hydraulic fracture growth and restrict the size of the fracture developed. Techniques to overcome this fluid loss problem include the use of higher pumping rates, higher viscosity injection fluids and various particulate materials that can be added to the fluid and then serve to block the entry to cross-cutting joints.

GEOTECHNICAL CHARACTERISATION

The orientation and growth rate of hydraulic fractures are determined by five key factors:

1. the stressfield acting in the rock mass at the time of treatment,
2. the permeability of the rock matrix,
3. the orientation and permeability of pre-existing joints,
4. the fluid injection rate
5. the characteristics of the injection fluid.

The fluid characteristics and injection rate are controlled through fluid selection and design of the pumping system. The other factors are characteristics of the rock environment that must be determined through geotechnical investigation.

At Moonee Colliery, a staged program of geotechnical investigations was undertaken in the period leading up to the first underground treatment. These investigations proved critical to the successful implementation and integration of hydraulic fracturing at the mine.

Visual Observations of Goaf Fall Geometry and Frequency

Visual observations and survey measurements of the goaf geometry provide an initial basis to assess the ground behaviour and the potential for using hydraulic fracturing.

Figure 2 shows the geometry observed following a goaf fall at the start of Longwall 1. The goaf caves to form a broadly arch-shaped stable geometry 12 to 15m high in the centre of the panel with an essentially open void above the fallen material. Numerous observations of both natural goaf falls and hydraulic fracture induced goaf falls indicate a generally similar arch shaped profile and height of caving. The material above the standing arch profile remains stable once the goaf has fallen.

In Longwall 1, there were approximately 40 individual falls. In the subsequent panels, prior to the introduction of hydraulic fracturing, the number of falls halved and the amount of standing goaf involved in each fall doubled. This observation indicates that horizontal stress and pore pressure within the rock mass are controlling factors in the formation of natural goaf falls.

In the first three longwall panels, the first goaf fall is approximately twice as long as the subsequent goaf falls. This observation suggests that standing goaf length, and by implication either time or gravitational forces are also significant factors in the caving process.

In Situ Stress Measurements

The in situ stress in the conglomerate strata was measured using two ANZI stresscells (Mills 1997) and the overcoring method of stress relief. The stress measurements indicate a relatively low horizontal stress environment pre-exists within the conglomerate rock mass. The major horizontal stress is approximately 8MPa acting at N30E, slightly anticlockwise of the axis of the longwall panels. The minor horizontal stress is 4MPa acting in a perpendicular direction, more or less across the panels. The vertical stress at the measurement site was 4MPa consistent with the overburden depth of 160m.

The measurements of in situ stress provided a basis to interpret the failure mechanics of the conglomerate strata, the options for treatment and predictiong the hydraulic breakdown pressures in boreholes oriented in various directions.

The in situ stress measurements confirmed that preconditioning of the conglomerate strata would be ineffective. A hydraulic fracture initiated in the conglomerate strata would align more or less along the longwall panels and would rotate from vertical to horizontal depending on the relative magnitudes of the two minor stresses. Fractures in these orientations are considered unlikely to be helpful in promoting caving and certainly would not provide control over the timing of caving events.

Overburden Properties

The Teralba Conglomerate is mainly composed of pebbly conglomerate strata in a sandy matrix. Located within this essentially unbedded strata, there are irregular lenses of fine-grained sandstone typically 0.3-0.5m thick. These are not laterally persistent and their thickness varies over distances as short as a few metres. There are no continuous horizontal partings within the conglomerate. The conglomerate is cross-cut by several sets of subvertical joints, but these do not appear to have a major influence on the timing of caving although they sometimes define the edges of a goaf fall.

A comprehensive set of mechanical property data was already available from tests on core recovered from several holes near the start of Longwall 1. These tests showed that the sandstone lenses are consistently stronger and have a higher elastic modulus than the conglomerate strata.

The conglomerate has an elastic modulus of 20 $\pm$ 5 GPa, a uniaxial laboratory strength 50 $\pm$ 10 MPa and a tensile strength of approximately 4 MPa. The sandstone has a higher, more variable elastic modulus ranging from 19 GPa to 39 GPa and a higher uniaxial laboratory strength averaging 80 MPa. Although the strength and stiffness properties of both materials are quite variable, there does not appear to be any consistent variation in stiffness or strength either up through the conglomerate strata or laterally along the panel.

Surface Investigation of Hydraulic Fracturing Parameters

A surface investigation was undertaken to determine the hydraulic fracture parameters (permeability and fracture growth rate) and to confirm that a horizontal fracture could be generated in a stress environment similar to that expected above the goaf. The surface investigation was very successful on both these key issues. There was an expectation by some observers that the treatment undertaken would also induce a goaf fall, and disappointment when it did not, but such an outcome was always considered peripheral to the investigation.

The surface investigation was conducted at a convenient surface location 30m from the outbye end of Longwall 2 on the panel centreline (location shown in Figure 1). The site offered stress conditions similar to those expected in the goaf above the extracted longwall panel, and had the advantage that CSIRO's high pressure pumping equipment and computer monitoring system could be used at the surface site without needing modification for underground use.

The investigation was conducted using a central injection hole and three surrounding monitoring holes each approximately 110m deep. The monitoring holes were drilled at distances of 5m, 10m and 13m radially from the central injection point to intersect the top of the fallen goaf. These holes provided further confirmation that the caved zone extends to about 15m above the coal seam and an open void 2.5-2.8m high exists on top of the fallen material.

The monitoring holes were plugged at the top of the goaf and piezometers were installed to detect the arrival of the hydraulic fracture during the injection trial.

The investigation was very successful in demonstrating the key issue that a horizontal fracture could be generated parallel to a free surface within 5m of that surface. The fracture initiated at a bottom hole pressure of about 5.0 MPa and propagated at a pressure of 1.4 MPa, growing to a radius of 13m in approximately 7 minutes at an injection rate of approximately 200 litres per minute. Based on the pressure records, the fracture appears to have grown to a radius of more than 25m by the end of the test.

Permeability tests confirmed that the natural jointing was significantly more permeable than the surrounding strata. The permeability of the conglomerate was measured in the central hole to be 0.35 millidarcy at 98m depth, but permeability in the conglomerate is expected to vary over a range from 0.01 to 5 millidarcy depending on secondary mineralisation and the existence of natural or stress-induced fractures.

Revision of the hydraulic fracture propagation model following the surface work indicated a likely injection time for the underground trials of between 50 minutes and 2 hours using water as the injection fluid. Modelling work indicated that, for sites with potential for high fluid loss into pre-existing fractures, a shorter time and greater efficiency in terms of fracture propagation rate could be achieved by the use of organic polymer gel as an injection fluid.

FIRST UNDERGROUND TREATMENT

The first underground hydraulic fracturing treatment at Moonee Colliery was conducted on 30th June 1999. With approximately 55m of goaf standing, some 70,000 tonnes of conglomerate strata was induced to fall after pumping water for approximately 2 hours.

The treatment was most significant in that it clearly demonstrated to all concerned that hydraulic fracturing could be used to control the timing of caving events. The success of this first treatment was particularly significant given the economic circumstances at the mine at that time (Hayes 2000).

The treatment involved drilling a near horizontal hole out over the block to a point 10-12m above the base of the conglomerate in the centre of the panel. The hole was completed prior to mining. The longwall face was then retreated 55m to form a standing goaf.

Approximately 40,500 litres of water was injected mainly at the mine supply pressure of 1.8 MPa. Only limited monitoring instrumentation was available during this initial treatment so it is difficult to be definitive on magnitudes. It appears that the fracture grew to about 30m radius in 15 to 20 minutes of pumping. From that point on, fracture growth seems to have slowed down, probably because of intersections with natural fracture systems.

Micro-seismic monitoring indicated an increasing flurry of activity prior to the fall that gave advanced warning of the event. A secondary fall occurred some 38 minutes later and was also preceded by a flurry of micro-seismic activity.

SECOND UNDERGROUND TREATMENT

A second hydraulic fracture treatment was carried out on July 15th, 1999. Figure 5 shows a summary plot of the pressure and convergence data recorded during this treatment.

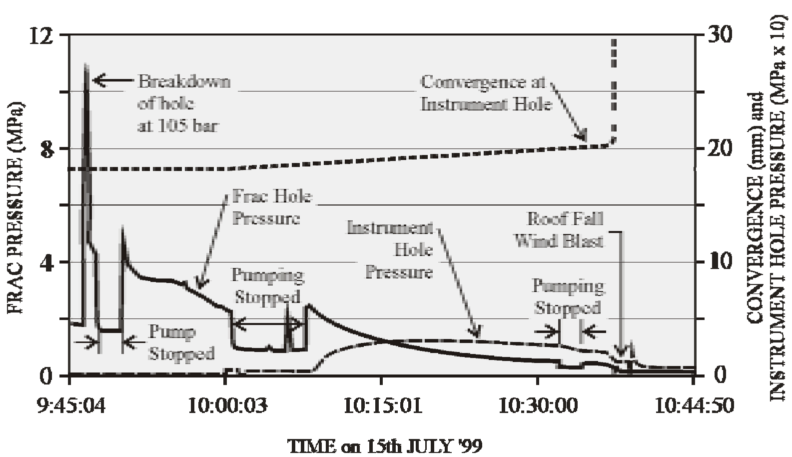


Figure 5 Pressure, flow and convergence records for second underground treatment.

The injection point detail was modified in this second treatment because of the high cost ($100,000) and time taken to drill a hole from the maingate. Two injection holes were drilled vertically upward from the centre of the face to about 12m. These holes were drilled after the longwall face had advanced 35m beyond the previous fall. Once the holes were completed, the longwall face moved on 30-35m and high pressure hose was trailed out between the supports into the goaf.

In this second fall, some 100,000 tonnes of rock (77m of standing goaf) was induced to cave after approximately 51 minutes of pumping 15,000 litres of water.

The vertical injection holes had a 25mm diameter injection pipe grouted into them with a short open space left at the top. Pressure monitoring tubes were run to the top of each hole to sense fluid pressure at the injection point through a datalogging system. These tubes were connected to pressure transducers to allow monitoring of the pressure in the boreholes during the injection.

Roof to floor convergence monitoring instruments were also installed at the collar of each hole to measure the convergence between the roof and floor strata behind the face as the face advanced and during the fracture treatment.

A hydraulic fracture was initiated at a fluid pressure of 10.5 MPa. This breakdown pressure is consistent with the horizontal stresses acting around a vertical borehole and the tensile strength of the conglomerate strata. Once breakdown occurred, the pressure dropped rapidly at first and then more slowly as pumping continued. The pump was stopped on three occasions and on each occasion the flow rate driven by mine supply pressure increased. The goaf fell after 51 minutes of pumping.

Roof to floor convergence was measured during face retreat and then during the treatment. Approximately 15mm of convergence was measured during 30m of longwall retreat at a point 35m from the tailgate edge of the panel. Assuming that the roof and floor movements are approximately equal in magnitude, downward movement of the roof alone is estimated to be the range 10 to 30 mm in the centre of the panel 50 m back into the goaf.

During the treatment, 2 mm of downward movement was observed until immediately before the fall when roof to floor convergence accelerated.

A pressure rise, consistent with the arrival of the hydraulic fracture, was recorded at the instrument hole 15m away from the injection point after 11 minutes of pumping water at 340 litres per minute.

Further Treatments

Since the second treatment, hydraulic fracturing from vertical holes drilled from the longwall face have become a routine part of the operation at Moonee with treatments conducted about once every 10 days.

Incremental improvements in the treatment process have been ongoing with monthly review meetings instrumental in bringing together personnel involved with the various stages of the process to improve the effectiveness of the treatments.

Figure 6 shows a comparison of the goaf fall geometries for goaf falls that formed naturally prior to the introduction of hydraulic fracturing and those that have been formed using hydraulic fracturing.

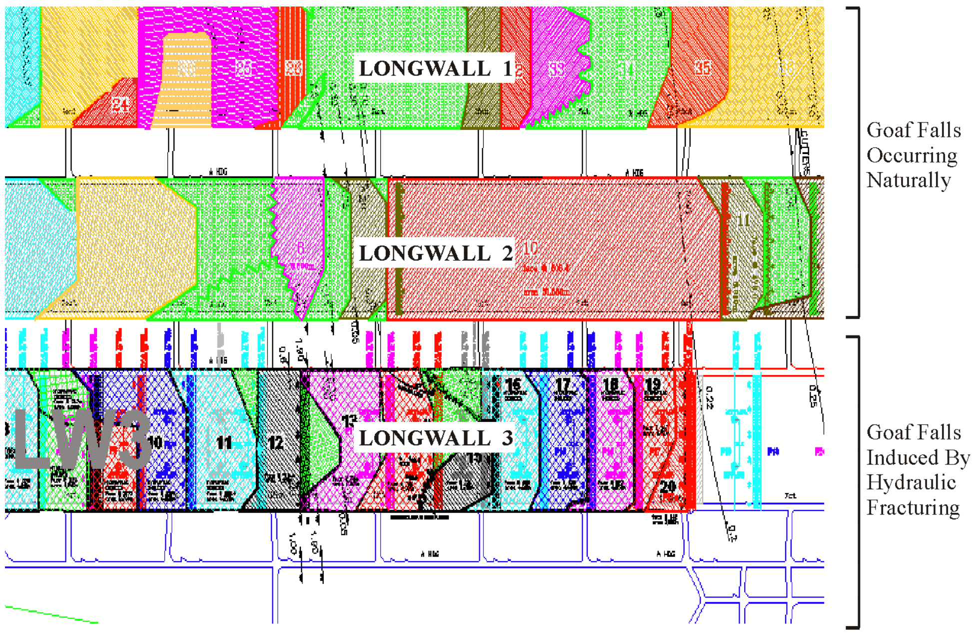


Figure 6 Comparison of goaf fall geometries with and without hydraulic fracturing.

The application of hydraulic fracturing at Moonee Colliery has provided the mine with a method of controlling the timing of caving events in the conglomerate strata. The integration of hydraulic fracturing and real-time microseismic monitoring as part of routine production at Moonee Colliery has enabled the mine to regain the level of productivity required to remain financially viable. These processes together have significantly reduced the risk of injury from windblast. Without this process it is unlikely the mine would have survived (Hayes 2000).

The geotechnical investigation undertaken to characterise the strata conditions and understand the basic caving mechanics was critical to and underpinned the successful introduction of hydraulic fracture to Moonee Colliery.

The successful implementation of hydraulic fracturing at Moonee relied on a good understanding of the stress environment, the strata behaviour, and hydraulic fracture mechanics combined with active and ongoing support from all levels of mine personnel.

OTHER APPLICATIONS

Hydraulic fracturing is a tool that has application in many mining situations to not only control the timing or size of caving events, but also to condition the strata to reduce undesirable caving behaviour such as periodic weighting, or improve conditions in pre-driven longwall takeoff roadways.

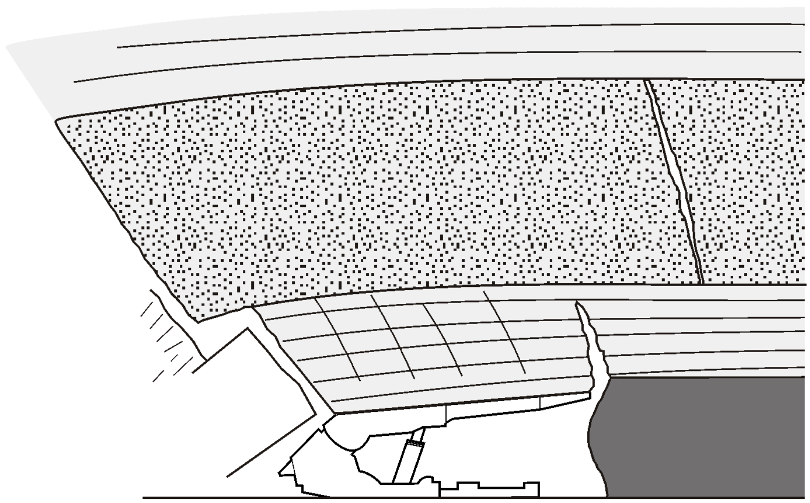
The great attraction of the method is that one or more fractures can be created and extended over a large distance with relatively little effort, typically using pumping equipment that is readily available and familiar to most mine sites. The orientation of the boreholes is not critical to the process, so injection holes can be drilled at any orientation that is convenient.

A key factor in the application of hydraulic fracturing is that the orientation of the fracture is controlled by the stress field acting at the time of fracture generation and the rate of fracture growth is a function of ground permeability. Thus it becomes essential to know with confidence the stress field and the permeability of the rock mass. The experience at Moonee Colliery confirms the benefits of using a well designed field measurement program to provide this data.

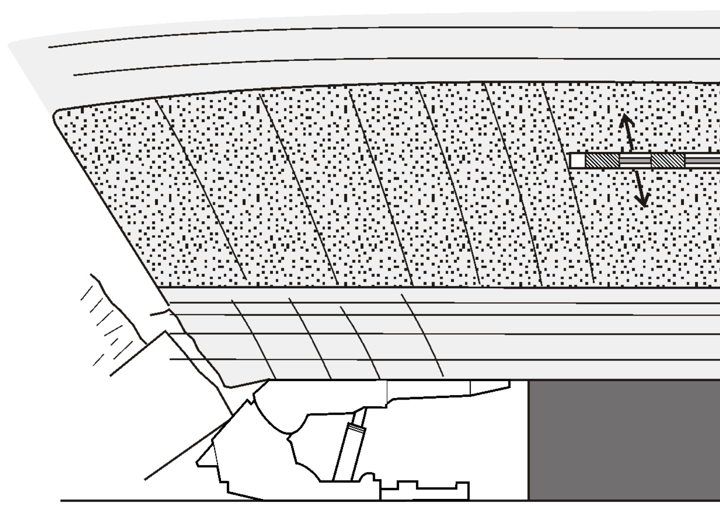
In some circumstances, the pre-existing stress field is not oriented in a direction suitable to achieve the desired outcomes. In these cases, the stress field modified by mining provides an alternative that is typically more useful. Hydraulic fractures can be placed as part of the mining cycle to take advantage of the stress field modified by mining. Moonee Colliery is one example of this, the application at Northparkes (van As & Jeffrey 2000) is another.

Figure 7 shows an example of how hydraulic fracturing may be used to reduce the effects of periodic weighting on a longwall face located under massive sandstone strata. The choice of which borehole orientation would best suit a particular operation would depend on individual circumstances and strata conditions.

Using a similar approach, the strata inbye of a pre-driven takeoff roadway could be treated using hydraulic fracturing immediately prior to the rundown so as to induce a caving cycle and reduce the weight active in the face area during takeoff.



a) Periodic weighting associated with massive strata.



b) Hydraulic fracturing used to break up massive strata just ahead of the face.

Figure 7 Possible treatment strategy to eliminate effects of periodic weighting.

In pillar operations under massive strata, hydraulic fracturing would improve the safety using this method of mining. The concept would to be to design panels to bridge between pillars while men are working in the panel, then when the men are evacuated from the area, caving would be induced remotely using hydraulic fracturing to eliminate the potential for windblast when mining in the area resumes.

In longwall operations that are planned to mine under massive strata, the longwall panels could be aligned with the in situ stress conditions (but also taking account of the effect this might have on roadway stability) to provide hydraulic fracture orientations favourable for pre-conditioning the rock mass prior to mining.

CONCLUSIONS

Moonee Colliery faced a serious problem of windblast that had injured men and had the potential to close the mine. Hydraulic fracturing offered a way to control the timing of caving events and therefore reduce the risk of injury.

Field investigations undertaken to characterise the stress field, the ground conditions and the hydraulic fracture growth provided the basis to achieve a successful outcome with the first treatment. These investigations were critical to the success achieved.

Moonee Colliery has been able to continue operating economically through integration of hydraulic fracturing into the routine operation at the mine.

There are opportunities at other mines where hydraulic fracturing could be used to improve mining conditions and reduce the impact of caving related phenomena such as periodic weighting.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the management, staff and workforce at Coal Operations Australia Ltd and Moonee Colliery. Their enthusiastic cooperation at all levels was instrumental to the success of this project.

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