Hydraulic fracturing applied to inducing longwall coal mine goaf falls

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ABSTRACT: This paper describes the first successful use of hydraulic fracturing to induce a goaf event and control the timing of caving events in Australia. Hydraulic fractures are initiated at 7 to 10 m above the bottom of a thick conglomerate roof and, because of the low vertical stress magnitude relative to the other two principal stresses, grow as horizontal fractures. The fractures extend radially outward from the injection borehole into the rock until a goaf fall occurs. Hydraulic fracturing has provided a means to control the timing of windblast events and thereby significantly improved safety. The successful implementation of hydraulic fracturing at Moonee Colliery to control the timing of goaf events has enabled the mine to continue operating.

1 INTRODUCTION

Hydraulic fracturing was introduced at Moonee Colliery, located just south of Newcastle, NSW in June 1999. Treatments are now performed by Moonee on a regular basis as part of their mining cycle.

Moonee Colliery extract 3 m of the Great Northern coal seam by longwall methods. The longwall panel is 100 m wide, from pillar to pillar. Upon mining, the immediate roof which consists of coal and claystone 1.5 to 1.8 m thick, falls in behind the supports. A 30 to 35 m thick conglomerate unit, above the immediate roof, will stand unsupported as the longwall advances. However, the lower part of this conglomerate eventually caves suddenly en-mass after anywhere from 35 to over 300 m of face advance. Caving events often generate windblasts as the air under the standing conglomerate is displaced by the falling rock into the adjacent mine headings. Windblast velocities of 100 m/s have been measured, posing a significant safety hazard to miners working at or near the face.

A microseismic monitoring system was introduced early on at Moonee to give warning of impending goafing events. This monitoring system has worked well, but relies on miners taking refuge in protected areas with warnings sometimes given only shortly before a fall. Hydraulic fracturing has provided a method to induce a controlled goafing event within a defined time period.

Infusing water to weaken rock and small-scale hydraulic fracturing, ahead of or over longwall panels, has been tried in Australia (Holt, 1989) and South Africa (Summers & Wevell, 1985) and continues to be used in China (Pan et al., 1983). A US patent that describes using hydraulic fracturing to modify the caving behavior of coal mine strata was awarded to Choi and von Shonfeldt in 1981. Hydraulic fracturing has been used in Poland (Konopko et al., 1997) and the U.S. (Haramy et al., 1995) to condition the roof over new panels and to modify the stiffness of rock around mine openings to reduce rock burst hazards. Hydraulic fracturing has been used successfully to induce ore to cave at the Northparkes block caving mine in NSW (van As and Jeffrey 2000).

2 GEOTECHNICAL BACKGROUND

An initial geotechnical investigation at Moonee found that the thick conglomerate roof was failing en-masse leaving a stable arch some 12 to 15 m high in the center. The arch extends at about 15^0 upward from the ribs on each side of the panel with a similar angle forming behind the longwall supports, extending back into the goaf after a fall. Failure of the rock along the arch cannot be reliably predicted and is a time dependent process that appears to vary as a function of changing pore pressure and stress conditions. However, once the arch forms, the bulk of the roof strata is stable. A comparison of the measured arch geometry produced by hydraulic fracturing induced falls with the arch resulting from non-induced natural falls (Figure 1), demonstrates that the final arch heights and shapes are similar in both cases.

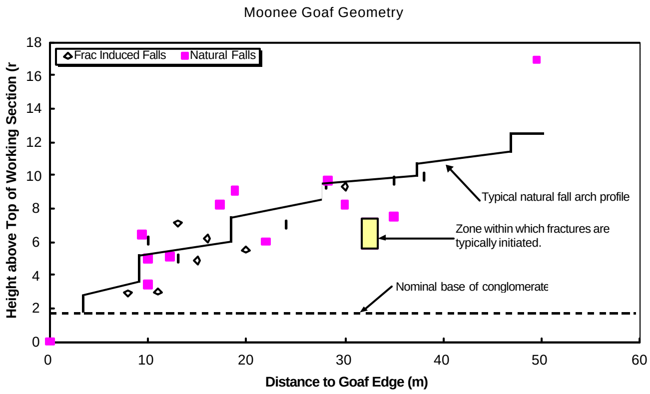

Figure 1: The (half) profile of the arch in the conglomerate established after the conglomerate roof caves.

Examination of the edges of the fallen goaf has revealed that the caved conglomerate is typically made up of large blocky pieces, averaging 5 to 10 m or more on a side. Some small slabs of conglomerate may eventually fall after the main roof failure, but these small falls have not produced windblasts events and are typically too small to register on the microseismic monitoring system or to be detected other than by repeated visual inspection of the goaf.

The undisturbed in-situ stress state has been measured by overcoring at one site. At the average depth of Longwall 3 (160 m), the stresses in the conglomerate roof are σ_v = 4.0 MPa, σ_{h1} = 8 MPa, and σ_{h2} = 4 MPa. The maximum principal horizontal stress, σ_{h1}, is oriented at N30E while the longwall panels are aligned at N50E.

The massive conglomerate roof contains sandstone lenses that are 300 to 500 mm thick. The sandstone lenses are higher in strength and stiffer than the conglomerate, but cannot be traced laterally for more than a few metres.

The conglomerate has, on average, a uniaxial compressive strength of 35 to 55 MPa and a tensile strength of about 4 MPa while the sandstones are stronger with UCS values averaging 80 MPa and tensile strengths of 7 to 10 MPa. The Young's modulus of the conglomerate, determined from core testing, ranges from 16,000 to 25,000 MPa with a Poisson's ratio of 0.3.

An injection well test, conducted as part of the first hydraulic fracture trial, measured a permeability of 0.35 md over a 1.1 m test interval in a vertical borehole drilled into the conglomerate. Clay minerals are present as pore filling in the conglomerate which has a porosity of 8 to 10 percent. A vertical joint set runs through the conglomerate oriented at N80E and spaced at 1 to 10 m.

3 HYDRAULIC FRACTURING

The process of hydraulic fracture growth in the conglomerate is similar to that described in the extensive petroleum literature, but differs in several important ways. The fractures at Moonee grow in a low compressive (or tensile) stress environment with potential for large fluid loss into, and crossing interaction with, natural or stress-induced fractures. The free surface at the lower part of the roof rock created by mining the coal has a significant effect on fracture opening compliance and this effect must be taken into account when calculating fracture width and growth rate.

The effective closure stress across the fracture plane decreases as the fracture grows and the strata below the fracture sags under its own weight. Fracture growth also appears to be influenced by the stress concentrations near the pillars and longwall face.

Hydraulic fractures orient and grow in a plane that minimises the energy required to open and extend the fracture and this plane is perpendicular to the minimum principal stress direction. Fracture growth will slow or stop as the leading edge of the fracture grows into higher stress areas, such as exist above ribs or face coal.

Figure 2 shows a plot of stress contours obtained from an analysis made using a 2D elastic finite element model with loads, material properties, and geometry representative of those at Moonee behind the longwall face before any goaf caving. FRANC2D (Wawrzynek and Ingraffea, 1995) was used for this modeling. The stress contours are labeled in MPa units and a line of symmetry runs vertically along the left side of the mesh. The modelling indicates a vertical stress, σ_y, between –0.20 and –0.30 MPa (tension is negative) at mid-span and 8 to 10 metres above the lower edge of the conglomerate roof rock. The horizontal stress, in contrast, is compressive and about 2 MPa. This stress state provides a strong control on the orientation of hydraulic fractures initiated and propagated in this part of the conglomerate, resulting in horizontal fracture growth parallel to the roof of the mined out and uncaved goaf. Hydraulic fractures initiated in this part of the roof, regardless or initial orientation, will orient and grow parallel to this free surface.

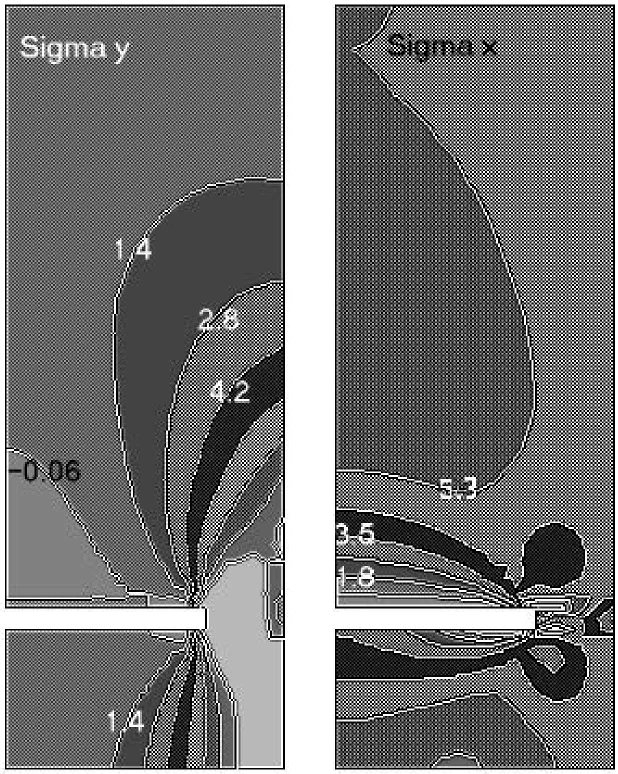

Figure 2: Contours of s_x and s_y after coal extraction. The opening is 5 m high and 50 m wide.

Fracture initiation is affected by the orientation of the borehole relative to the stress field and by the possible presence of pre-existing flaws or fractures in the rock at the borehole wall. The fractures at Moonee are initiated from boreholes drilled vertically into the roof and it is expected that many of the fractures initiate as vertical fractures along the axis of the borehole. Numerical simulation demonstrates that these fractures rapidly reorient to become horizontal.

3.1 *Effect of Free Surface on Hydraulic Fracture Growth*

The opening of a hydraulic fracture depends on the excess pressure distribution inside the fracture and on the fracture compliance. The compliance, in turn, depends on the fracture geometry (shape and size) and on the elastic properties of the rock. For example, the width in a uniformly pressurized 2D line fracture is given by:

$$w(x) = \frac{4(1-n^2)\Delta P(L^2 - x^2)^{1/2}}{E} \qquad (1)$$

where ΔP is the uniformly distributed excess pressure (pressure minus far field stress) in the fracture, L is the fracture half length, x is the position from the center of the fracture at which the width is calculated, E is the Young's modulus of rock, and n is the Poisson's ratio of rock. The opening compliance, C_f, is defined as the ratio of width at the centre of the fracture to the excess pressure:

$$w(x=0) = C_f \Delta P \qquad (2)$$

and for a uniformly pressurised line crack,

$$C_f = \frac{4(1-n^2)L}{E} \quad . \qquad (3)$$

Equation 1 and other closed form expressions for hydraulic fracture opening or growth assume the fracture is contained within a infinite elastic isotropic rock mass.

Pollard and Holzhausen (1979) obtained a solution for the opening width and elastic deformation around a pressured fracture which includes the effect of a free surface located some distance from the fracture plane. They applied their solution to the problem of calculating deformation on the free surface as a result of the open hydraulic fracture. Figure 3 contains a graph showing the ratio of the fracture opening, for a fracture located parallel to and a distance d from a free surface. In Figure 3, the width is normalised by the width of a fracture located at $d = \infty$, while the distance of the fracture from the free surface is normalised by the fracture half-length or radius. As a fracture grows in size while located at a distance, d, from the free surface, its compliance increases as shown by the curve.

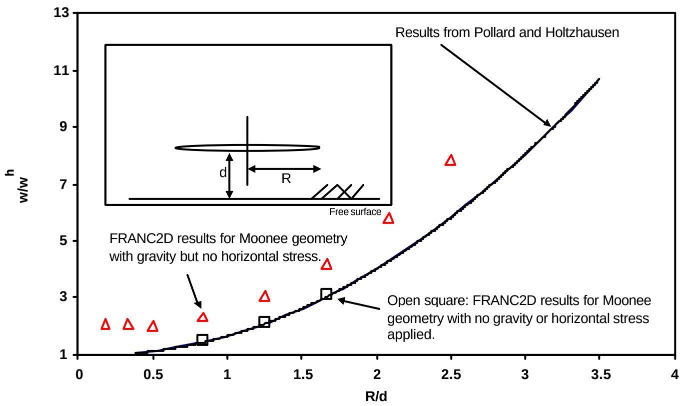

Figure 3: Finite element (FRANC2D) and analytical results for change in compliance of the fracture as a function of its proximity to the free surface.

The increase in opening compliance shown in Figure 3 can be included into exiting fracture propagation models by introducing a multiplier to the compliance, found from the curve for the fractures current R/d ratio. For example, in the hydraulic fracture model the Young's modulus of the rock may be divided by this factor to obtain the modified compliance. The models will then generate wider fractures that grow more slowly than otherwise. In addition, the calculated pressure at any time will be lower.

3.2 *Effect of Roof Sag on Fracture Growth*

Upon extraction of the coal, the stress acting on the base of the conglomerate changes, from an upward acting support stress equal to the downward acting vertical stress, to zero. The vertical and horizontal stresses in the conglomerate are redistributed to account for this new boundary condition. As shown in Figure 2, the vertical stress is zero at the bottom of the conglomerate and is tensile for up to about 15 m above this level. At 8 m above the base, the numerical modeling indicates the vertical stress can be tensile and a horizontal hydraulic fracture growing at this location will be affected by these stresses.

The effect of the tensile stresses, that act across the fracture plane, can be treated in fracture models by adding the stress to the pressure inside the fracture. An excess pressure that is higher than the fluid pressure in the fracture results. In other words, a fracture in this stress field with zero fluid pressure in it will sag away from the thicker conglomerate strata above it unless the tensile stresses are applied as a traction over its surface. This approach of increasing the excess pressure to account for the tensile stress is easily done in a hydraulic fracture model if the lateral variation in the vertical stress is small. A constant stress-induced pseudo pressure can then be added to the fluid pressure everywhere inside the fracture.

The tip region of a fracture propagating in a compressive stress field is not pressurised by the fluid. A fluid lag zone exists at the tip and the compressive far field stresses act across this zone. In contrast, the fracture growing in a tensile stress field is aided by the stress field. The fluid pressure added inside the fracture has been observed to drop to essentially zero before a fall. The uniform tensile stress becomes the dominant force driving the fracture growth once the fracture reaches a certain size. A radial fracture will grow unstably when its radius, R, reaches a values given by:

$$R = \frac{pK_{IC}^2}{4s_y^2} \qquad (4)$$

where K_{Ic} is the fracture toughness of the rock, and, as before, s_y is the uniform vertical (tensile) stress acting across the fracture plane. Inserting values of 0.2 MPa for s_y and 1.5 MPa$\sqrt{m}$ for K_{Ic} into equation 4 (conditions appropriate for the fracture growth at Moonee), the radius of the fracture at this critical point is found to be about 30 m.

Toughness has been measured on laboratory samples of the congolomerate, but the size of the larger pebbles compared to the sample size adds to the uncertainty of such a measurement. The measured laboratory value was 0.3 MPa$\sqrt{m}$. Once the critical radius is reached, growth of the fracture is expected to accelerate, leading to a roof fall event.

4 APPLICATION OF HYDRAULIC FRACTURING AT MOONEE

As of February, 2000 there have been 26 fracture treatments at Moonee with 19 of these producing a goaf fall event during the treatment. The other 7 treatments were not as successful because, for these treatments, a fall was not produced immediately. However, 6 of these 7 failed treatments suffered either from installation failures in the grout or hose, or from delayed breakdown of the hole because the pump was not able to deliver sufficient pressure to both holes in the two-hole array. In three cases the roof fell shortly after the treatment or over the weekend when miners were not working on the face. The roof did not fall in the remaining cases until mining had resumed and some face advance occurred. The microseismic monitoring system used at Moonee (Edwards 1998) provided adequate warning that a fall was imminent in these cases.

4.1 *Surface Treatment at Test Site*

Prior to the first full-scale treatment using hydraulic fracturing at Moonee, an investigation program was undertaken from the surface. The investigation had two main objectives: 1. to measure the fracture growth rate and, 2. to verify that a horizontal fracture could be propagated far enough to affect the roof stability. These key measurements were needed before a design of the first underground treatment could be made.

A central injection hole and three surrounding monitoring boreholes were drilled from the surface over an previously mined existing goaf. The conglomerate had already caved at the site, but a 2 m high air gap existed between the arched roof and the fallen goaf, providing a free surface similar to that existing at, but recognised to be more stable than, an uncaved situation.

The central injection hole was drilled to a depth that left its end about 5 m above the free surface. This blind end was isolated with a packer and a water treatment was pumped, consisting of 10,500 litres of water injected at 400 litres per minute. The fracture grew through the monitor hole located 13 m to the S of the injection hole in 7 minutes. One of the other three monitor holes failed and the third monitor hole did not detect the fracture, most likely because the fracture plane passed through the hole at the level of a packer.

A record of the pressure and injection rate recorded for this test treatment is shown in Figure 4. The pressure in the injection hole was recorded at the surface and a calculated bottom hole treating pressure is included in the plot. The low pressure recorded at the monitor hole was puzzling until the effect that the free surface on vertical stress and opening compliance were taken into account.

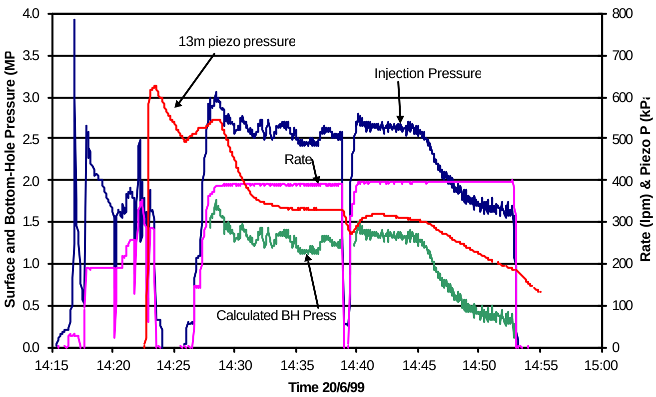

Figure 4: Pressure and rate data from the treatment at the surface site.

4.2 *Underground Treatments*

The first treatment from underground in Longwall 3 was carried out 10 days later. An up slant hole was drilled from an outbye cut through so that its end was positioned about 10 m above the base of the conglomerate and in the center of the longwall panel. A high pressure pipe was grouted into this hole, leaving the end open, to serve as the injection line. The treatment was carried out with 55 m of standing roof and a roof fall occurred after injection of 40,500 litres of water at an average rate of 340 litres per minute. The treating pressure response was similar to that observed at the surface test site.

The second treatment on Longwall 3 was performed from a vertical hole drilled 11 m up into the conglomerate roof from the longwall face. Figure 5 shows the pressure record from this treatment. A roof fall was induced after injecting 15,000 litres of water at 340 litres per minute. The pressure labeled as "instrument hole" was recorded from a pressure sensor installed into the open end of a second vertical hole drilled up into the conglomerate. This second hole served as a back up injection hole and as a monitoring hole. A roof-to-floor convergence device was installed below this hole and the convergence measured by this instrument is also shown in Figure 5. The instrumented hole was located 15 m from the injection hole toward the tailgate side of the panel. The hydraulic fracture grew to intersect the instrumented hole after 13 minutes of injection.

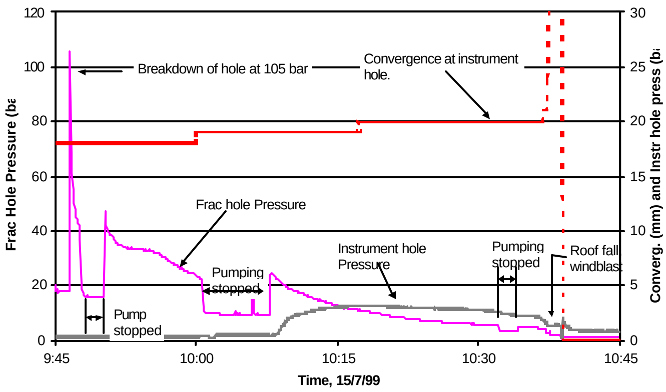

Figure 5: Pressure, rate and convergence data from the 2nd treatment on Longwall 3.

The third treatment was configured with two vertical injection holes spaced 25 m apart across the centre of the standing goaf. This configuration allows sufficient fracture growth, before the fractures short circuit into the fallen goaf, to induce caving of 40 m of standing roof. This two hole injection array has become the standard configuration for all treatments.

4.2.1 *Last (Fracture 26) Treatment in Longwall 3*

The last treatment on Longwall 3 (fracture 26) was intensively instrumented because it was critical to insure that the roof was brought down without face advance and with the caving extending to both ribs and to the face. A complete roof fall was required to allow the longwall equipment to be removed from the end of Longwall 3 in a safe and efficient manner.

Two vertical injection holes were drilled 7 m into the conglomerate roof for fracture 26. Each hole had pressure sensing tubes grouted into the top of the hole and convergence meters installed below them. In addition, three backup treatment holes were installed and each of these had pressure sensing tubes grouted in next to the main injection lines.

The treatment was conducted into the two primary injection holes with the total injection rate of 480 litres per minute split evenly between them by a mechanical flow divider. Figure 6 shows the pressure, injection rate and convergence data recorded during the injection stage that produced the roof fall. A previous injection stage had extended a fracture from hole 16, but not from hole 35. A shut-down of the pump and a separate breakdown injection cycle into hole 35 was then performed before starting on the stage shown in Figure 6.

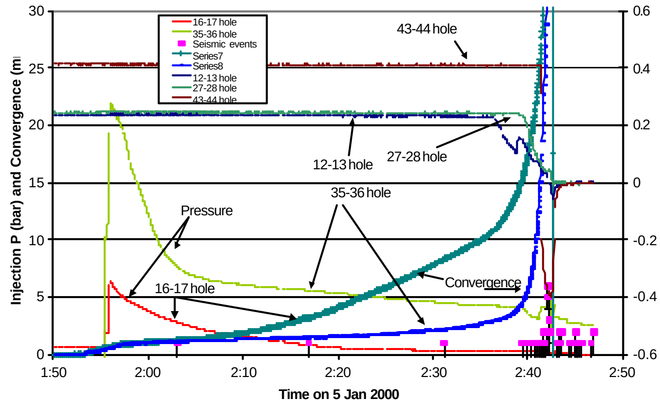

Figure 6: Pressure and convergence data recorded during frac 26 at the end of Longwall 3.

The pressure at hole 35 remained higher than the pressure at hole 16 throughout the treatment, most likely as a result of the earlier initiation of a fracture from hole 16, but also reflecting different stress conditions on the tailgate and maingate sides of the goaf. The roof to floor convergence was similar at the two injection holes for the first 1/3 of the treatment. This period of equal convergence is interpreted as an expression of equal fracture growth in the roof at each hole above the convergence gauges. After 2:10 am, the convergence rate at hole 16 became greater than that at hole 35. Only just prior to the goaf fall did the convergence rate at hole 35 exceed the hole 16 convergence rate. The microseismic events detected are plotted as filled squares with most of them occurring after 2:40 am. Microseismic activity indicated a fall was imminent at 1 min. 41 sec before the fall occurred.

The three monitoring holes detected decreasing pressure, starting 6.5 minutes before the fall at 12 hole, then at 4 minutes before the fall at 27 hole, and finally at 2 minutes before the fall at 43 hole. These pressure changes are not well understood. The ends of the sensor tubes may have been plugged with grout when they were installed. The pressure changes observed are not thought to represent the first arrival of the fracture growing through the monitor holes, but rather to be associated with more general failure of the roof, progressing from the maingate to the tailgate side.

Fracture pressure monitoring, convergence data, and monitor hole pressure response data are consistent. All of these measurements indicate that the fracture on the maingate side, at hole 16, grew to a larger size during the treatment than the fracture at hole 35. The unequal growth of the two fractures eventually resulted in a roof failure that started at the maingate side and progressed toward the tailgate. Upon later visual inspection, the fall was complete extending across the panel and up to the back of the face supports.

4.3 *Disscussion*

The data from each of the treatments at Moonee are essentially consistent. The data shows a decreasing pressure with time trend that within 15 to 20 minutes reaches a value of less than 20 bar at the injection holes. The pressure continues to decrease to a value less than 5 bar before a fall. As the fractures grow in the conglomerate, they soon reach a size where the effect of the free surface affects the opening compliance and reduces the pressure required to propagate the fracture. Any pre-existing tensile stresses in the roof contribute to even lower propagation pressures. Eventually, the fracture may reach a size where each additional growth increment results in an increase in fracture width and fracture volume that exceeds the volume injected during that time by the pump. The fracture can continue to grow, even with zero fluid pressure in it, because the weight of the rock is sufficient, at this late stage, to propagate the fracture.

5 MODELING THE MOONEE FRACTURING DATA

The solution for hydraulic fracture growth given by Geertsma and de Klerk (1969) has been modified to account for the effect of the free surface and for a small uniform in-situ tensile stress, as discussed above. The GDK model does not include the effect of leakoff (loss of fluid from the fracture into the surrounding rock) on fracture growth. A numerical model, that includes leakoff into permeable rock and can include the effect of the fracture intersecting a discrete high-loss area, such as a natural fracture, has been used to study this effect.

5.1 *Fracture Growth Near a Free Surface*

The GDK radial fracture growth solution (Geertsma and de Klerk 1969) gives pressure as a function of injection rate and fracture width, for a constant-injection rate treatment, as:

$$P = -\frac{5Gw}{4\pi R}\ln\left(\frac{R_w}{R}\right) \tag{5}$$

and the maximum width at the wellbore, w, is given by:

$$w = 2\left[\frac{\mu QR}{G}\right]^{1/4} \tag{6}$$

where R_w is the wellbore radius, R is the fracture radius, and G is the shear modulus of the rock and a Poisson's ratio is 0.25 was assumed in the derivation.

The change in compliance is included by using the factor obtained from Figure 3 and applying it as a divisor to the shear modulus, G, in this equation.

Figure 7 shows pressure and size of the fracture as a function of time. The base case is for a fracture growing far from a free surface in a rock that has a Young's modulus of 15,000 MPa and Poisson's ratio of 0.25.

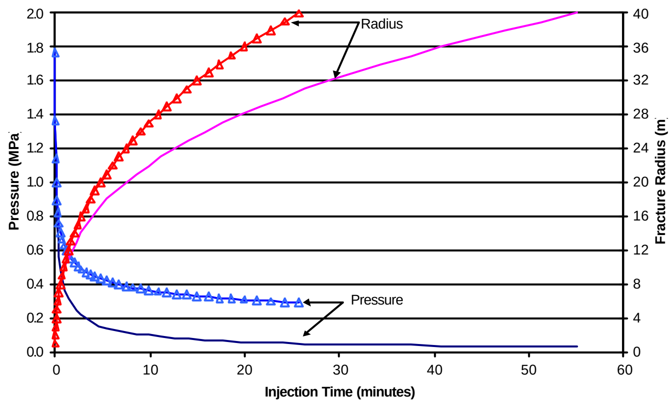

Figure 7: Pressure and radius for a fracture located far from a free surface (lines with symbols) and for a fracture 8 m from a free surface.

In both of the cases shown in Figure 7, the fracture reaches a final size of 40 m. The fracture's opening compliance is increased by the nearness of the free surface, and as a result, it opens more widely, grows more slowly with a lower pressure in it. Growth rates with leakoff included would be considerably slower and the pressure versus time curves would decrease less rapidly.

5.2 *Leakoff Effects*

Leakoff is an important process that limits the rate of growth and ultimate size of a hydraulic fracture. Leakoff into natural (or stress induced) fractures crossed by the hydraulic fracture can be significant. Fluid pressure entering natural fractures can open them, increasing their conductivity and the fluid loss into them.

A numerical fracture model for radial growth (Settari 1988) has been modified to include the effect of the fracture growing into a zone of high leakoff. The pressure and growth curves shown in Figure 8 demonstrate the effect that such a zone has on fracture growth and pressure. The base case curve represents growth of a fracture in a uniformly permeable rock while the other case represents the effect on pressure and growth rate for a hydraulic fracture growing in the same rock but intersecting a zone that results in loss of 1/2 of the injection rate.

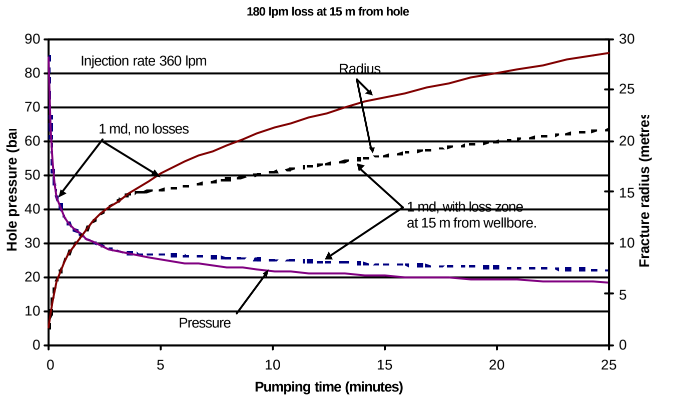

Figure 8: Pressure and radius for a fracture growing in a rock of 1 md permeability compared to growth of the same fracture with intersection of a loss zone 15 m from the well.

The fracture growth rate is significantly slowed and the fracture pressure decline flattens after the high loss zone is intersected. If the fracture were to grow into an open high conductivity fracture, growth would essentially stop and the pressure curve would become constant with time.

5.3 *Growth Trajectory and Fracture Mechanics*

A 2D finite element fracture mechanics program, FRANC2D, was used to model the fracture growth in the stress environment above the uncaved goaf. The model allows a pressure to be applied inside the fracture, but does not couple the fluid pressure to the injection rate and fracture opening. The pressure in the fracture was therefore adjusted after each growth step so that it produced a stress intensity factor equal to the rock fracture toughness.

The fracture path followed for this simulation is shown in Figure 9. The pressure to extend the fracture became zero at the point indicated and the weight of the rock alone was sufficient to continue the fracture growth past this point. The upper surface of the fracture trajectory is similar to the arch formed after goaf falls as shown in Figure 1.

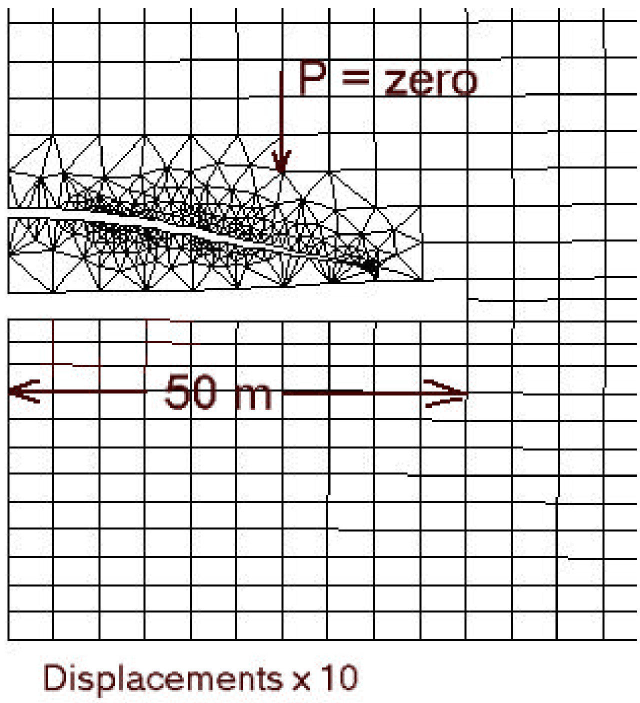

Figure 9: Fracture growth trajectory in the conglomerate roof modeled using FRANC2D.

6 DISCUSSION AND CONCLUSIONS

The application of hydraulic fracturing at Moonee Colliery to induce goaf caving events in a massive conglomerate roof has provided the mine with a method to control the timing of these goafing events. Two-dimensional stress and hydraulic fracture modelling has been used to analyse the data collected. Three-dimensional modelling will be used to study and include the potential effects from stress variation across the panel width which result from the in-situ horizontal stress not being aligned with the longwall panels.

The stress conditions in the roof conglomerate promote horizontal fracture growth parallel to the free surface created by mining the coal.

The opening compliance of the fractures is increased by their interaction with the nearby free surface and this effect must be taken into account when modeling the fracture growth.

Fluid loss from hydraulic fractures that grow through natural or stress-induced fractures in the roof will slow or even stop the hydraulic fracture growth and flatten the pressure versus time record.

The arch profile in the roof rock after caving that is induced by hydraulic fracturing is similar to the profile produced by 'natural' goaf caving events. The arch formed after caving is stable.

7 ACKNOWLEDGMENTS

We acknowledge the management, staff, and workforce of Coal Operations Australia Ltd. and Moonee Colliery who have supported the work described in this paper. Their willingness to undertake special data acquistion tasks as required has contributed greatly to developing an improved understanding of the fracturing and roof failure processes that occur at Moonee.

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