EVALUATION OF A TWO LIFT THICK SEAM MINING METHOD BASED ON PARTIAL EXTRACTION OF 6 m HIGH SQUARE PILLARS WITH RELATIVELY SMALL WIDTH

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ABSTRACT

This paper presents the results of in-situ and laboratory investigations into a mining method which utilises conventional continuous mining techniques to carry out two passes in thick coal seams, resulting in the development of stable pillars with relatively small width dimensions and heights up to 6 m.

Geotechnical investigations included structural mapping, brightness logging and standard laboratory testing. Virgin stress was measured using overcoring techniques. Two approaches to pillar design were used in the study. These were; pillar design based on empirical formulae and laboratory testing, and pillar design using calibrated mathematical models.

A trial panel was developed at 300 m depth to study pillar deformation and stress changes due to mining. The extent of rib deformation was studied using borescopes and extensometers. In-situ geotechnical measurements were used to calibrate displacement discontinuity and finite element mathematical models of the coal seam. These models were then used to predict the behaviour of a small panel of pillars which were to be developed to 6 m height.

The mining method was shown to be feasible provided adequate rib support was installed. The benefit of rib support was found to be two-fold, in that it increased confinement of the pillar in zones of low horizontal stress, while reducing horizontal stress relaxation in zones of high horizontal virgin stress. The possibility of roof control by designing the small pillars to yield on retreat is discussed.

INTRODUCTION

This paper details results of investigations into a proposed mining method utilising continuous mining techniques to carry out two passes in a 6 m high seam, by development of stable pillars with relatively small area dimensions to full seam height. The study was conducted with reference to Utah Development Company's Harrow Creek Trial Colliery (HCTC), and was funded by the National Energy Research Development, and Demonstration Program, with the general aim of improved recovery from thick coal seams.

A comprehensive coal strength testing program was undertaken to obtain representative coal strengths at different locations throughout the HCTC mine workings in association with detailed geotechnical mapping.

Two approaches to small pillar design were undertaken. The first was a conventional approach based on empirical formulae and laboratory testing. The application of three commonly accepted pillar design formulae is discussed. The second approach to pillar design was based on the calibration of mathematical models using geotechnical measurements recorded in a trial pillar panel. Both displacement discontinuity and finite element mathematical modelling techniques were used. Pillar ribs in the trial panel were reinforced with wooden dowels. Calibrated mathematical models were then used to model the proposed small pillar partial extraction mining method. Pillar size, roadway width and pillar height were examined.

The original two pass mining method was revised based on the results from the geotechnical investigations. The revised method involved the rapid development of headings to the boundary of a panel followed by development of the small pillars on retreat. Rib bolting during the first pass of the mining cycle would be necessary to maintain optimum pillar strength.

CONCEPT AND METHODOLOGY

The concept of increasing reserves recovery by making a second pass through the workings around pillars originated from methods developed at Collinsville, Moura, Irmidich and Collie at various times during the last twenty years. In those operations the feasibility of bottom brushed working was proven, but problems were known to occur with ramping into the floor coal.
usually when the mining equipment had to return back up the ramp. Minimal ramping and maximum horizontal bottom brushing was perceived to be a solution to this problem and was incorporated into the proposed mining method. Rib stabilisation by rib dwelling or bolting and strapping was recognised as a probable requirement.

The greatest problem was perceived to be whether or not the coal and strata properties at HCTC would allow the development of small stable pillars.

LABORATORY TESTING OF COAL STRENGTH

A comprehensive rib mapping program was undertaken and was reported elsewhere (Shepherd et al, 1984). Development of mining induced fractures was shown to be a major cause of rib instability in the weak Harrow Creek seam. Various rib failure mechanisms were identified and a classification scheme developed.

A total of 116 standard UCS tests were made on samples from different locations in the mine, and from different intervals in the seam. UCS strength varied from 5.3 MPa to 25.6 MPa with a mean of 14.5 MPa and standard deviation of 5.6 MPa. Strength values were dependent on coal brightness. Samples with more than 50% bright had strengths around 10 MPa, while samples with less than 20% bright had strengths of around 20 MPa.

A consistent relationship between coal strength and type of rib failure could not be determined. The onset of each type of rib failure was related to the combined effect of increased stress with depth, and an increase in coal brightness of the working section to the south-east. Tensile strength was also dependent on coal brightness, with an average value of 0.45 MPa and a standard deviation of 0.23 MPa for 86 tests.

The effect of increased confinement on coal strength is shown in Figure 1. With an increase in confining pressure from 0 to 5 MPa, average coal strength increased by 3.5 times to 50 MPa.

The benefits of rib reinforcement were studied in the laboratory by unconfined compressive testing of 150 x 150 x 75 mm blocks of Harrow Creek coal with and without rib reinforcement. Two rows of wooden dowels were modelled by gluing 25 mm match sticks 25 mm into the ribs of the blocks. Average strength of (5) dowelled blocks of 20.1 MPa was 10% greater than that of 7 undowelled blocks. Although this result cannot be extended to in-situ conditions, the laboratory studies showed that the main advantage from dowelling was that the pillar ribs were kept relatively intact after failure of the specimen, thereby supplying increased confinement of the pillar core. The failure mechanism in the laboratory involved crushing of the outer region leaving a relatively intact specimen core, with the crushed edges held together by the dowels.

Fig. 1 - Uniaxial and triaxial strength of Harrow Creek Seam.

PILLAR DESIGN USING EMPIRICAL FORMULAE

A significant amount of research has been applied to the relationship between laboratory test results and pillar strength observed in-situ. Coal pillar design based on laboratory measurements and empirical formulae was used as a first approach to pillar design.

EFFECT OF SPECIMEN SIZE

Experimental results have shown that coal strength reduces with increase in specimen size. Bieniawski (1968) showed that there is a 'critical size' ($S_c$) above which, continued increase in specimen size produces only small decreases in specimen strength. This critical size for Witbank coal was found to be 1.5 m. The relationship between specimen strength and specimen size up to the 'critical size' is controlled by spacing and orientation of discontinuities throughout the coal, and has been shown to obey the following power law:

$$ S = k D^{-b} $$

where $S$ = specimen strength, MPa

$k, b$ = constants for the coal

$D$ = side length of a cube, mm

Hustrulid (1976) and others have shown that the constant $b$ is around 0.5 for different coals. Results of UCS tests on cubes of Harrow Creek coal are listed in Table 1.
Table 1  
UCS tests results for cubes of Harrow Creek coal

<table>
<thead>
<tr>
<th>Cube Size (mm)</th>
<th>Number of Tests</th>
<th>Cube Strength (MPa)</th>
<th>Constant, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>2</td>
<td>19.7</td>
<td>171</td>
</tr>
<tr>
<td>150</td>
<td>3</td>
<td>14.4</td>
<td>126</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>7.8</td>
<td>156</td>
</tr>
<tr>
<td>750</td>
<td>1</td>
<td>6.8</td>
<td>164</td>
</tr>
</tbody>
</table>

Calculated values of the constant K for an assumed value of $a = 0.5$ is also shown in Table 1. Results for the larger cube sizes of 500 and 750 mm were measured in a uniaxial creep testing rig. Normal UCS values for these tests could only be estimated as failure was time dependent. Given that the results for the two larger sizes were estimates, the calculated values of K appeared to be representative up to the larger specimen size.

Figure 2 shows plots of cube strength against cube size for Witbank, Pittsburgh and Harrow Creek coals. It can be seen that the Harrow Creek data is similar to Bienia’s results for Witbank coal. Laboratory strength of Harrow Creek coal was similar but slightly less than that reported for the Pittsburgh Seam (Peng, 1978).

Fig. 2 - Plot of cube strength (MPa) vs cube size (mm).

Table 2 shows calculated values of Harrow Creek cube strength for various critical sizes, using $K = 1.70$. The upper limit of cube size is the actual height of the pillars in-situ and would be 2.2 MPa for 6 m high pillars.

Table 2  
Cube strength for varying cube size

<table>
<thead>
<tr>
<th>Cube Size (m)</th>
<th>0.9</th>
<th>1.5</th>
<th>3.5</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube Strength (MPa)</td>
<td>5.7</td>
<td>4.4</td>
<td>3.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

EFFECT OF PILLAR SHAPE

Pillar strength has been shown to depend on the ratio of pillar width to height (Wh), (Bienia, 1975). Design formulae proposed by various authors can be grouped into the following three types.

(a) Linear function of Wh (Bienia, 1975)

$$S = S_0 + S_1 (Wh^{-0.5})$$

Using $S_0 = 4.4$ MPa for Harrow Creek coal the relationship was,

$$S = 2.82 + 1.58 (Wh^{-0.5})$$

(b) Power function of $W$ and $H$ (Salamon, 1967).

$$S = D W^a H^b$$

$D$, $a$, $b$ = Constants

The following formula was proposed by Salamon (1967) for South African conditions based on a number of in-situ pillar failures.

$$S = 7.2 W^{0.46} H^{-0.66}$$ MPa

(c) Progressive Failure Theory (Wilson, 1983).

Wilson (1983) proposed the following formula for square pillar strength based on consideration of the effect of confining restraint rendered by the yielded rib zone.

$$P = \tan \beta \left( \frac{W^2 - 9.80nH^2}{32h^2} \right)$$

where $P$ = Pillar strength, kN

$\tan \beta$ = Average slope angle of curve for failure stress versus confining stress = 75 degrees from 0 to 20 MPa confining pressure for Harrow Creek coal, i.e. $\tan \beta = 3.73$

$h$ = depth below ground surface, m

Figure 3 shows plots of safety factor against pillar width, calculated for a 3.5 m
pillar height, and depth of 300 m, using the three pillar strength formulae with estimated constants for Harrow Creek coal. Pillar load was calculated using the tributary area approach with 7.5 m wide roadways. Pillar strengths predicted by formulae (a) and (b) were similar for pillar widths from 15 m (12 MPa) to 30 m (16 MPa). Wilson’s formula (c) calculated higher strengths in this width range. Formulae (a) and (b) predicted that a square pillar width of 24 m will have a safety factor of unity for a 3.5 m pillar height.

![Graph](image)

**Fig. 3** - Safety factor vs pillar width Harrow Creek seam - 300 m depth, 3.5 m height, 7.5 m roadway.

Figure 4 shows similar plots for the three formulae with pillar height of 6 m. Again, Bieniawski’s and Salamon’s formula gave similar values for pillar widths from 15 to 30 m. Estimated pillar widths for a factor of safety of one with a height of 6 m vary from 25 to 35 m with Salamon’s formula being the most conservative.

![Graph](image)

**Fig. 4** - Safety factor vs pillar width Harrow Creek seam - 300 m depth, 6 m height, 7.5 m roadway.

**UNDERGROUND TRIAL PILLAR PANEL**

Pillar design based on laboratory testing and empirical formulae has the disadvantage of not being able to account for full scale effects of geological structures and redistribution of stresses around roadways. A trial panel of small pillars was developed to the west of D heading in the Harrow Creek south-east development area (Figure 5) to study immediate and time dependent deformation of small pillars in-situ. In-situ measurements made during the development of the trial pillars were then used to calibrate a mathematical model of the Harrow Creek seam.

![Diagram](image)

**Fig. 5** - Location of trial panel.

Overburden depth at the study site was 300 m. An initial 30 m square pillar was developed following the sequence shown in Figure 6. The 30 m square pillar (rib to rib) was split into 12 x 29 m pillars. Most of the panel was dowelled using 35 mm x 1.5 m wooden dowels and resin cartridges. 150 mm square wooden plates were used with split wedge end fasteners. The north-west corner of the 30 m square pillar and opposite ribs were not dowelled for comparison with the dowelled areas.

Stress gauges, extensometers, and roof to floor convergence stations were used to monitor stress change and pillar deformation as development took place. Width and location of cracks in the ribs were logged using a borescope. Figure 7 shows the location of stress gauges which were installed when face positions were as shown. Vertical stress at location A, 6 m from the rib, increased 1.63 MPa during separation of the 30 m pillar compared to an increase of average stress of 3.9 MPa predicted from tributary theory. After development of the pillar split, the total stress increase was 2.38 MPa. The centre of the
12 m wide pillar had not reached a stress level equivalent to the calculated average stress for the 30 m pillar even after the pillar split. This implied that abutment load was still in the outer sections of the 12 m wide pillar on completion of the pillar split.

3.5 m into the rib was approaching complete stress relaxation at the completion of the split.

![Diagram](image)

Fig. 6 - Development sequence and timing.

The N-S horizontal stress gauge at B recorded horizontal stress relaxation of 2.75 MPA during development past the gauge up to face position 6. Horizontal N-S stress remained relatively constant during the split. Previous over-core stress measurements have shown that the principal stress was horizontal, roughly N-S in direction, and around twice the vertical stress. Therefore the N-S virgin stress field was estimated to be around 15 MPA in the area of the panel. This implied that there was significant horizontal confining stress remaining (12.25 MPA) at a depth of 5 m into the pillar. Longer term stress measurements showed a gradual relaxation of around 1 MPA per month.

Stress relaxation in the E-W direction at location B, recorded during the pillar split was 4.5 MPA up to the limit of the gauge. Figure 8 shows the E-W stress change during development of the split. The greater stress relaxation at location B was attributed to the shatterbox gauge depth of 5.5 m into the rib. The estimated value of the virgin stress in the E-W direction was 5 MPA; therefore the horizontal stress at

![Diagram](image)

Fig. 7 - Installation of stress gauges at face position 3 (full lines). B&W installed at face position 6 (dashed line).

Both borescope surveys and extensometer measurements concluded that immediate rib deformation had not taken place beyond 2 m into the dowelled rib. In most cases open fracturing was limited to around 1.8 m. Immediately beyond a zone of open fractures in the immediate rib sides, the boreholes showed signs of being highly stressed, consistent with the presence of a stress abutment zone. Wedged shaped coal pieces had fallen out of the borehole roof consistent with the existence of tensile stresses, and the sidewalls were often crushed at a borehole depth of around 3 to 4 m. Horizontal extensometers confirmed that most lateral movement was within 2 m of the rib side.

Wooded dowelling was not sufficient rib support where cutters were dipping at less than 75° into the roadway. Where this occurred adversely dipping dip planes occasionally combined with rib fractures to delimit large blocks of coal, approaching 2.5 m³ in volume. Upper dowels had not penetrated the cutter, or dowelling was completely absent at most locations where these blocks fell out.

**MATHEMATICAL MODELLING**

The major outcome of the trial pillar panel modelling studies was a reliable, calibrated mathematical model, suitable for predictive use in other parts of the mine. The trial panel was modelled at various face positions during the pillar split where predicted stresses and deformations were compared with those observed in-situ. Material parameters in the model were
initially based on laboratory test data and subsequently adjusted to agree with observed stresses and deformations. In this way representative in-situ material parameters were obtained. Figure 9 shows an example of the results obtained from displacement discontinuity modelling of the pillar split, being a plot of vertical stress at different face positions along an E-W section through the trial panel.

The calibrated mathematical models were then used to study a number of small pillar layouts with varying pillar widths.

Displacement discontinuity studies concluded that 22.5 m pillars would be stable, but as this method cannot consider pillar height, this conclusion needed to be further tested using FEM methods. Results of the FEM modelling of 6 m pillar heights indicated two possible failure areas - instability of the stone roof during development of roadways in the top of the seam, and ribside spalling problems. It was expected that effective bolting would hold the roof, if three bolts are installed per metre length of roadway, providing bolt strength and anchorages are adequate.

Directly after development, the coal rib sides in each model were fairly stable, showing limited slip and tensile fracturing to two or three metres depth. However, despite the use of dowels, ribside spalling soon developed to depths of one to two metres, with interior pillar movement detected to as much as five metres from the ribside.

Fig. 8 - E-W stress change during pillar split at location B

Fig. 9 - Displacement discontinuity model results for vertical stress in seam with dowelled rib sides.

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Upon pumping the floor, the newly exposed lower ribside portion was practically free of failure in the 5 MPa horizontal stress models (E-W), and had only limited failure in the 15 MPa horizontal stress models (N-S), Figure 10. The old upper ribside portion, however, gave cause for concern in the 5 MPa horizontal stress models, with renewed spalling and failure extending to as deep as 5m into the ribside. This did not occur in the models with 15 MPa horizontal stress.

![Diagram showing symbols indicating failed areas in horizontal stress models.](image)

**Fig. 10 - FE results for 15 MPa horizontal stress.**

Horizontal primitive stress was the controlling parameter for the overall behaviour of the excavations modelled. The increase in horizontal stress from 5 to 15 MPa was responsible for a multitude of excavation responses including:

- Decrease in depth of upper ribside spalling following pumping;
- Increase in depth of lower ribside spalling following pumping;
- Increase in immediate coal floor fracturing during development;
- Increase in laminite floor fracturing after pumping;
- Increased stone roof failure during development;
- Avoidance of tensile failure of stone roof and floor above and beneath the centre of the coal pillar;
- Increase in maximum vertical stress within the pillars by as much as 50%;
- Increase in maximum roof-floor convergence within the heading by as much as 33%.

**DISCUSSION**

Mathematical modelling showed that the minimum safe pillar array dimensions in Harrow Creek Trial Colliery would be with square pillars of 22.5 m side lengths with 7.5 m roadways, giving a recovery per pillar of 26% of the reserves if only one 3.6 m high lift is worked, or 44% if a second lift is taken to complete full seam height of 6 m. Subsequent windowing of the pillars on retreat may be possible which would bring total recovery up to 50%.

The rate of horizontal stress relaxation has important implications in the eventual strength to be expected from a pillar over a given period of time. Triaxial testing of Harrow Creek coal has shown that strength increases 3.5 times with an increase in confining stress from 0 to 5 MPa. When mining in areas where the horizontal stress is the most significant stress direction, the inherent strength supplied by this confining stress can be used to advantage when partially extracting coal by developing small pillars. By reducing the rate of horizontal stress relaxation and monitoring stress reduction with time an optimum recovery can be achieved. Empirical formulae were more conservative in estimating safe pillar dimensions, predicting that a pillar width of up to 35 m was required for a factor of safety of unity with 6 m pillar height. Mathematical models which were calibrated using in-situ measurements predicted pillar widths of 22.5 m would be stable, provided the ribside could be stabilised. The presence and direction of cutters in the Harrow Creek seam will have a significant influence on rib stability and safety. The cutters would form very large blocks when extended over 6 m. Steel bolt lengths of 2.5 to 3.0 m will need to be installed during the first pass, to safely stabilise these blocks for the second pass.

The original mining concept proposed the development of a panel of small pillars of the minimum dimensions still providing stable long term roof support. Such pillars would require a stable elastic pillar core and a factor of safety greater than unity for longer term stability.

A modified approach was developed recognizing the time dependent nature of horizontal stress relaxation. Progressive rows of stable pillars can be split off in the upper seam section, immediately followed by full face bottom extraction from a ramp in the main heading as shown in Figure 11. Extraction of the bottoms would be rapid as support elements would not be installed during the bottom pass. Less conservative pillar sizes could be considered based on initial experience. Smaller pillars would allow progressive yielding in a controlled manner while providing temporarily stable conditions in the actual mining face areas during retreat. This approach would enable a higher recovery of reserves, but viability depends on a number of presently...
unknown factors including the actual time dependent pillar behaviour, and the magnitude of the front abutment loadings which would develop in the working areas as the pillars yield. The working face could be abandoned if conditions deteriorate and a new split developed inbye leaving a barrier pillar.

![Diagram](image)

Fig. 11 - Revised development sequence.

Pillar sizes of 25 m would prevent the formation of a true goaf and would accordingly minimise the magnitude of additional abutment loadings in the working face area. It was therefore concluded that the more conservative approach of developing pillars with 25 m side length should be initially adopted with the recommendation that experimentation with a yielding pillar method be carried out in the latter stages of the first panel by reducing the pillar width.

CONCLUSIONS

Two approaches to the evaluation of a two pass small pillar partial extraction mining concept have been discussed. Empirical pillar design formulae were shown to be more conservative than the use of calibrated mathematical models.

Empirical formulae do not take in-situ stress fields, or time dependent behaviour, into account. The use of mathematical models which are calibrated by in-situ geotechnical monitoring provides a more reliable predictive tool for mine design.

Time dependent relaxation of the horizontal stress is a major factor contributing to eventual pillar failure. The existence of high horizontal stresses can be used to advantage by reducing relaxation of the pillar using rib reinforcement techniques.

Partial extraction at 300 m depth using 6 m high, 25 m square pillars and 7.5 m roadways, is technically viable at HCTC provided the following conditions are complied with:

- Seam conditions are similar to those experienced in the trial panel.
- Installation of adequate rib support as part of the mining cycle during the development in the upper section of the seam. Rib support must be of sufficient strength and length to hold large coal blocks defined by "cutters" in place. Steel W strap to be installed between rib bolts, especially around corners.
- Adequate roof bolting is installed during development.
- Small pillars to be developed as part of a panel retreat sequence so that any change in seam conditions, or poor mining control, can be rectified by pulling back to a stable area where pillar development can be resumed.
- Access to working around small pillars which have been left standing for periods longer than three months be prohibited.

Economic viability of the method in weaker seams is dependent on the successful development of a rapid mechanised means of rib support close to the face.

The method will result in recovery of reserves within the panels of at least 44% in the weak Harrow Creek Seam. Recovery may be improved by windowing small pillars during retreat provided rib stability can be maintained above the miner. Greater recovery would be possible in thick coal seams which have greater strength than the Harrow Creek seam.

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REFERENCES


