Fender Geomechanics and Behaviour in the Wongawilli Pillar Extraction System

J. Shepherd and T. Lewandowski

1Shepherd Mining Geotechnics (Aust.) Pty. Ltd.
13 Kurrawa Avenue, Kiama Downs, NSW 2533
2Strata Engineering (Australia) Pty. Ltd.
P.O. BOX 11, Teralba, NSW 2284

Abstract: Pillar extraction using the Wongawilli System has been investigated with particular reference to fender stability and design at two widely separated collieries in New South Wales and Queensland. Strata performance was evaluated by instrumented trials of different fender widths ranging from 7 to 13m. Monitoring programs measured stress changes, fender/stook dilations and roof sag. The wider fenders performed better structurally than the narrow ones, producing safer extraction conditions at the goaf edge. Fender stiffness is indirectly evaluated from pillar extensometer displacement measurements and significant differences were found between an 8m and 10.5m wide fender. An overall industry-wide change to generally wider fenders, with w:h ratios ≥ 2.5, is beneficial for stability and numerous collieries are benefitting from this using remote controlled continuous miners and mobile (breakerline) roof supports. A triangular diagram guideline is proposed to assist fender width design according to working depth.

Key words: pillar extraction, fender design, instrumentation, goaf (gob)

Introduction

The Wongawilli System of extraction was developed about 1960 in the Southern Coalfield collieries of New South Wales by the Broken Hill Proprietary Company mine staff. Few early records survive and it was not until after 1970 that published information emerged (Joint Coal Board 1972-73, Hams 1974, Shepherd and Chaturvedula, 1991)

The System was devised largely for strata control reasons (Thomas, 1980), the essential characteristics being the formation of limited access roadways and pillars to gain access to a solid block of coal. One of the main reasons for instigating this was the instability of multiple 4-way heading intersections in older pillar splitting and lifting operations.

The method involves driving long splits out into the solid coal block leaving a long, narrow pillar or fender between the split and the goaf. This fender is then systematically extracted by lifts. Before and during lifting the fender serves as a barrier against the goaf.

The width of this fender is crucial for safe extraction. This paper presents a summary of detailed geomechanics investigations of fenders and provides guidelines for their design (Shepherd and Lewandowski, 1994).
Need for a Fender

When mechanised extraction of pillars was permitted again in NSW collieries in 1954, timber props and bars were the principal method of support supplemented with mechanically-anchored roof (rock) bolts. A commonly used method was taken from hand-working practice using a coal cutter and open-ended lifting of a pillar (Peascod, 1960 and Sleeman, 1986) fully exposed to the caving goaf except for timber breaker props as support (Figure 1).

This method was quickly found to be unsatisfactory as the goaf would regularly flush into the “lift”, burying machinery. The earliest attempts to prevent this was by the use of fenders (a narrow barrier), leaving < 1m thickness of coal between a “lift” and the goaf. Sometimes this very narrow fender was also taken. At the time it was believed that the fender gave a false sense of security, because of its slenderness and low strength (Peascod, 1960, p.25). This method rapidly progressed into pillar splitting leaving a much wider protective fender between the “lift” and the caving edge. Later on this evolved into the Wongawilli system (Hams, 1974, Shepherd and Chaturvedula, 1991) and the Modified Wongawilli using mobile roof (breaker line) supports (Bracken, 1991) (see Figure 1, C,D). As is the case for longer term pillars needed for the safe support of workings, fenders were found to be an essential component of pillar extraction to maintain safe working conditions.

The Wongawilli or modified Wongawilli system involves the development of a coal block (generally 70-100m wide) using two or more development headings and “splitting” in a perpendicular direction to form long and narrow fenders (Figure 2a). A successful variation of the modified Wongawilli system is to lift left and right from a split (taking lifts out of the solid coal as well as the fender) and using the development headings to split both sides into solid, thus effectively halving the development needed (Figure 2b). A combination of both of these modifications can be used to optimise productivity. In the USA, lifting left and right from pillar splits is termed the “christmas tree method” (Chase et al, 1996).

The most dangerous event that can occur during pillar extraction is a unexpected goaf fall that overruns outbye into to a working lift or even as far as the outbye intersection. Experience has shown that accidents are most likely within 1-3 lifts of the fender end as the outbye intersection is approached.

Fender Design Related to Pillars.

For many years fenders were not designed by geomechanics, but their width was set on the basis that the continuous miner driver did not venture out beyond the split roof support. Until recently, there were no design rules such as for pillars.

One of the most important parameters in designing fenders and pillars is fender width to height ratio (w:h). As observed by Salamon and Munro (1967) and confirmed by Madden (1991, Fig.9) and the School of Mines (1995), the strength of
the pillar is highly dependent on the w:h ratio i.e. strength of the pillar increases proportionally with a power of the w:h ratio.

Generally fenders in Australia are designed for w:h ratio in the range 2.0-4.0. Although minimum w:h ratio specified by the Mines Inspectorate is 2.0 (Pillar Extraction Manual, 1992), on some occasions fenders with w:h ratio of around 1.5 are extracted. This is mainly due to fender rib spalling under heavy loading conditions.

At low w:h ratios, the risk of sudden failure is high. This was discussed by Madden (1991 p.33) who specified that pillars up to w:h ratio of 3.75 are known to have suddenly collapsed. Fenders by their nature are relatively narrow and, therefore, speedy extraction is essential to avoid time-dependent deterioration.

**Strata Mechanics of Fenders**

When a fender is utilised in pillar extraction it is the main support to the roof in the split (Shepherd and Lewandowski, 1993). In Australia, a wide range of fender widths were tried by trial and error, especially during the late 1950's and early 1960's when the Wongawilli System was devised. Fender widths ranged from 1m (purely protection against the goaf) (Peascod, 1962) to 3m minimum at South Blackwater in Queensland (Greenhill and Gibson, 1980) up to 13-14m and even wider (Figure 1). Recommendations for 9m wide fenders were made after the Wongawilli System had come into common use in Australia (Joint Coal Board,1972-3). Since most scams or extraction sections were <3m, the w:h ratio was > 3. During the 1980's, however, there was a "rule of thumb" approach applied to fender width according to the distance of the driver's cab from the cutting head of continuous mining machines, nominally 6.5-7.0 m. If the fender width equalled this distance, then the operator did not become exposed to unsupported roof in the lift. However, there was no geotechnical basis for this design.

The work reported in this paper was aimed at measuring the stresses and displacements in fenders of variable width in production cycles. Also, an additional aim was to find a way of estimating fender stiffness for comparative purposes.

Some Indian researchers have measured the stresses across small pillars under partial extraction (Singh et al, 1991 and Singh et al, 1996). Their "stooks" are in fact residual pillars 7.5m wide. In some cases the method involved stowage, so it is difficult to compare our results. However, under caving conditions only small vertical stress increases occurred in these pillars of <1MPa.

Two sites were available for this instrumentation work: Charbon Colliery in NSW at a cover depth of 145m and a working height of 3m, and Laleham No.1 Colliery in Queensland at 115-120m depth and a height of 2.8m. At Charbon, an advanced modified Wongawilli extraction system was already operational in contrast to Laleham where a Wongawilli system was in use. All the instruments were installed
into the solid “Wongawilli coal block” prior to splits being driven and outbye of the goaf edge.

At Charbon, 80m long splits were driven out on both sides of panel pillars (3 pillars per row) that were not extracted. Consequently, the two extraction blocks were separate and sub-critical at m depth. At Laleham, the panel pillars were also extracted by split and lift row by row once the adjacent solid had been taken by the Wongawilli method. The extraction width was approximately 210m.

The use of wide fenders had been favoured at Charbon and with the acquisition of a Joy 12CM-30 continuous miner (remotely controlled), mine management wished to increase fender width to achieve higher productivity.

Charbon fenders

The standard fender width had been 8m and permission was obtained from the Mines Inspectorate to trial wider fenders at 10.5 and 13m and continuous miner and mobile roof support recovery procedures were documented in case of unexpected burial. An array of instrumentation was installed to measure fender stresses and displacements. 3 types of cells were installed: hydraulic pressure cells, Geokons and CSIRO hollow inclusion (3-D). These were placed in solid coal to be extracted at the future fender ends (stook ‘x’ at the end of each lifting sequence). The pressure cells were fabricated in-house according to Riley and Edward’s (1989) design.

The cells and extensometers were monitored intensively during the extraction sequences (see Figure 3). Significantly lower vertical stress was found in the wider fenders, see Table 1 and Figure (4). Generally, vertical stress increased throughout fender lifting and into the stook and the goaf. Some “protection” was present from the adjacent solid pillars (see Figure 2) and a partial pillar left on the east side of the Wongawilli block. Details of the stress histories for the 3 fender widths is in Figure 4. In all 3 cases, the vertical stress levels rose sharply as the stook was reached, but the wider fenders reached lower stress levels (Table 1 and Figure 4).

For example, a detailed graph of the 10.5m fender vertical stress is in Figure 3b. The stress build-up was relatively low in this fender even when it was lifted off. Of particular interest is the comparison of the results of the three types of cells used. The hydraulic pressure cell was less sensitive under the low loading (pre-split) conditions, but all 3 cells gave similar results in the goaf where the Geokon cell failed at ~ 7mpa. The other 2 cells unloaded slowly over a period of 15 days as the stook ‘x’ slowly crushed.

Lower dilation of the fender rib was also recorded in the wider fenders and at the end of lifting the contrast between the 8m and 13m fenders was 130mm compared with only 25mm (Table 1 and Figure 5). This demonstrates the superior strength of a wide fender and its improved roof support role in the split, behaving as a barrier.

An overall summary of the stress/displacement results is in Figure 6.
Blackwater Fenders

The overall mining sequence at Laleham No.1 Colliery was as shown in Figure 2a. Instrumentation was installed to be in the end of one fender (F2) (see Figure 7). Detailed monitoring was carried out during extraction of adjacent fenders, before and after F2.

An array of 5 borehole hydraulic pressure cells (uniaxial) was installed to measure stress across the fender for the purpose of defining a stress profile and rib extensometers measured the dilation of the fender on the split side (opposite the goaf).

Stress Profile

A summary of the results from Shepherd and Lewandowski (1994) are presented as fender cross sections in Figure 7. Split 1 drivage removed one of the cells (cell 1), leaving 4 cells. Stress increases were measured as extraction proceeded with stress magnitude increasing and decreasing from lifting off F1 to splitting S2. However, as F2 was lifted a marked stress peak developed (see Figure 6) and the fender ribs yielded and spalled. As the goaf side of the fender yielded the stress peak migrated towards S2 and the solid. At the site of the thirteenth lift, <5m from the cells and 5m from the fender stook position, further unloading occurred on the goaf side of F2, but the peak stress increase remained almost constant at ~15 MPa. During the stress increase, rib extensometers recorded dilations. Extensometer PE2 (see Figure 7 for location) measured a relatively linear rate of dilation of the fender on the split side during F2 lifting (see Figure 8). It should be observed that the maximum detected depths of softening during fender splitting and fender lifting were 1.0m and 1.5m respectively (see Figure 8). According to the fender extensometer results the remaining core of the fender did not yield at any time during the fender extraction process. The extensometer measurement alone is a strong indicator with respect the substantial load carrying capacity of the fender during fender splitting as well as during fender lifting. The obtained extensometer results are consistent with stress increases in the core of the fender.

A reconstruction of the stress profiles from F2 and the nearby solid coal is shown in Figure 9. These clearly show that the fender (F2) stresses were consistently higher than the solid coal stresses by a factor of x3 to x4.

Stiffness Variation

The impact of the goaf line and induced high abutment stresses during Wongawilli extraction raise the issue of the fender performance under extreme loading conditions. One of the most accurate parameters which quantify the fender performance is the “stiffness” parameter. The stiffness (k) of the fender is defined as the vertical displacement (d) under a vertical load (L) i.e. $k=L/d$ (School of Mines, 1994).
For the Wongawilli extraction system the fender stiffness depends on the following factors:

- the location of the measurement in the fender
- the surrounding environment i.e., extraction pattern, and
- the state of the adjacent pillars.

An available method for pillar/fender stiffness measurement involves an imaginary replacement of pillar/fender by a hydraulic jack. The results obtained from the hydraulic jack i.e., the load-convergence curve would represent the stiffness of the pillar/fender in that particular location.

An alternative method for the fender stiffness estimation has been developed and is presented below. Each of the analysed fenders was instrumented in the same manner i.e., the stress cell was positioned in the middle of each fender and in line with the centrally positioned horizontal extensometer. The major assumption in this analysis is that the imposed increase in the vertical load in the centre of the fender causes vertical shortening strain and, therefore, an increase in the horizontal displacement. The impact of the stresses on the edge of the fender is omitted.

The measured stress changes and fender displacements during fender extraction were converted to change in the vertical loads using stress as a function of load and surface area formula and vertical shortening of the fender respectively. The assumed conversion factor used for the horizontal to vertical convergence transformation was the Poisson’s Ratio of 0.25. For example, a measurement of 100mm in horizontal fender dilation will be equivalent to 25mm in vertical fender shortening (compaction).

The stiffness which is the slope of the resulting load versus vertical deformation for two different fender widths is presented in Figure 10. Although there is some scatter in the results it is quite clear that substantially different fender behaviour (different stiffness) has been measured for the two varying width fenders namely 8.0 and 10.5m. At the extraction site observations show that consistent mining and geological conditions (fenders spaced no more than 20m apart) prevailed and therefore the only differentiating factor is the fender width. Based on the introduced stiffness estimation method, the following points were concluded:

- the local stiffness of the fender is directly proportional to the fender width for a given set of geological conditions.
- The variation in the fender stiffness among different collieries is responsible for dissimilar fender performance.

Extraction with a narrow fender was practised at Blackwater (high stiffness) over many years. At Charbon, however, narrow fenders were generally regarded as unsuitable and this is borne out by the relatively low fender stiffness.
Stress Abutments

The occurrence of higher stresses in pillars adjacent to fully extracted areas of coal scams has been recognised for about 50 years when the “pressure arch” theory was evolved, (see for example Wardell, 1968, Britton, 1980, Hebblewhite, 1986). Within the arch, de-stressed ground was believed to occur and the maximum width was generally held to increase approximately linearly with increasing depth (Wardell, 1968, p.636).

Most of this work, however, was based on longwall extraction panels and yield pillars, and the theory was much hazier as applied to panel and pillar layouts.

Hams (1974) suggested that pressure arch theory could be applied to Wongawilli extraction, with the main arch bridging across on to the solid coal (see Figure 11). Shepherd and Chaturvedula (1991) suggested that this was not the case with a 9m wide fender that was found using instrumentation, to carry high load. The recent work reported in this paper supports the view that the fender is not extracted in a “de-stressed” zone unless it is narrow and yields. The School of Mines (1993) has also commented on the strength and greater stiffness of wider fenders attracting more load than those at a width of ≤ 7m.

Fender Guideline

Based on measured seam stresses, practical mining experience and safety considerations it is proposed that fender w:h ratios can be varied according to depth of working as shown in Figure 12. It must be emphasised that this represents a guideline only and is based on fender instrument results and observations across more than 30 collieries. Numerous factors are not accounted for, such as coal strength, panel width and local geology.

If narrow fenders are used without regard to depth, then they may yield and produce unstable roof conditions. Experience has shown that fender width is an important issue and “crush” has often resulted in unstable split and intersection roofs. If a fender starts to “crush” then lifting back to the stock “x” is precarious.

Conclusions

Provided the split centres and thus fender width is appropriately designed to suit the coal seam conditions, Wongawilli extraction can be safe with stable conditions. Fenders with w:h ratios of <2.5 cannot always be relied upon to maintain stable roof and rib conditions. Wider, stronger and stiffer fenders support the split roof better and resist encroachment of the goaf from the split across the fender, a deleterious process known to occur with narrow and yielding examples.

The use of remotely controlled continuous miners and mobile roof supports assists the use of wider fenders, but with the present generation of miners and shuttle cars, fenders wider than 11-12m are unsuitable because of the distance from the split
roof support to the rear of the miner that may expose the shuttle car operator to unsupported roof.

Instrumentation is a powerful and practical tool for designing pillar extraction investigations. During fender extraction, conditions often change suddenly and the capability of monitoring these has very useful applications.

Acknowledgments

This paper is based on studies at ACIRL funded by the ACARP/AMIRA research program, Project No. 1603 during the period 1990-93 and by a number of collieries subsequently supporting one of us (JS). In particular, Charbon and Laleham No.1 management and engineers provided the sites and the logistical support for which we are very grateful. Special help came from Bill Irvine (manager, Charbon) and Richard van Laerden (then at Blackwater). Bob Hedger installed much of the instrumentation.

References


Hams, A., 1974. Coal production and research policy (lecture 9), statement from Australia, 2nd Int. Conf. on coal research, London, U.K.


Joint Coal Board, 1972-73, 26th Annual Report, extraction methods - “Wongawilli” and “Old Ben” systems, Appendix 7, pp.224-229.


School of Mines, University of New South Wales., 1995. Strata Control newsletter No. 7, pages 1-6


References


Table 1. Summary of Charbon fender stress ($\sigma_v$), MPa and extensometer results, displacement (mm), instruments monitored into the goaf.

<table>
<thead>
<tr>
<th>Fender width (m)</th>
<th>Prior to splitting</th>
<th>Splitting</th>
<th>Lifting off</th>
<th>End of lifting off</th>
<th>Stook in goaf</th>
<th>Splitting for next fender</th>
<th>Lifting next fender</th>
<th>Stook crushes in goaf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_v$</td>
<td>displ.</td>
<td>$\sigma_v$</td>
<td>displ.</td>
<td>$\sigma_v$</td>
<td>displ.</td>
<td>$\sigma_v$</td>
<td>displ.</td>
</tr>
<tr>
<td>8.0</td>
<td>1</td>
<td>15</td>
<td>1-1.5</td>
<td>68</td>
<td>1.5-3.0</td>
<td>70</td>
<td>4</td>
<td>113</td>
</tr>
<tr>
<td>10.5</td>
<td>1-1.5</td>
<td>7.5</td>
<td>1.5</td>
<td>14</td>
<td>1.5</td>
<td>21</td>
<td>1.5-2.0</td>
<td>30</td>
</tr>
<tr>
<td>13.0</td>
<td>&lt;1</td>
<td>7</td>
<td>1-1.5</td>
<td>13</td>
<td>2</td>
<td>13</td>
<td>3.5</td>
<td>25</td>
</tr>
</tbody>
</table>

* small stook left

Note: extensometer stopped working before pressure cells
Figure 1. Use of a coal fender as a barrier at the goaf edge, A and B are “open-ended” lifts in the 1950’s, C is Wongawilli or Split and Lift methods and D is modified Wongawilli lifting left and right from the Split.
Figure 2. Pillar extraction layouts monitored using instrumentation.
A. South Blackwater (Laleham No.1) Colliery, Wongawilli method.
B. Charbon Colliery modified Wongawilli method leaving central panel pillars.
Figure 3. Location of instruments at Charbon Colliery showing details of fender lifting sequences, sketch map only.
Figure 4. Measured fender vertical stress at Charbon Colliery: 8m, 10.5 and 13m fenders compared.
Figure 5. Measured fender dilations measured by pillar extensometers at Charbon Colliery: 8m, 10.5m and 13m fenders. Note much lower dilations in the wider fenders.
Figure 6. Summary graph comparing the stress and horizontal dilation in the Charbon fenders.
Figure 7. Uniaxial (vertical) stresses measured in Lakham No.1 Colliery Wongawilli fenders according the mining sequence during splitting and lifting. Explanations are in the stress diagrams A-G related to the sketch map.
Figure 8. Measured dilations of Leahein No. 2 (F2) during spilling and
Hilting. Fender No. 1 yielded to a depth of 1.5m (second day).

Figure 10. Distributions of the load for different depths.

Elapsed time (days)
0.00 0.06 0.12 0.18 0.24 0.30 0.36 0.42
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
0.00 0.04 0.08 0.12 0.16 0.20 0.24 0.28

0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14

0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07

0.00 0.005 0.01 0.015 0.02 0.025 0.03 0.035

0.00 0.001 0.002 0.003 0.004 0.005 0.006 0.007

0.00 0.0005 0.001 0.0015 0.002 0.0025 0.003 0.0035

0.00 0.0001 0.0002 0.0003 0.0004 0.0005 0.0006 0.0007

0.00 0.00005 0.0001 0.00015 0.0002 0.00025 0.0003 0.00035

0.00 0.00001 0.00002 0.00003 0.00004 0.00005 0.00006 0.00007

0.00 0.000005 0.00001 0.000015 0.00002 0.000025 0.00003 0.000035

0.00 0.000001 0.000002 0.000003 0.000004 0.000005 0.000006 0.000007

0.00 0.0000005 0.000001 0.0000015 0.000002 0.0000025 0.000003 0.0000035

0.00 0.0000001 0.0000002 0.0000003 0.0000004 0.0000005 0.0000006 0.0000007

0.00 0.00000005 0.0000001 0.00000015 0.0000002 0.00000025 0.0000003 0.00000035

0.00 0.000000005 0.00000001 0.000000015 0.00000002 0.000000025 0.00000003 0.000000035

0.00 0.0000000005 0.000000001 0.0000000015 0.000000002 0.0000000025 0.000000003 0.0000000035

0.00 0.00000000005 0.0000000001 0.00000000015 0.0000000002 0.00000000025 0.0000000003 0.00000000035

0.00 0.000000000005 0.00000000001 0.000000000015 0.00000000002 0.000000000025 0.00000000003 0.000000000035

0.00 0.0000000000005 0.000000000001 0.0000000000015 0.000000000002 0.0000000000025 0.000000000003 0.0000000000035

0.00 0.00000000000005 0.0000000000001 0.00000000000015 0.0000000000002 0.00000000000025 0.0000000000003 0.00000000000035

0.00 0.000000000000005 0.000000000000001 0.0000000000000015 0.000000000000002 0.0000000000000025 0.000000000000003 0.0000000000000035

0.00 0.0000000000000005 0.0000000000000000001 0.00000000000000000015 0.0000000000000000002 0.00000000000000000025 0.0000000000000000003 0.00000000000000000035

0.00 0.00000000000000005 0.000000000000000000001 0.0000000000000000000015 0.000000000000000000002 0.0000000000000000000025 0.000000000000000000003 0.0000000000000000000035

0.00 0.00000000000000000000005 0.0000000000000000000000001 0.00000000000000000000000015 0.0000000000000000000000002 0.00000000000000000000000025 0.0000000000000000000000003 0.00000000000000000000000035

0.00 0.000000000000000000000000005 0.000000000000000000000000001 0.0000000000000000000000000015 0.000000000000000000000000002 0.0000000000000000000000000025 0.000000000000000000000000003 0.0000000000000000000000000035
Figure 9. Detailed cross sections of Lalcham Noll colliery fender 2 (F2) and the solid coal showing yielding and vertical stress measured during extraction. A and B show "typical" stress profiles for a narrow barrier at the goaf edge when F2 was at lift 7 (cf. Figure 7) and the fender partly extracted. C and D show a stress increase and shift of the peak stress towards the solid coal up to the time of extraction of F2 to the stock.
Figure 10. Stiffness comparison for Charbon fenders at different widths.

Increase in stiffness due to increase in fender width.
Figure 11. Front abutment stress profiles for Wongawilli extraction. A model proposed by Hams (1974) and B. revised model proposed based on recent studies.
Figure 12. Fender design triangle (based on empirical data and observations).