STRATA MECHANICS OF PILLAR EXTRACTION GOAF EDGES

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ABSTRACT
Pillar extraction carried out using various methods (split and lift, Mongavelli and Old Ben) involves the formation of narrow fences (commonly 7 m of coal) formed by driving "splitters" few lifting off with a continuous miner.

The strata above a split and fender adjacent to the goaf consists of a single-layer beam (usually 2-3 m thick) that extends from the solid coal and bridges across the fender. Lifting off the fender from the split in safe conditions depends upon the bridging capability of the cantilever and the fender strength. The nature and competence of the immediate and near roof, the support capability of the coal fender, and the presence of faults and or joints can adversely affect the bridging behaviour of the cantilever. Insufficient knowledge of these parameters can lead to extraction under dangerous conditions.

Remnants of fencers ("stockia") also support the cantilever and WADAL SUBSTATIONS are critical to obtain regular caving and goaf falls. Stock area, goaf roof span and roof stand-up time after lifting can be related and only a relatively small increase in stock area of 30-15 m² can lead to a significantly increased stand-up time, especially under a massive roof. Such conditions strongly influence the redistribution of abutment stress and can create increased outbye pillar loading.

Based on detailed underground geotechnical investigations, it is concluded that strata competency, roof cantilever behaviour, fender SW ratio and remnant stock area are critical parameters for successful and safe pillar extraction.

INTRODUCTION
The development of underground "Bord and Pillar" coal extraction methods took place largely by trial and error over a long period of time (40 years) and without the benefit of现代 rock mechanics techniques. In Australia, where until about the early 1960's, pillar extraction was the mainstay of coal production, different methods had been developed to suit a variety of strata conditions at depths ranging down to 500 m.

As well as the need for high productivity, the safety of extraction methods has been an ongoing concern and has lead to the local invention of the Mongavelli system of extraction and the adoption of modified versions of the Old Ben System from the USA (Shepherd & Chaturvedula, 1991).

Except for some earlier and limited work by ACRL engineers (notably Sybala [1962], Humphrey [1988] and Nixon et al [1988]) and CSIRO (Wardle and McNabb [1985]), the geomechanics of Australian pillar extraction had remained largely uninvestigated. This paper presents detailed results, based on extensive underground geomechanical instrumentation of numerous pillar extraction panels and identifies the critical elements required for the design of safe pillar extraction. These underground measurements were made using a suite of novel devices, designed especially for use at the goaf (gob) edge.

MINING METHODS
All modern pillar extraction methods involve the formation of a long, narrow pillar (or fender) between the working place and the goaf. A review of these working methods is given by Sleeman [1966], and the history of the development of the Mongavelli System by Shepherd and Chaturvedula [1991]. Outline plans of these methods are given in Figure 1.

One of the recent high production variants of the Mongavelli System in current usage is shown in the plan in Figure 1b. Such a system, termed "modified Mongavelli", involves extracting a wider block of coal on both sides of the entries and arranging the split centres generally on a 20 or 21 m spacing. This facilitates lifting off left and right a fender on the goaf side and some coal from the solid pillar. The roof spans opened up on retreat are thus considerably wider than in the traditional system (25 m in contrast with 12 - 15 m).
TELEMETERING

In the past, attempts to quantify the strata mechanics of the environment in pillar extraction have been few. Even these were largely confined to stress measurements in sandstone (Shephard and Chattervedula, 1971).

Roof and pillar displacements (movements) had not been measured in the crucial lifting cycles in a fender, although considerable work was carried out at Collinsville by Davidson (1983). He and other workers had found the main drawback in goaf edge instrumentation to be the lack of devices that could be read from a safe distance, but he had certainly seen the need for this prior to goaf falls.

A review of available instrumentation technology was carried out by us in 1987 and it was found that the US Bureau of Mines had been active in the development of various devices for use in coal extraction panels. McVey and David (1993) discussed some details of a tele-testing potentiometric extensometer designed to be remotely read and provide warnings at the goaf edge. Later, Maks and McVey (1993) described a range of instruments for use in pillar extraction and longwall panels. Their aim was to detect impending roof falls by remotely-read instruments. Their review and findings (p.7, Table 1) indicate that convergency measuring devices were the most suitable as compared with micro-seismic and ultrasonic devices trialled. They present results from telescopic convergency rods and a type of short extensometer, termed a 'convergency'. An example of closure measurements using a convergency rod during pillar lifting (robbing) (Figure 3, p.5) shows similar results to those mentioned in this paper. Their main conclusion was that "the detection of critical rate of movement has been shown to be an effective tool in ground control efforts".

Based on this information remotely-read convergency rods and roof and pillar extensometers were developed for measuring displacements using resistance potentiometers and power supplied by an approved (16) multimeter. Novel resistance wire extensometer units were devised using mounting sections made of PVC tubing and PVC anchors. A full description of these is given by Shephard et al (1990).

These dimensional stress changes were measured using CSM (Cyclically Hollow Inclined stress cells (also remotely-read) inserted into the mine roofs above pillar and fenders.

The instrumentation was monitored as it receded out into the goaf ensuring that a complete history of stresses and displacements was recorded throughout the extraction cycles and through to pre-goaf fall condition.

FENDER STABILITY

The geotechnical environment at the goaf edge in a pillar extraction panel is probably one of the most complex of those encountered in an underground coal mine. The extraction of coal from the fender gradually reduces the amount of support offered to the roof by the fender. Consequently, the stability and hence the safety of the working area is determined to a large degree by the reaction of the roof to this loss of support. However, the stow left at the end of the fender design are ideally being designed to gradually crush out under the load of the roof does offer a certain amount of support immediately after its formation.

The fender can thus be regarded as the most important support element during extraction. As such the efficiency and safety of the extraction layout depends upon the correct estimation of the possible loads imposed upon the roof by the fender. In turn this allows the choice of the optimum fender width for the given conditions. As mentioned earlier, choice of fender width in Australian collieries was by trial and error, partly due to the lack of modern geotechnical instrumentation and methodology. Recently it has been determined largely by the operating ranges of modern continuous miners. However, an effort has been made in this paper to verify the suitability of the traditional 'ultimate strength approach' of pillar design in estimating the relative stability of a typical fender.
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As an example, the WiH ratio of a fender at a colliery in the South-Western Coalfield (NSW) is 4.0. Using Salomen’s (1991) formula for the estimation of pillar strength or Hardy and Agapito’s (1977) approach, the strength of this fender is in the range of 12-15 kPa. It is appreciated that the application of these formulas to fenders does have its limitations. Based on the virgin vertical stress at 400 m of 10 kPa reduced by 25% to allow for unknown goaf influence and adding the 6 kPa stress change (measured) then sub-vertical roof stress would be in the region of 12 kPa and thus fenders would highly loaded. Visual observations of the fenders and extensometers both suggested that the vertical load on the fenders was close to their ultimate strength.

In order to use the WiH ratio of a fender as a criterion for more effective design, an effort has been made to relate the total vertical stress on the fender (vir gin vertical stress plus measured maximum stress change) and the WiH ratio of the various fenders studied to their stability. The data obtained as far as are plotted in Figure 2. The stability fields marked in Figure 2 are qualitative, but they are based on underground measurements and observations. More data is needed to establish definite relationships. However, a WiH ratio of 3.0 is the minimum for a “stable” fender in the range of mining depths investigated.

In this context, historical Industry-wide experience has shown that narrow fenders (≤3m) and 2.5-3.0 m high are prone to excessive premature “crushing” and inbuilt safe extraction. Conversely few stability problems have been experienced with wider fenders (≥5m) and 2.5-3.0 m high. As successive lifts reduce the length of the fender to the dimensions of that approaching a stow, then high vertical loads are imposed upon it. If premature overloading and “crushing” occurs then the mining crew is invariably “chased out”. This is common with 5-7 m wide fenders. A wider fender offers increased roof support and greater resistance to crushing. Further, the fender-end stock (commonly known as “stock x”) dimension can be regulated without adverse incidents.

GOAF EDGE ROOF

Three principal types of strata commonly occur in Eastern Australian collieries: Massive roofs, typically sandstone; bedded roofs composed of mudstone and laminated rocks consisting of coal, mudstone and shale.

Independent of the method of extraction, the consequence of lifting off coal is the formation of a beam, supported at one end or either by the wet to be extracted fender or by a pillar of solid coal and supported by a relatively thin stock at the other end or, in many cases, not supported at all. This beam behaves as a beam with the dimensions of which vary according to the roof capability. Under ideal extraction conditions this cantilever beam will hinge above the closest solid pillar immediately outside of the goaf edge and this “hinge” is the breaker line for future goaf falls.

Extraction of fenders takes place beneath the cantilever beam and safety of the split and lift roof is largely dependent on:

1. the ability or otherwise of this beam to span across the length of the lift
2. the amount of support that the wet to be extracted fender or solid pillar can offer to this cantilevering beam and
3. the relatively low, yet in some cases quite substantial support offered by he stock at the other end of the cantilever.

A conceptual cross-sectional view of the goaf edge is shown in Figure 3. The height of most beams is in the range of 3-5 m for initial goaf fall caving. This has been determined from roof extensometer measurements.

If extensive cantilevering beams form during extraction (common in massive sandstone roofs) then tensile cracking is the upper portions of a beam gives way dynamically to compression in the immediately...
Figure 3 - Roof cantilevering and extraction of the fender under the vertical stress abutment.

Vertical stresses can increase several fold from the influence of large beams and this is the front abutment (Shepherd and Chaturvedula, 1981).

The location of compressive stresses in such a beam is important for stability, because in many cases in bedded and laminated roofs, shearing occurs in the splits as lifting off proceeds due to the beam 'hinge line' directly above the split. This hinge line is generally the 'breaker line' in subsequent goaf falls.

HORIZONTAL STRESSES

In Worongiri extraction 3-D stress measurements have shown that there is often an increase in horizontal compressive stress perpendicular to the goaf edge up to a position about 25 m from the caving edge and due to formation of the cantilever. Keefer to the goaf these stresses unload as the cantilever begins to fail and depend on stocks for support. For 'split and lift' extraction, however, such compressive stresses increase generally as the adjacent pillar row is extracted and cantilevering begins. These stresses stay higher until the adjacent pillar in the same row is taken and then relief occurs.

GOAF BREAKER LINE

The position of the cantilever hinge line is generally a function of a number of variables such as, roof type (massive or laminated), the presence and size of stocks left and the dimensions of the fender, split and outbye intersection. For 'split and lift' extraction (on the hinge or breaker line) will align diagonally across the workings (see Figure 4A) from the corners of the nearest solid pillars. If ten large stocks are left behind or the area of the 4-way intersection near shaft 'm' is too large, then a typical 'safe' breaker line at b\(^{-}b\) can become unsafe as in b\(^{-}b\) or worse as in b\(^{-}b\). The difference between these cases is especially critical for massive sandstone roofs.

The position of the breaker line is also influenced by roof jointing if the

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ROOF STAND-UP TIME

Remotely read telescopic convergence rods were used to measure roof to floor closure between the completion of a particular lift in a tender and the occurrence of a goaf fall. A typical plot of cumulative closure and closure rate is shown in Figure 6. Over a measure of increase in support for the cantilevering beam. Figure 8 shows that there is a large effect of increasing stock size (area) for massive roofs and less for laminated roofs. Large stand-up times, measured in HOURS, shifts of 240 days are detrimental to safe pillar extraction. An increase in area of stocks of 20 m² under a sandstone roof can be expected to increase the stand-up time by about 300 minutes (5 hours).

Figure 6 - Pre-fall convergence measurements at the goaf edge.

50 substantial goaf falls have been monitored using these rods. In addition, the timing and magnitude of roof displacements were measured using roof extensometers. A typical pre-goaf fall plot of bay movements is given in Figure 7. In this case the thick coal roof (5-6 m) of the Wongawilli seam only saga 25-30 mm prior to failure.

INFLUENCE OF STOCKS

The most important aspect of standing “goaf” roof is its stand-up time. Where instrumentation was used, detailed sketch maps of the workings were prepared on site. This enabled reasonably accurate estimates to be made of a number of parameters such as roof area standing, stock area and roof stand-up time. If the roof ‘hangs up’ for a while then as the roof area increases so does the stock area too. It is, therefore, possible to compare stand-up time with increase in stock area (which is in effect a sandstone roof can be expected to increase the stand-up time by about 300 minutes (5 hours).

CAVING ASPECTS

It is clear that the roof type and depth of cover are critical factors influencing caving angle. The angle is particularly significant in relation to safety and goaf fall magnitude. Idealised sketches are shown in Figure 8. Massive roofs at shallow depths cave at angles as low as 20° and are liable to propagate by flexural shear and tensile cracks along the bedding - even massive roofs tend to have some bedding anisotropy. Such low angle caving produces so-called “feather edge” breaker lines that overrun breaker props and create unsafe conditions. The overall caving pattern of the strata up to the surface has not been investigated so far.

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EVALUATED TIME, DAYS
- 5.5m to 5.4m
- 5.4m to 4.9m
- 4.9m to 2.3m
- 2.3m to 1.0m
- 1.0m to 0.3m

Figure 7 - Roof movements recorded by an extensometer leading to rapid sag prior to a goaf fall.

Figure 8 - Roof roof stand-up time according to stock area increase.

STOCKS
Remnant stocks are the remains of the coal fender left ideally to support the cantilevered roof just sufficiently to permit extraction and then fall or "crush" quickly (Figure 4A). There are stocks, however, for different purposes, most should be as small as possible and others protecting key intersections should be geotechnically designed. This is analogous to the need for "purposful" design of pillars as recently discussed by Salamon (1992).

Too many and too large stocks carry the penalty of over-supporting the roof cantilever beam and increasing stand-up times and consequently redistributing the vertical stresses (also magnified by cantilevering action) loading the outbye pillars and fenders.

High vertical loads have been measured in stock 'z' at several sites where peaks as high as 20-30 MPa have been found. Extensometers in fenders eventually preserved in stocks also showed extensive displacements. A stock measured in Figure 10 was 8 m wide and about 9-10 m long and although deeper movement had occurred to a depth of 1.76 m a small core remained transmitting load and resisting the unfallen roof.

Reducing the dimensions of stocks is a continuous process. In some cases, it can be done safely and is advantageous.

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subsequent behaviour at the way edges in pillar extraction had hitherto been only sketchily examined. Using a suite of sophisticated geotechnical instruments such as the CHI20 R1 cables, resistance wire extensometers and convergometer rods (all remotely read) the strata behaviour at the goaf edge has been thoroughly investigated. This instrumentation, some of it novel and fabricated in-house, was used to measure stresses and displacements in the roof and pillars into the goaf to evaluate pre-fall conditions.

From a geotechnical standpoint all these methods use a fender that is lifted off and systematically reduces the support to the cantilever beam roof. The caving ability of the goaf roof, the bridging capacity of the split and fender roof and the stability of the fender itself are all key elements in pillar extraction. Successful extraction is only achieved by regular caving.

Cantilevering is the principal mode of roof behaviour prior to a goaf fall. The cantilever beam hinge line is effectively the breaker line for caving, its location and the panel angle influence the safety of extraction. A sudden and sustained increase in convergence rate between the roof and floor in the goaf is a reliable indicator of an impending goaf fall. The roof at stand-up times have been measured and are largely dependent upon the nature of the roof and the size and nature of remnant stocks. Leaving large stocks in the goaf is wasteful and prevents regular, safe caving.

The width of the fender is another important parameter determining the safety and efficiency of extraction. The W/H ratio of the fender has been identified as a design criterion. In the R128 studies extraction was found to be generally safe where the W/H ratio of the fender was between 2.5-4.0, depending upon the depth. It is concluded that more detailed investigations are required to evolve more specific guidelines for fender design. However, fenders with a W/H ratio ≤ 3.0 should provide safe conditions. It should be emphasised that the fender W/H ratio must be evaluated in conjunction with other design parameters.

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CONCLUSIONS

Several pillar extraction methods have been investigated, including split/lift, modified Old Bon and modified Wongswilli. The mechanism of the formation and

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Figure 10 - Panel and stock movements recorded by a pillar extensometer (PEI) during extraction (inset map shows sequence).

Figure 11 - Intersection roof movement recorded by a roof extensometer (PEI) during reduction of stock 61 to promote improved caving (see inset map for details; extraction using modified Wengawilli).
REFERENCES


