Numerical Modelling of a Monitored Site in an Underground Coal Mine in the Bowen Basin

by

M.E. Duncan Fama¹, R. Trueman¹ and T.P. Medhurst¹

ABSTRACT

The aim of the paper was to model numerically some aspects of the extraction of coal pillars by split and fendering. A two-dimensional elastic-plastic plane strain model with strain softening and interface modelling was used. The model was able to simulate the improvement of conditions experienced in lifting from the fender, when the roof adjacent to the fender has caved. In contrast, when a stope was left, providing support to a span of uncut roof, the model predicted the fender would suffer considerably more deformation and strain.

INTRODUCTION

A companion paper, Edlington et al. (1992) describes the design, commissioning and utilization of a breaker line support (BLS) monitoring system. The system was designed to record hydraulic leg pressure and canopy position measurements and relay these, in real time, to the surface. The system is shown in Figure 1.

The mining method required a split to be driven through the pillars, which resulted in the formation of a fender (see Figure 1). This fender was subjected to high stresses so that it yielded and shed stress. As it was progressively extracted, the remnant yielded further and its capability to carry stress was further reduced. The ability to quantify this stress in a numerical model requires a knowledge not only of the geometry and the extraction process, but of the yield conditions of the coal, roof and floor and their constitutive behaviour.

This situation was clearly three-dimensional, because as the fenders were lifted, the resulting stress deficiency was carried by neighboring structures in both horizontal dimensions. It was decided, however, that a preparatory two-dimensional study would be useful to highlight requirements for future full-scale modelling, and to gain insight into the mechanisms of yield and deformation. A full description of the mine site, the mechanized mining method and some of the problems encountered by the mine are to be found in Edlington et al. (1992).

THE MODEL

A two-dimensional elastic-plastic model was employed to explore possible mechanisms of yield and deformation in the fenders, as well as their post-peak load-carrying capability and strain deformation in the roof and floor. The model used was a CSIRO developed package called FESOFT, with the graphical input and output produced by the interface, FEMIND.

FESOFT is a two-dimensional finite element code which was developed by CSIRO Division of Geomechanics to model yield zones in rock, especially coal and coal measures, Duncan Fama and Craig (1992). FESOFT can provide a stress and displacement distribution for any cross-section of a mine plan, taking into account both yield zones and intact core structures. The mathematical theory on which the yield zone modelling is based is a deformation theory of plasticity as described by Kachanov (1974). The problem in plasticity has been shown to be equivalent to an elastic problem where the yielded regions have a reduced Young's modulus and a modified initial stress. An iterative technique is used to calculate the modulus reductions necessary to satisfy the Mohr Coulomb yield criterion postulated for the material and the displacements and stresses are found by solving the equivalent elastic problem. The mathematical background to the model is described in Duncan Fama (1992). Strain softening is incorporated in the analysis.

MODEL CONFIGURATION

Figure 1 shows in plan view one of the problems encountered in the extraction of fenders, namely.group "flushing" after yielding of remnant fenders. This term refers to the unraveling of the roof as it cavers, so that the debris fuses into the working area.

The pillar extraction sequence modelled was the mining of part of what remains of the pillar (the last five units on the right of the figure, labelled as in Table 1).

¹CSIRO Division of Geomechanics, Brisbane, Australia.

11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1992.

151
Duncan Pama, M E, Traemar R and Medhurst T P.

![Diagram](image)

Figure 1: Yielding of Remnant Feeder Allowing Flushing of Goaf

<table>
<thead>
<tr>
<th>Fender 1</th>
<th>Split 1</th>
<th>Fender 2</th>
<th>Split 2</th>
<th>Fender 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 metres</td>
<td>6 metres</td>
<td>7 metres</td>
<td>6 metres</td>
<td>7 metres</td>
</tr>
</tbody>
</table>

Table 1: The Pillar Extraction Sequence

Figure 2 shows the detail of an elevation through the region to be modelled. This figure shows just a cross-section through the pillar to be extracted, which was at a depth of 150m. The figure shows the remaining part of the pillar divided into the three fenders and two splits described above. The sequence of extraction is described below. The whole region modelled extended to the surface above, to 40m below the seam (where the boundary was constrained from displacement in the vertical direction) and 140m to the left and right of the pillar. The goaf on the left (which was 94m in height) extended for the full 140m, and was divided into three equal regions of low stiffness material. The stiffness of each block increased into the goaf such that the vertical stress in the most distant region reached cover stress. The unmined coal seam to the right of the pillar was also approximately 140 metres wide, so that again the vertical stress went to cover stress on the right hand boundary of the region. Both boundaries were constrained against horizontal displacement (to prevent bending of the whole region into the low-stiffness goaf). The analysis was done by unloading in situ stresses from excavations, not by loading outer boundaries of the mesh. The assumed in situ stresses in each unit of the medium are shown in Table 2.

In Figure 2, the two windows shown on the right hand side allow the geology of the section and the material parameters to be entered interactively.

The analysis was performed in seven increments as follows: (see Figure 2):

Increment 1: The existing roadway (on the right) and the first split only were driven.

Increment 2: The lifting of fender 1 (on the left) was simulated by firstly removing the left hand third of this fender (black).

Increment 3: The usual stock remaining from this fender was simulated by removing the middle third of this fender (grey), so that the fender was reduced to one-third of its original size (black).

Increment 4: Two cases were now modelled for the mining of the middle fender:

Case (a): crushing of the stock and caving of the roof above; it was modelled by removing all this material from the mesh.

Case (b): the modelling proceeded with the stock and roof above it still standing.

The increments that follow were identical in both cases:

Increment 5: The middle split (split 2) was driven (grey).

Increment 6: The lifting of the middle fender (fender 2) was simulated by firstly removing one third of this fender (black) - by removing 1.1667m from each rib.

Increment 7: Fender 2 was reduced to one-third of its original size (black) by removing another 1.1667m (grey) from each rib.

Table 2 shows properties of the strata used for the modelling. These were obtained from data supplied by the mine. \( \phi \) is the Dilution Angle.

Note that the cover stress has been reduced from 3.6MPa to 1.7MPa in an attempt to compensate for the fact that in the three-dimensional situation the load deficiency of the goaf and the mined areas are often shifted to abutments in the third direction. The stock and the fenders as they were mined did not extend indefinitely in the third direction as the two-dimensional model assumed. This level of reduction was inferred from the results of a previous comparison of the stress levels predicted by two and three dimensional modelling, Duncan Pama and Craig (1991).

Three parings are modelled as shown in Figure 2. Details of their normal and shear stiffness will not be included here as they vary with shear and tensile yield of the parings. It should be noted, however, that the determination of suitable values for these parameters is still a matter of trial and error in numerical models and presents a major difficulty where there are...
Table 2: Geomechanical Properties used in the Study

<table>
<thead>
<tr>
<th>Strata Type</th>
<th>Young’s Modulus (MPa)</th>
<th>Poisson’s Ratio</th>
<th>Vertical Stress (MPa)</th>
<th>Horizontal Stress (MPa)</th>
<th>Triaxial Failure Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interbedded Silites</td>
<td>5,600</td>
<td>0.2</td>
<td>1.7</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>2,800</td>
<td>0.24</td>
<td>1.7</td>
<td>1.2</td>
<td>1.73</td>
</tr>
<tr>
<td>Siltstone</td>
<td>1,700</td>
<td>0.2</td>
<td>1.7</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>10,000</td>
<td>0.25</td>
<td>1.7</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Coal 1</td>
<td>50</td>
<td>24</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Coal 2</td>
<td>80</td>
<td>24</td>
<td>0.36</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Coal 3</td>
<td>130</td>
<td>24</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Detail of Modelled Region

11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1992.
several interfaces or partings to be modelled.

Yield in the coal only was modelled, the other strata being treated as linear elastic for this exercise, since we are concerned with bending of the roof strata leading to fracture not yield.

The yield criterion assumed for the coal was a Mohr-Coulomb one. The form of the yield criterion was as follows:

\[ \sigma_1 = \sigma_2 + \sigma_3^*, \]

where

\[ \sigma_3^* = \sigma_3 - (1 - \exp^{-\gamma h})(\sigma_c - \sigma_3^*) \]

with \( \delta = 0.01 \). Here, \( \sigma_1 \) and \( \sigma_3 \) are the major and minor principal stresses respectively in the vertical plane, \( \sigma_c \) is the pre-failure, \( \sigma_3^* \) is the residual post-failure, unconfined compressive strength of the rock and \( k \) (triaxial strength) is related to the angle of internal friction (\( \phi \)) of the rock:

\[ k = (1 + \sin \phi)/(1 - \sin \phi). \]

\( \gamma \) is the total plastic shear strain. The reduction in unconfined compressive strength with total plastic strain given by equation (2) is shown in Figure 10.

The cohesion \( c \) of the rock is related to \( \sigma_c \) and \( \phi \) by the following:

\[ c = \sigma_c \tan \phi/(k - 1) \]

It was assumed that the stress in the out of plane direction was a principal stress and was intermediate in value between \( \sigma_1 \) and \( \sigma_3 \). It was further assumed that \( \sigma_3 \) was limited by a maximum value for tension. The pre- and residual post-failure yield criteria are shown in Figure 9, where plotted points from the feeders and the barrier coal have been included.

RESULTS

Finally results are presented of the deformed mesh with yielded regions darkened. The colour legend to the right of the plots represents a measure of the reduction in the Young's modulus in the finite elements of the mesh.

For each of Increments 5, 6 and 7 the results showed that the feeder had undergone considerable more deformation for case b) where the stock was still standing. The modelling confirmed the experience of the mine in this respect.

Figures 3 and 4 show the deformed mesh (with yielded regions darkened) for Increment 6 and for case a) and b).
MODELLED STRESS DISTRIBUTION

The two dimensional vertical stress distribution in stocks, fenders and abutments from cases a) (without stock and unexcavated span) and b) (with stock and unexcavated span) are presented in Figures 5, 6 and 7 respectively. The importance of the yield modelling in the fenders is demonstrated by the contrast between Figures 5 (which is totally unrealistic) and 6. Although high stresses are noted in the core (centre line) of yielded fenders the average stress on the most deformed fenders are less than half the average peak stress. Note the average vertical stress carried by fender 3 in case a) is more than the average vertical stress in case b). The average vertical stress vertical strain curve for the fenders can be seen in Figure 8. Here the strain has been averaged over all elements of the respective fender. As more roof to floor closure has occurred in case b) the fenders are further down the post peak stress strain curve and inherently less stable. This can lead to good flushing around the fender under extraction, Fillingon et al, 1995.

Figure 5: Vertical Stress Distribution at Increment 5 with goafing

Figure 6: Linear Elastic Vertical Stress Distribution at Increment 5 with goafing

Figure 7: Vertical Stress Distribution at Increment 5 with stock standing

The numerical modelling shows that the average vertical stress vertical strain curve for the fenders, Figure 8, is an outcome of the assumed pre- and post- failure yield criteria and also is highly dependent on the fender width. Where the middle fender width has been reduced, as in Increments 6 and 7, the average post-peak stress of the fender is substantially

11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1992.
reduced (about half for Increment 6 and half again for Increment 7). The average strain increased very little, probably because of the initial confined state of the core.

The post-peak deformation response of coal pillars has a marked influence on the load-carrying capability of fenders. The determination of values for these parameters for coal at mass size is difficult. Even were this to be well-known, it has been emphasized above that this stress-strain behaviour cannot be input directly to the model. Yield and post-peak stresses in the fenders and pillars are determined by the assumed yield criteria, so by the Mohr-Coulomb parameters and the geometry.

Figure 8: Average Fender Vertical Stress versus Strain

![Graph showing Average Fender Vertical Stress versus Strain.](image)

Figure 9: Pre- and Post-Failure Yield Criteria

The resulting stress-strain behaviour of any particular structure (eg the fenders here) can be determined by averaging over the elements of the fender - as has been done here. If this stress-strain behaviour differs from the known or inferred behaviour, the triaxial yield criterion parameters (pre- and/or post-) can be altered and the model rerun to obtain a new estimate of the stress strain behaviour. This "back analysis" (which may employ systematic techniques developed for the determination of input parameters of geomechanics to fit measurements) eventually yields an estimate triaxial yield criterion. Needless to say, the fit to monitoring and observation is only as good as the ability of the model to describe the deformation and yield mechanisms accurately. For this reason, the back analysis was not taken very far for this rather crude study, because the ability of the two-dimensional model to describe the three dimensional situation is definitely limited.

Note that some confusion can arise as to the term "residual strength". Figure 9 shows that virtually all the elements in the fenders lie on the residual post-failure line whereas Figure 8 shows fender 3 in case (a) somewhere between peak and residual strength.

More work needs to be carried out to determine mass mechanical properties if realistic predictive models are to be developed to solve complex geomechanics problems such as that described in the paper. A knowledge of both peak and post peak properties for various pillar widths is required.

Figure 10: Reduction in Unconfined Compressive Strength with Total Plastic Strain

![Graph showing Reduction in Unconfined Compressive Strength with Total Plastic Strain.](image)

CONCLUSIONS

The model has been able to show some aspects of the deformation and yield behaviour of coal fenders. The unloading of the stress from yielding fenders to the unmined pillars is plausible. The excessive deformation caused to a fender by the sagging of a roof plate on to it has also been well-modelled.

What is required now is

- A three dimensional model capable of analysing a reasonable sized area of a mine plan with the capability of modelling
  - yield in the coal and also in roof and floor
  - parting planes, joints and shear zones in the roof and the ability to determine their frictional characteristics
- supports, both roadway support and mechanised supports
- A realistic failure criterion for coal and the ability to determine in situ parameters. It is believed that a Hoek-Brown criterion is more suitable than a Mohr-Coulomb, and this will be used in future modelling.

CSIRO Division of Geomechanics is well on the way to developing such a model and is also addressing the issue of the determination of in situ parameters.

REFERENCES


11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1992.