SIDEWALL FRACTURING IN COAL ROOM AND PILLAR AND PILLAR EXTRACTION PANELS

By André Vervoort

ABSTRACT

In coal room and pillar, and pillar extraction panels, the sidewall conditions were investigated based on underground measurements and numerical simulations. Three-dimensional linear elastic models provided a useful and quick prediction of the amount of sidewall spalling. However, more complex constitutive models were required to simulate more accurately the extent of fracturing and its effect on the stress redistribution. The input parameters of a Mohr-Coulomb model were determined by back-analysis of underground measurements, and the effect of the depth of the workings and the time dependent occurrence of coal pillar fracturing was analyzed.

INTRODUCTION

In room and pillar workings of South African coal mines, the sidewalls and pillar corners can be fractured extensively. During pillar extraction coal fracturing in the remaining pillars can even increase, due to a stress redistribution. From a safety point of view, the amount of spalling is not the only factor to be considered, but the manner in which it occurs and the time of occurrence are equally important. Large blocks falling have to be considered as very dangerous. However, spalling in the form of small pieces also has a negative effect on the overall safety.

1. It can create large overhangs which subsequently fall in large blocks.
2. It increases the roadway width and decreases the pillar width, resulting in lower pillar safety factors.

The aim of investigating the sidewall conditions in room and pillar, and in pillar extraction panels was to learn more about the process of sidewall fracturing, with the final aim of predicting the degree of spalling. Underground observations were combined with numerical simulations. In room and pillar panels the extent of pillar fracturing was measured using a borehole petroscope. In a pillar extraction panel, the pillar corner conditions were classified based on the amount of sidewall spalling which had occurred. This classification was conducted by visual observations. The numerical simulations were based on linear-elastic and on Mohr-Coulomb models. Although a linear-elastic model does not simulate fracturing, it provided a useful and quick means of predicting the amount of sidewall spalling based on the vertical stresses calculated. However, to learn more about the process of fracturing, more complex models were required and a Mohr-Coulomb model was developed.

LINEAR ELASTIC SIMULATIONS

UNDERGROUND OBSERVATIONS

In a coal pillar extraction panel, the four corners of intersections were classified by visual observations. Although this method of classification can be considered to be subjective, provided that it is conducted by the same person, it can be used as a suitable means for comparison purposes. Eight classes of sidewall fracturing and spalling were considered (see Table 1) and the classification was applied to investigate the deterioration of the sidewalls during progressive extraction of the pillars.

In Figures 1.a and 1.b, the pillar corner rating is presented for two mining steps. A continuous miner was used to extract the pillars. One pillar was mined at a time and one row of pillars across the panel (south-north) was extracted before the next row was started. In each row, pillar extraction started at the south side (adjacent to the A intersections). The two mining steps monitored were:

1. Step I: The situation when the work-
As the first row of intersections was closest to the mined out area, the pillar corner conditions around the first row of intersections was poorer than around the second row. In step I, the corners of intersection 1D were in a better condition than those of 1C and certainly than of 1A and 1B. In Figures 2.a and 2.b, the owners of the intersection 1D are represented for both mining steps. In mining step I, only one corner around intersection 1D was classified as moderate to severe spalling. The others were in a better condition. By mining two more pillars in step II, the corner conditions of 1D deteriorated, as illustrated. In the second row of intersections, no significant difference was observed between both mining steps (Figures 1.a and 1.b).
Numerical Simulations
Numerical simulations of the strata in coal mining can be considered as an aid to understand or explain underground phenomena, and as a tool to predict strata behaviour. In both cases numerical simulations are better suited as a means of comparison rather than as a method of determining absolute values.

However, for both approaches, a back analysis and a verification by underground measurements is a fundamental requirement. The absolute values of the calculations are affected by numerous parameters, for example the constitutive model chosen, the input parameters for the model, the element size and the area being modelled. A more complex constitutive model does not always provide a more useful tool. With the complexity of the constitutive model, does not only the run time and the time to get up a model increase, but the values of input parameters are generally less well known. Therefore, a linear elastic model can still be a useful tool to provide a quick approximate answer.

The difference in pillar corner conditions shown in Figure 1 is mainly caused by a difference in the vertical stress values acting on the pillar corners. For three groups of vertical stress values, the relative distribution between the 8 sidewall classes was calculated for both mining steps (Figures 3a and 3b). The numerical simulations were conducted using the three-dimensional boundary element program MINLAY (Hardle, 1988) in the linear elastic domain. For the simulations the following input parameters were chosen, based on laboratory tests and past modelling experience.

1. Coal strata: Young's modulus: 3000 MPa
   Shear modulus: 1250 MPa
   Poisson's ratio: 0.25

2. Strata: Young's modulus: 5000 MPa
   Poisson's ratio: 0.25

3. Goaf: Modulus: 50 MPa
   Bulking factor: 1.4

Table 1
Pillar Corner Classification

<table>
<thead>
<tr>
<th>CLASS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No sign of fracturing</td>
</tr>
<tr>
<td>1</td>
<td>Slight</td>
</tr>
<tr>
<td>2</td>
<td>Slight—moderate</td>
</tr>
<tr>
<td>3</td>
<td>Moderate—severe</td>
</tr>
<tr>
<td>4</td>
<td>Slight spalling</td>
</tr>
<tr>
<td>5</td>
<td>Moderate spalling</td>
</tr>
<tr>
<td>6</td>
<td>Severe spalling</td>
</tr>
<tr>
<td>7</td>
<td>Severe—very severe</td>
</tr>
</tbody>
</table>

Fig. 2a — Mining step II.
Fig. 3 — Pillar corner conditions around intersection 1D.

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An element size of 3.0 m by 1.0 m was selected, so that a sufficient large area could be modeled with a 120 x 120 grid (360 m x 360 m). In the strata, the stresses were calculated at the center of each element, the stresses analyzed were 1.5 m inside the pillar. If the vertical stress calculated was less than 16 MPa, the majority of corners were, for both mining steps, in classes 2 and 3 (slight to moderate spalling). However, if the calculated vertical stress was larger than 20 MPa, more than half of the corners recorded were characterized by severe to very severe spalling (classes 6 and 7).

In Figure 4.a, the calculated vertical stress of the pillar corners around intersection ID are presented for both mining steps and, in Figure 4.b, the increase in vertical stress is presented. Between both mining steps, there was an increase of 3 to 6 MPa, which caused the deterioration of the pillar corners, as illustrated in Figures 2.a and 2.b.

**MOHR-COULOMB SIMULATIONS**

For all constitutive models, the major problem is the determination of the values of the input parameters. The more complex the constitutive model chosen is, the more difficult it is to determine realistic values for the input parameters. In this section, a Mohr-Coulomb model was chosen and the input parameters were determined by re-analysing underground measurements of coal pillar fracturing and stress measurements. Two-dimensional simulations were conducted using the explicit finite difference FLAC-code (Cundall and Board, 1988). In the middle of the pillar, PKN strain conditions can be considered realistic.

**MOHR-COULOMB MODEL**

FLAC is a two-dimensional numerical simulation program which applies the explicit finite difference method. The rock mass investigated is divided into two-dimensional zones which are inter-connected at their gridpoints. At each gridpoint, the form of the applied equations are solved in a time-stepping manner. Each element follows a prescribed linear or non-linear stress-strain law in response to the applied forces and boundary constraints. Six constitutive laws are incorporated in the FLAC-code. The Mohr-Coulomb plasticity law is one of them and it is defined by seven properties: density, bulk modulus,
Fig. 4.a - Absolute values for mining steps I and II.

Fig. 4.b - Increase in vertical stress between mining steps I and II.

Fig. 4 - State of stress calculated above the corners of intersection 1D.

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shear modulus, angle of internal friction, cohesion, tension cut-off and dilation (optional). The first three properties are identical to the parameters defining an elastic material. The plasticity formulation in FLAC assumes an elastic, perfectly plastic solid in plane strain which conforms to a Mohr-Coulomb yield condition and non-associated flow rule (Cundall and Board, 1988). If the calculated principal stresses indicate yield in a zone and in a particular time-step, plastic corrections are made in that zone to remove conformity to the yield surface. After yield, that zone can only sustain stress changes in the elastic domain. If the tensile stress calculated in a zone and in a particular time-step exceeds the tension cut-off strength, the stress is cut to zero in that zone at that time-step. The code then assumes that the material in that zone has failed in tension and can no longer sustain tensile stresses in the direction of the principal stress corresponding to the tensile stress. Thus, for subsequent time-steps, no tensile stress will be allowed in that zone. The code considers five plastic states at any time-step (Cundall and Board, 1988).

1. at yield,
2. elastic but previously at yield,
3. surpassed tension cut-off in uniaxial tensile stress,
4. at yield, but also surpassed tension cut-off,
5. surpassed tension cut-off in general tension.

In this study, the assumption was made that a zone, which is one of the zones defined, has failed and that underground fractures would have been induced at that location.

The cohesion of the coal seam was estimated based on observations of the depth of fracturing into pillars and on measurements of the vertical stress above coal pillars. In 12 m wide pillars at a depth of 250 m, fractures were observed over a maximum length of 1.5 m into the pillar (Madsen, 1969). These observations were recorded between two roadways, justifying plane strain assumptions during the simulations. In Figure 5, the failure zone calculated in the pillar is presented for various values of cohesion (between 1 and 5 MPa). For a cohesion value between 2 and 3 MPa a good correlation was found with the underground measurements (1.5 m). The vertical stress calculated for these values of the cohesion conformed with underground measurements (Madsen, 1969). The fractured zone carried a significant load. The stress peak occurred just behind the fractured zone and deeper into the pillar the vertical stress decreased. If the cohesion of the coal seam is high (5 MPa or more), the curve of the vertical stress is similar to an elastic model without failure criteria. The back-analysis of other case studies determined cohesion values of the coal seam between 1.5 MPa and 4.5 MPa. The spread in the cohesion values is acceptable and, if the scale factor is taken into account, the method of back analysis provides a better correlation than any laboratory test.

As the stress components calculated in a coal pillar do not tend to be large tensile stresses, the value of the tension cut-off had no effect in this application. The angle of internal friction had, however, a significant effect on the failure zone, but it is generally accepted that its value is about 27 degrees.

**TIME DEPENDENT FLEXIBILITY**

The fracturing of a coal seam is a time dependent phenomenon, even in a constant stress environment. The FLAC code enables the study of the extension of the failed zone as a function of calculation time-steps, which do not necessarily correspond to physical time-steps with a known magnitude. In the FLAC code, the time dependent stress state is calculated (Cundall and Board, 1988). In Figure 6, stress profiles and the extent of the failed zones are presented at various stages during the calculation of the case study mentioned above and for a cohesion value of 3.5 MPa.

1. The failed zone grows during the first
five thousands time-steps, when the model reaches equilibrium.
2. During the extension of the failed zone, the stress peak increases and
moves further inwards.

The extent of the fractured zone is a function of the vertical stress and of the
lateral confinement stresses. At the edge of the pillar, an uni-axial type of loading occurs
and fractures are induced if the strength of the material is exceeded. Further into the
pillar, a tri-axial state of stress is present. Due to the lateral stresses, a larger vertical
stress can be carried without exceeding the Mohr-Coulomb failure criteria.

**EFFECT OF DEPTH**

After the values of the input parameters of a constitutive model were determined, the
model was applied in numerous applications. Two warnings should, however, be formulated.

1. During the interpretation of the results, the assumption that the strata behaviour was simulated using a
   particular constitutive model should not be forgotten.
2. Even that the determination of the input parameters was based on a good correlation with underground
   measurements, extrapolation to other application areas have to be conducted with great care.

In Figure 7, the effect of the depth of the coal seam on the fractured zone is presented for a lay-out with 24 m wide pillars,
8 m wide roadways and a mining height of 2 m.

The cohesion varies between 1 and 5 MPa. In Figure 8, the variation of the pillar safety

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factor (Madden, 1989) is presented as a function of depth. This latter relation is independent of the cohesion of the coal seam. For a cohesion of 3 MPa, about 25% of a vertical cross-section through the centre of the pillar would be fractured at a depth of 500 m and no fractures would be induced by the state of stress if the coal seam is at least 30 m. Of course, existing induced fractures or fractures related to geological discontinuities can occur at that depth. If the cohesion would be as low as 1 MPa, 11% of a pillar cross-section would have failed at 100 m and 100% at a depth of 500 m.

DISCUSSION OF FINDINGS

Three-dimensional linear elastic models have been applied successfully to simulate coal strata behaviour around room and pillar, and pillar extraction panels. These linear elastic models were useful as a tool to compare various layouts and conditions, and to give an approximate but quick indication of strata behaviour and failure. In a pillar extraction panel, a comparison between the sidewall conditions observed and the vertical stresses calculated showed a close correlation. The biggest disadvantage of linear elastic simulations is that fracturing and failure cannot be simulated and, as a consequence, the effect of failure on the stress distribution and deformation cannot be determined. However, a Mohr-Coulomb model can simulate these phenomena. Cohesion values of between 1.5 and 4.5 MPa were determined by back analysis of underground measurements of in-situ stress and pillar fracturing.

Once realistic values were determined for a Mohr-Coulomb model, the number of practical applications was large. In this paper, the effect of the depth of the workings and the time dependent occurrence of coal pillar fracturing were analyzed. It was found that, before reaching an equilibrium, the stress peak above the coal pillar increases and moves further inwards while the failed zone becomes larger. For all the latter calculations conducted, an explicit two-dimensional finite difference code was applied.

Three-dimensional Mohr-Coulomb simulations are planned and should improve the results and increase the number of applications. It is hoped that non-linear elastic simulations will replace, in the long term, linear elastic models. However, in the short term, linear elastic models are still a useful tool to provide a quick approximate answer in lay-out design and in prediction of strata behaviour. It should be noted that even with the most complex constitutive models, assumptions are made and that regular verification by underground measurements is a fundamental requirement. But, a good combination between advanced modelling techniques and accurate underground measurements will add supplementary knowledge and explanation to the understanding of strata behaviour, resulting in more optimum design and safer working places.

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REFERENCES


DESIGN OF YIELD PILLARS IN THE SOUTHERN COAL FIELD
OF NEW SOUTH WALES

By

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ABSTRACT

With increasing demand for more efficient production from the underground coal mines in the Southern Coalfields of New South Wales, their design and operational aspects are constantly being reviewed and improved. One key area in such pursuits is the reliable design of stable and yielding pillars. The current designs of pillars based mostly on experience leads to unnecessary sterilisation of coal or strata control problems. To explore such mine design problems, computer based modelling is increasingly being applied.

In the study described in this paper, the object was to determine the particular width of pillars separating three roadways in a panel at which the pillars yielded completely and their loads largely transferred to the undermined coal at the flanks of the panel. This was approached through a computer simulation of the behaviour of the strata around a panel, in which the three roadways were separated by pillars of progressively decreasing width. A computer program called FLAC based on the finite difference method was used to simulate the relevant strata behaviour in vertical sections. The appropriate in situ values of the deformability parameters relating to the coal seam, roof and floor were determined from the back analysis of some displacement measurements in such a panel. The process involved successive modelling of a vertical section through such a panel, starting with realistic values of the parameters and varying them until the measured and modelled displacements agreed closely.

Based on the results of the numerical modelling, the width of a yielding pillar for the given conditions is suggested.

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INTRODUCTION

Black coal is one of the major minerals exported from Australia. In 1990 about 113.18X10\textsuperscript{6} t of black coal worth approximately $5.54 x 10\textsuperscript{10} was exported (I.C.B., 1991). Of the total 165.74 x 10\textsuperscript{6} t of black coal produced, about 112.57 x 10\textsuperscript{6} t i.e. 67% was from surface mines. The remainder was produced from underground mines.

Due to considerable operating cost advantages, surface mining of coal has been increasing since the 1970's. However, due to the depths and surface restrictions involved, about 80% of the mineable black coal reserves in Australia can be extracted only by underground methods.

The current underground mining layouts require the development of generally rectangular panels. The boundaries of a panel are delineated by multiple parallel 'headings' i.e. roadways on each side. The parallel headings are separated by 'pillars' of coal of uniform widths and lengths.

Geological conditions and the existence of high horizontal stresses in many of the coal fields in Australia cause serious problems in the support and stability of the roadways. Such problems slow down the mining operations and increase costs. The stability and support of the headings are greatly influenced by the load bearing characteristics of the separating pillars.

For a given set of conditions, the 'strength' i.e. load bearing capacity of a pillar is determined mainly by its width. If the width is, say, 3-10% of the pillar's depth below the surface, its load bearing capacity is high and it can isolate neighbouring excavations from affecting one another. Such a pillar is considered to be 'stable'. It, however, sterilizes a large amount of mineable coal and also, increases the length of the cross-cuts connecting the parallel headings and thereby, the time and cost of development.

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