Modelling of Caving over the Lingan and Phalen Mines in the Sydney Coalfield Cape Breton

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ABSTRACT

The paper discusses modelling of the effects of the interaction between workings in the Harbour and Phalen Seams in the Sydney Coalfield, Nova Scotia, Canada. Lingan Colliery worked the upper Harbour Seam and the Phalen Colliery mines the Phalen Seam some 140 m (500 ft) below. With the flooding of Lingan Colliery in November of 1992, all Phalen Seam workings for several years will now be conducted under flooded abandoned panels 140 m above. The simultaneous water inflows on Lingan 2 East due to interaction effects and on Phalen 5 East, associated with a severe weighting, raised considerable concern over the potential effects of interaction between the two seams. The water inflows are discussed elsewhere by Cain, et al 1994.

At the time of these incidents, it was recognised that the University of Nottingham were established in modelling research in this field. They were commissioned through Jacques, Whitford and Associates (JWA), Dartmouth, Nova Scotia to apply their U.K. techniques to the Sydney Coalfield to increase understanding of the mechanisms of interaction. Two models were used to explore the interaction effects.

Firstly, an empirical fracture development model was used to examine potential fracture development by extrapolation of strain levels from physical models of different coal mining geometry. Results appeared to predict a previous water inflow from Phalen 1 East Panel, and the subsequent dry conditions on the Phalen 4 East Panel. While the method looked promising for single seam extraction, it has limitations when it was applied to multiple seam mining.

A second model was needed. This was a finite element model (FEM) developed and validated for U.K. conditions against the National Coal Board Subsidence Engineers' Handbook (NCB SEH). This model allows yielded material and predicts displacements, stress and strain distributions around the modelled longwall excavation. Use in the U.K. has yielded fairly accurate results with respect to the prediction of surface displacements. Although not fully calibrated for conditions in the Sydney Coalfield at a relatively early stage of the work, the model did give indications of processes of strata deformation during interaction and highlighted the presence of zones of potential fracturing above the various longwall gobs.

INTRODUCTION

Longwall mining encourages large scale stress redistribution by inducing the overburden to massively cave. The caving process involves fracturing of the overburden above the longwall extraction. These potentially large fractures can allow aquifer horizons or subsurface water bodies a route of access to the workings. The degree and nature of the fractures, the aquifer's character and the detailed geology ultimately control the water inflow. Physical and numerical modelling techniques allow the engineer a fuller understanding of the fracturing and stress behaviour over longwall panels, and thus with further consideration of the aquifers physical characteristics and geological setting, a risk assessment can be made.

The problem described above becomes more complicated in multi-seam mining due to the interaction effects between seams. Generally, the following four mechanisms govern the interaction effects on an adjacent seam (Haycocks, et al, 1990) (see Figure 1):

1. Fracture zones;
2. Load transfer;
3. Subsidence; and
4. Inner burden shearing.

Quantification of these four parameters constitutes the basis for detailed analysis of interaction due to multi-seam mining.

In order to understand the four mechanisms, both physical modelling and finite element modelling techniques developed at the University of Nottingham have been used to investigate the effects of various parameters on ground movement due to multi-seam mining. In particular, the models have been applied to the interaction between workings in the Harbour and Phalen Seams in the Sydney Coalfield, Nova Scotia, Canada. At the time of water inflow incidents at the two mines in November 1992, it was recognised that the University of Nottingham were established in modelling research in this field. They were commissioned through Jacques, Whitford and Associates (JWA), Dartmouth, Nova Scotia, to apply their U.K. techniques to the Sydney Coalfield scenarios to increase understanding of the mechanisms of interaction.

Based on a number of case studies for the Lingan and Phalen Mines in the Sydney Coalfield, Nova Scotia, Canada, this paper demonstrates the ability of empirical models to predict fracture zones development above longwall gobs. The paper also indicates the application of the finite element technique to model the interaction effects of subsidence due to multi-seam mining.

CASE STUDY SITE

The Sydney Coalfield is located on the eastern coast of Canada, offshore of Cape Breton Island, Nova Scotia (see Fig.2). The high/medium volatile bituminous coals are of Upper Carboniferous age, part of the Pictou Group of the Upper Carboniferous rocks of eastern Canada. The depositional environment was essentially fluviatile, with braided channels originating in the east and migrating westwards.

The Harbour and Phalen Seams outcrop on land and dip northward, under the ocean at gradients from 15% to 30%. The strata between the Harbour and Phalen Seams consists of about 140m of siltstones and sandstone, with interbedded mudstones, shales and occasional limestone. Two thin coal seams are also present, at 40 m and 120 m above the Phalen Seam. Of particular concern with respect to the water inflows are two thick sandstone deposits, one just above the Phalen Seam, and one just below the Harbour Seam. These sandstones are strong, massive, and contain hypersaline connate water. Traces of oil have also been occasionally reported in the strata immediately on top of the Phalen Seam. The sandstones may also act as gas reservoirs.

Extraction in the Phalen Seam by the new Phalen Colliery (1987) was originally planned for the most part beneath the Harbour Seam workings of Lingan Colliery. The eastern extremities of the Phalen east side panels were also to take coal from beneath flooded working in No.26 Colliery. In the absence of local data on interaction/subsidence effects, the extracted heights in the first of these areas (Phalen 5 East Panel) were restricted as a precaution to reduce interaction effects. Flooded workings in the Phalen Seam also flank the Phalen Colliery workings to the east (No.1B Colliery) and West (No.15 Colliery). Substantial unworked pillars were left in both the Harbour and Phalen Seams, between No.26/Lingan and No.1B/Phalen respectively.

Figure 3 indicates a cross section of the Phalen 1 East to 5 East Panels and the overlying old Lingan workings. Lingan and Phalen Collieries have extracted seam heights varying between 1.5 and 3.0 m with face lengths between 100 and 250 m at depth between 200 m and 700 m. A seam dip of 12 has been assumed. At Lingan, the mining is single seam, affecting the seabed only, however, the resultant ground movement above the Phalen longwalls will not only affect the seabed but also the intermediate Lingan workings.

EMPIRICAL MODEL FOR FRACTURE PATTERNS PREDICTION AROUND LONGWALL PANELS

Data derived from the physical modelling results investigated in the University of Nottingham (Gaskell, 1989) has been analysed to form an empirical model to predict principal tensile and compressive strains along with potential fracture propagation. In this section, the model is presented, and then it is applied to assess potential for water inflow into mine workings through a number of panels in the Lingan and Phalen mines. This model was based on single extraction and considers only effects above the longwall extraction. The principle of superposition of strains is used to partially model interaction. Additional effects to underlying seams and fracturing below the extraction are ignored by this relatively quick and simple to use model.

Empirical model development at Nottingham

The physical model results have been employed to investigate the change in magnitude of the tensile strain between the surface and mining extraction horizon. Figure 4 shows magnitude of the principal tensile strain in relation to depth, whilst Figure 5 shows a rationalised presentation of the results. Figure 5 employs a multiplying coefficient for extraction height/depth ratio (M/h) to obtain the principal tensile strain using a similar approach to that employed in the SEH. (NCB, 1975)

Fracture occurrences in the physical models have been analysed and related to the magnitude of the tensile strain value. Figure 6 illustrates a generalised presentation of the results for a longwall ribside in relation to the tensile strain magnitude. The results were obtained visual examination of numerous physical models. Continuous fracturing is where fractures are seen to migrate vertically with continuity. Discontinuous fracturing is where there are a number of fractures migrating vertically but there is no apparent connection between them. Dissipating fracturing is illustrated by fractures that are isolated and sparse.

Application to the Sydney Coalfield

It should be mentioned that the model described in the above section uses the subsidence factor of 0.9 for U.K. Coalfield rather than 0.7 for the Sydney Coalfield (JWA, 1992). Therefore, modifications are required in order to apply the Nottingham model to the Sydney Coalfield. It is obvious that Principal Tensile Strain is proportional to the Strain Multiplier, which is proportional to the subsidence factor. Therefore, a reduction factor of $\frac{0.7}{0.9}$ (0.78) has been applied in the presentation of the strain and subsidence magnitudes for Sydney Coalfield results.

Using the modified model, the No.1 and 4 East panel were initially investigated. Then, the interaction effects on the fracture patterns from mining Harbour and Phalen seams will be examined. The aim of the research is to assess the possibility of water inflow into these panels through analysis of the fracture patterns potentially developed.

Although the predictive model described before has been established for a level seam, it can be modified for slightly inclined seams allowing for the principal that the significant strain zone should be perpendicular to the relevant point in the workings (NCB, 1975).

Case studies

Based on Figures 5 and 6, the fracture patterns developed around a longwall panel can be predicted if the panel geometry is known. The following section concentrates on the fracture patterns prediction around No.4 East Panel in the Phalen Mine. Additionally, the interaction effects of fracture zones between No.2 and No.3 East Panels in Lingan Mine and No.5 East Panel in the Phalen Mine are investigated.

Case No.1 - No.4 East Panel in the Phalen Seam

The mining dimensions of this panel are as follows:

Depth, h	=	425 m
Width, w	=	210 m
Seam Thickness, M	=	2.6 m
Dip of seam, α	=	12°
Length, L	>	2h

Based on Figure 5, the principal tensile strains at different horizons can be determined for flat seam. Since the coal seam in this case is slightly inclined, the method of adjusting equivalent flat seam tensile strain values for use in steep seams from the SEH (1975) is used to determine the tensile strains on both rise and dip sides of the panel. The magnitudes of principal tensile strain on both rise and dip sides at different horizons has been indicated in Table 1.

Figure 7 indicates the fracture patterns developed in this case. Based on this Figure, the following comments can be made for this case:

Table 1. Principal Tensile Strain (PTS) Magnitude for Case No.1 - Phalen 4 East Panel

Horizon	Height above Seam (m)	% depth	Strain multiple	PTS	PTS_r	PTS_d
1	15	3.5	>3900	>23.86	>14.32	>33.40
2	20	7.0	2964	18.13	10.88	25.38
3	45	10.5	2262	13.84	8.30	19.38
4	60	14.0	1716	10.53	6.32	14.74
5	75	17.5	1482	9.07	5.44	12.70
6	90	21.0	1326	8.11	4.87	11.35
7	105	24.5	1014	6.21	3.73	8.69
8	120	28.0	858	5.25	3.15	7.35
9	135	31.5	780	4.77	2.86	6.68

1. On the dip side, continuous and at least discontinuous fracturing occurs up to a height of 45m above the seam, while on the rise side there is only dissipating fracture;

2. At the base of Sandstone and Lingan seam, the PTS magnitudes are approximately 11 mm /m and 7 mm/m on the dip side, 5 mm/m and 3 mm/m on the rise side;

3. Since the continuous and discontinues fracturing zones are quite away from the Sandstone base (more than 40 m away), it is unlikely that any water will flow to the panel on either the rise or dip side unless there are other influences acting;

Phalen 4 East Panel was in fact dry, a similar analysis at Phalen 1 East Panel indicates that water make from the sandstone aquifer in the dip side of the panel would be possible. There was in fact an inflow on 1 East which peaked at 500 gpm (CANMET 1994).

Although only these two cases have been conducted, the results appear to coincide with observations in situ. This suggests it may be possible to use the fracture development model in conjunction with other methods to assess the potential for water inflow into the Phalen Seam from the Harbour Seam flooded workings.

Case No.2 - Interaction Effects between No.2, 3 East Panels in Lingan Mine and No.5 East in the Phalen Mine

The model can also be used to predict the interaction effects of fracture zones from multi-seam mining. Based on the given geometry of the above three panels illustrated in Figure 8, the cumulative fracture zones around these three panels have been determined as shown in Figure 8. The results can be concluded as followings:

1. The model shows continuous vertical fracturing on the dip side of Phalen 5 East up to 55 m above the workings.

2. Previous image analysis of fracturing in physical models tested at Nottingham has indicated horizontal fractures at development to a height of 2.5 to 3 that of vertical fractures (CANMET 1994). Based on this simple assumption it can be predicted that horizontal fractures will develop up to a height of 140 - 170 m above the Phalen Seam.

3. This range includes the Harbour Seam.

A similar situation has been observed in the U.K. but to a height of 80 m only where bed separation cavities parallel to the face advance open up behind the faceline and inside the rib over the panel.

FINITE ELEMENT MODEL FOR STRESS ANALYSIS

As mentioned before, the empirical fracture development model can only be used to give general insight into the interaction effects of fracture zones from multi-seam mining. However, the finite element modelling (FEM) can allow a more detailed insight to be made of the interaction effects of subsidence from multi-seam mining. In addition, the accompanying distributions of displacement, induced principal stress and strain can be determined for the ground between the mining horizon and the surface that is effected by the longwall extraction.

The background to the non-linear finite element model developed at the University of Nottingham for subsidence research has been discussed by previous researchers (Reddish, 1990, and Yao et al, 1993). The FEM allows the user to model post-failure properties of the rock based on a modified Mohr-Coulomb failure criterion under transversely isotropic plane strain condition. The model determines whether an element has failed based on the failure criterion, and then calculates new Young's Modulus values. Lower post-failure modulus values result in more dramatic post-failure movement.

The model has been used in the U.K. to model both surface subsidence and interaction effects. The amount of subsidence observed on the model is used to calibrate the output of the model. Surface subsidence over longwall workings in the U.K. can theoretically be predicted to within $\pm$10%. The model parameters can therefore be modified so that the surface subsidence results are within reasonable limits, allowing some confidence in other results.

The use of the FEM in the Sydney Coalfield was not calibrated to Sydney Coalfield subsidence values. However, at the width depth ratios of the panels modelled, the difference between the Sydney Coalfield subsidence development and the subsidence developed over panels in the U.K. (CANMET 1994) is less important. The results obtained are therefore probably fairly close to those that would be seen on a fully calibrated model. The basic computational procedure of this model has been given by Whittaker and Reddish (1989). In practice, the program is run twice for each situation in order to subtract the results obtained through gravity loading of the intact strata from those in the mined-out case. This is to enable the results of mining alone to be obtained.

In order to gain an appreciation of the interaction effects between longwall workings in Phalen and Lingan seams, this finite element package has been used to ascertain the patterns of displacement, induced principal stresses, strains, and subsidence profiles for a few mining stages. It is considered that this model can provide some useful guidance to mining layouts to help minimise the interaction effects on the stability of faces, thus water hazards can be reduced.

Subsidence model validation

In modelling applications, any model used needs to be validated against reliable data, defining the behaviour being modelled. Here the resulting subsidence profiles were compared with those predicted by the SEH model in the absence of reliable local data. In this case, the model has been validated on a section involving three mining stages including five panels; stage one is where Lingan panel 1, panel 2 and panel 3 are worked, stage 2 is where Phalen 4 is extracted and stage 3 is where Phalen 5 is worked. Figures 9 to 11 show the comparability of the subsidence profiles produced by the FEM. and those produced by the SEH. The model has been validated against a SEH with a S/m factor of 0.9. It therefore over predicts for the Sydney Coalfield by a factor of $\frac{1}{0.78}$ and so the y-scale has been adjusted to show values for the Sydney Coalfield.

Figures 9 and 11 illustrate some basic features from the two models. The SEH profiles are sharper, showing abrupt changes in subsidence, and the pillars appear to be solidly founded features, while the FEM allows pillars to partially punch and fail producing smooth and more rounded profiles. With the FEM the profiles are wider in extent, and the subsidence is more progressive as the final stage produces significantly more subsidence. This is a cumulative effect not found with the SEH model, as the latter treats each panel in isolation and then simply adds their effects together.

As a conclusion, the FEM produces subsidence profiles with a reasonable surface fit overall, comparing them to those produced by the SEH, although they have a tendency to over predict.

Results from the study

The results produced with the FEM are presented in three different forms, namely displacements, principal strains and principal stresses, to allow the most comprehensive analysis as some diagrams address particular aspects, not visible on the other diagrams.

To permit a clearer understanding, the analysis has been done stage by stage and is summarised below. At the time this work was done, CANMET and the Cape Breton Development Corporation (CBDC) were monitoring the interaction effects of Phalen 1 Centre Panel on Lingan 5 East Top Level. A huge amount of data was obtained. It is intended, in ongoing future work, to evaluate the findings of this model against the field data.

<u>Displacement results</u>

These results are useful in interpreting general patterns of behaviour.

<u>Stage 1</u>

Figure 12a shows that the Lingan pillars partially punch into the strata, above and below themselves. This has resulted in the three subsidence profiles combining into a single, large, wide, flat-bottomed profile, with a maximum subsidence of 1.18 m and, a few gentle humps over the pillars. The figure also clearly illustrates large scale floor heave in the three panels. However, this was not observed in the Lingan 5 East/Phalen 1 Centre monitoring data, and ongoing studies are investigating this matter.

Stage 2

The new excavation has significantly disturbed the strata above the Lingan Seam in the region of panel 1, and caused the subsidence profile to double in magnitude, The maximum subsidence rose to 2.37m (Figure 12b).

It can also be seen (Figure 12b) that the first pillar in the Lingan sequence between panel 1 and panel 2 has been undermined with extra displacement occurring on the dip side of panel 1. Overall, this panel has significantly reactivated the old Lingan gob with considerable movement on the dip side of panel 1, due to the pillar undermining and punching.

Stage 3

The second Phalen panel (panel 5) has undermined the Lingan pillar between panel 2 and panel 3, causing a significantly increased subsidence in the Lingan overburden, particularly in the region of panel 2 to panel 3, see Figure 12c.

Major principal strains results

This form of result is best used as a measure for tensile fracturing potential. The induced tensile strains have been shown to be closely related to levels of fracturing.

Stage 1

A number of features are observed from Figure 13a and are listed below:

a. The outer edges of the gob in the Lingan seam suffer the greatest strains, in terms of magnitude and extent with a maximum strain of 16 mm/m. The middle panel shows a reduced strain condition. This effect is thought to be due to the pillars providing a softer edge to the excavation.

b. The strains in the rise side of the excavations are far more intense but less extensive than those on the dip side. The dip side tensile strains extend further above the excavation but are less intense.

c. The high tensile strains are clearly associated with the region just inside the panel edges, and can be easily likened to fracture areas on physical models.

Stage 2

Similarly the features observed from Figure 13b are listed below:

a. The mining of panel 4 results in effects on two Lingan panels, panel 1 and panel 2.

b. Panel 1 rise side strains are increased in extent overall, the 6 mm/m strain level increased from 117 m, in the previous stage, to 183 m above Lingan seam.

c. Panel 2 rise side strains are completely dissipated, but the dip side strains are increased in extent, as the pillar has been undermined causing a new phase of roof movement.

d. The pillar between panel 1 and panel 2 has a zone of major tensile strains underlying it, connecting to the dip side rib in Phalen seam. This area is an area of intense shear (see minor strains diagrams).

Stage 3

From Figure 13c the main features are:

a. The major effect of stage 3 is on Lingan panel 3;

b. On the dip side of panel 3 the strains are significantly increased in extent, the 6 mm/m strain extends to 200 m above Lingan seam.

c. There is a tensile strain/shear fracture between the dip side of panel 3 and the dip side of panel 5 developing, although this is not as clear as the same feature observed in the previous stage.

d. The new area of increased tensile strain runs from the dipside edge of Phalen panel 5 to the goaf region of Lingan panel 3 - a good potential reservoir. This contacts with the high tension region on the dip of Phalen panel 4, which runs into the edge of the pillar between Lingan panel 1 and 2. The pillar would provide a poorer water reservoir.

Minor principal stress results

These are best used as a measure of the additional loading of the pillars and the surrounding regions.

Stage 1

From Figure 14a, it can clearly be seen that the abutment on the pillars are wider and more extensive than the ones on the ribs in that they expand further down towards the Phalen seam.

Stage 2

The extraction of panel 4 has resulted in a combination of abutment on the rise side of panel 2 and dip side of panel 4 resulting in a region with a very high state of stress. This effect to a lesser extent is also observed on the rise side of both panel 1 and panel 4.

Stage 3

After extracting panel 5, the situation in the region between the rise side of panel 2 and the dip side of panel 4 has worsened, and another combined effect has occurred between the dip side of panel 3 and the dip side of panel 5 (Figure 14c).

Another important feature observed is that after panel 4 and panel 5 have been extracted, the abutment on the pillars in the Lingan seam are connected to the abutment on the pillar in Phalen seam in a converging triangular area.

CONCLUSIONS

This work is ongoing and is still approach orientated. It is still too early to draw firm conclusions. However, indications as to interaction effects can be summerised as follows:

The fracture development model suggested firstly, the presence of sub-critical fractures above the Phalen 1 East Panel, which suffered a water inflow and secondly, the apparent non-development of connecting fracture zones above the Phalen 4 East Panel, which was dry. Thus validating the model for the interaction study. The fracture development model appeared to be less reliable when interaction effects were analysed, possibly due to the complex nature of seam interaction, and to the fact that the model was developed to consider only fracture development immediately above the workings.

The elastic finite element numerical model with post-failure analysis capability was then used to analyse interaction effects between the Harbour and Phalen Seams. The model results appear intuitively to give reasonable indication of the strata deformation and stress development processes.

The numerical model work indicates that the undermining of pillars in the Harbour Seam by panels in the Phalen Seam produces zones of concentrated tensile stresses that could be of particular interest with respect to the development of pathways for water between the two sets of workings. As workings extend to greater depths, the stress redistribution around panels and pillars can be expected to increase, with the potential for the further development of fracture zones.

Overall, the completion of this work, and of the working leading up to it, has provided CBDC with new tools and a greater understanding of the factors surrounding the development of mining subsidence and seam interaction and their effects on overlying strata.

Ongoing work is designed to physically model the actual Lingan/Phalen geology for the first time and then to evaluate the finite element work against recent interaction monitoring data at Lingan. In this way it is hoped to better evaluate future layouts for assessing water hazards and interaction effects.

Acknowledgement

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The views expressed in this paper are those of the authors and not necessarily those of the sponsor.

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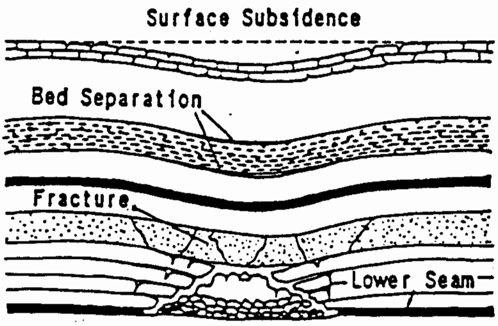


Fig. 1 Influence of previous mining on overlying strata and upper seam

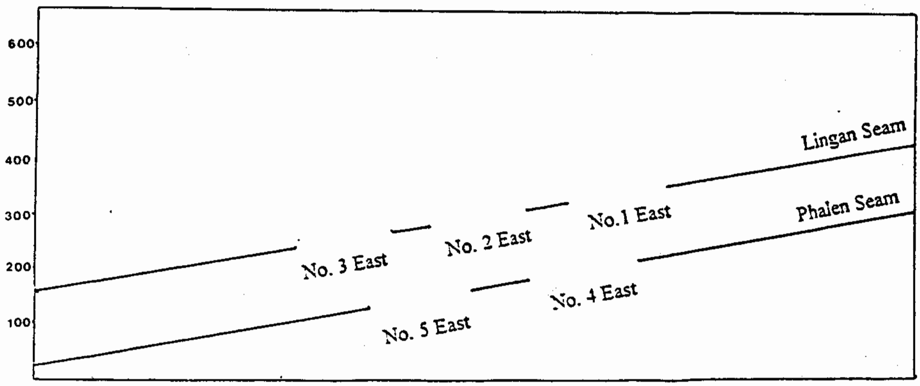
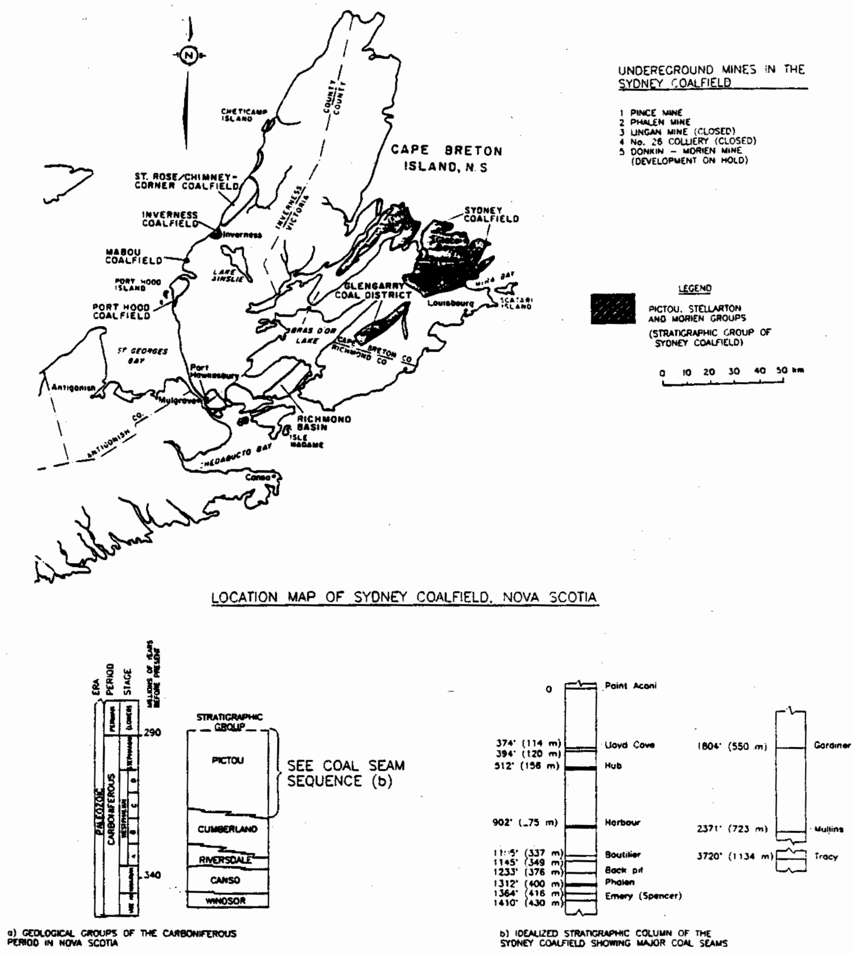


Fig. 3 Projected mining geometries in the region of this study

Figure 2: Regional geology of the Sydney Coalfield (after Calder, 1985)



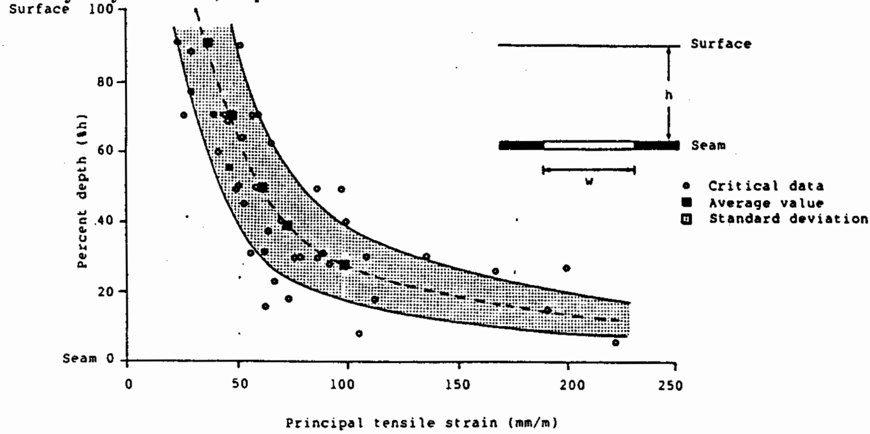


Fig.4 Principal tensile strain vector value in relation to depth below surface

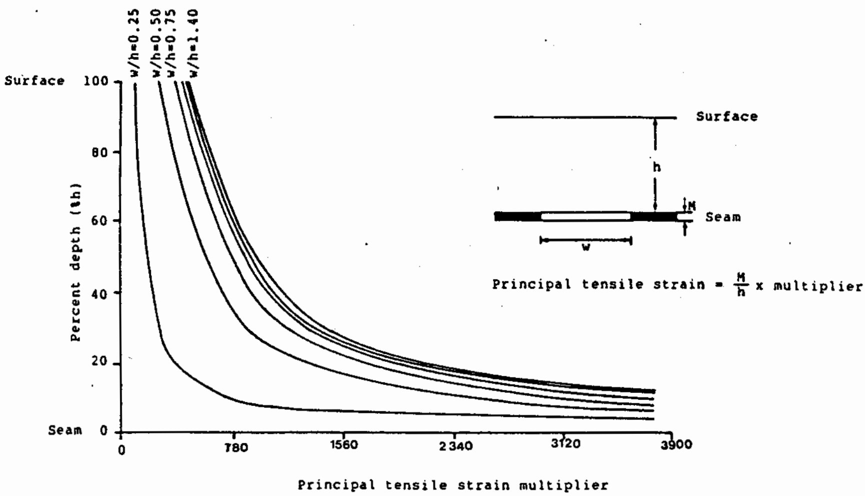


Fig.5 Principal tensile strain multiplier in relation to depth below surface for different w/h ratio for Sydney Coalfield

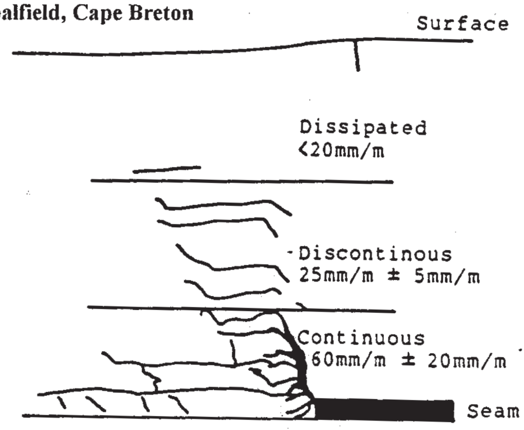


Fig.6 Fracture continuity in relation to the magnitude of the tensile strain vector for a longwall extraction ribside

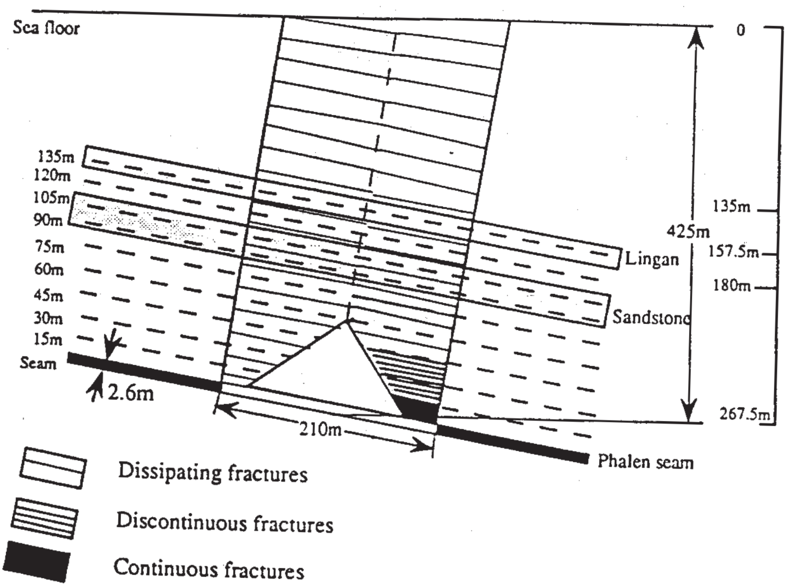


Fig.7 Determination of fracture continuity for No.4 East Panel

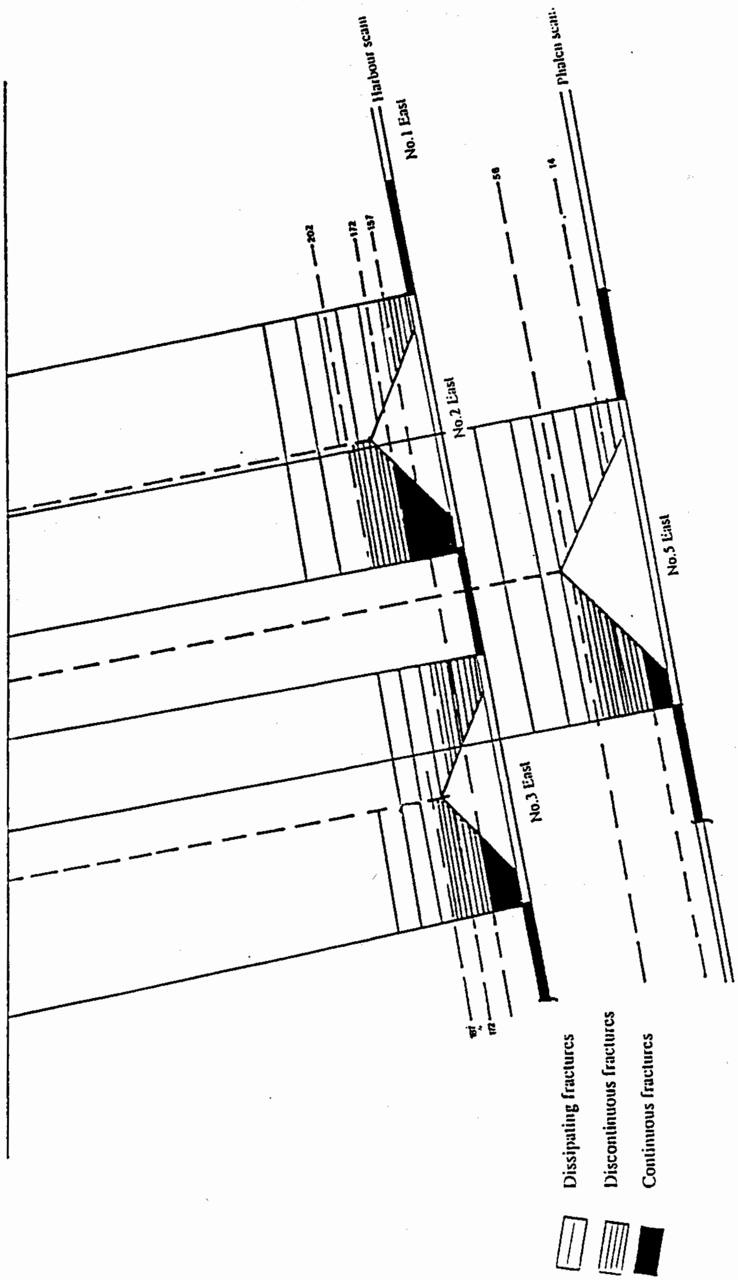


Fig.8 Cumulative fracture zones development around No.2, 3 East Panel in Lingan Mine and No.5 East Panel in Phalen Mine

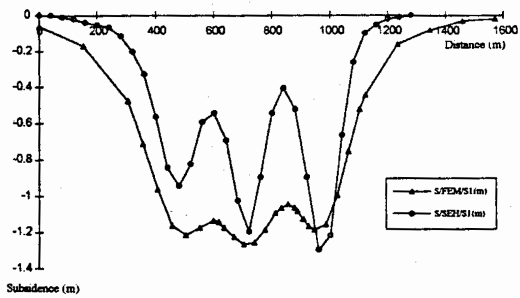


Fig. 9 Surface subsidence profiles using S.E.H and F.E.M (Stage1)

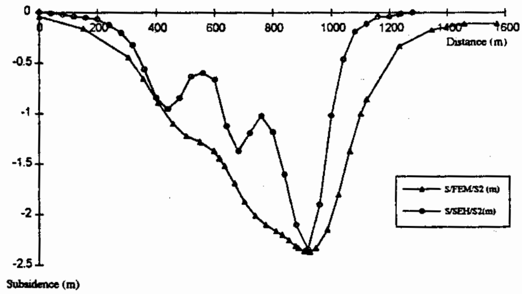


Fig.10 Surface subsidence profiles using S.E.H and F.E.M (Stage2)

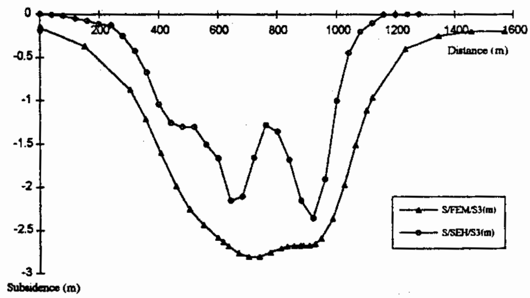


Fig. 11 Surface subsidence profiles using S.E.H and F.E.M (Stage3)

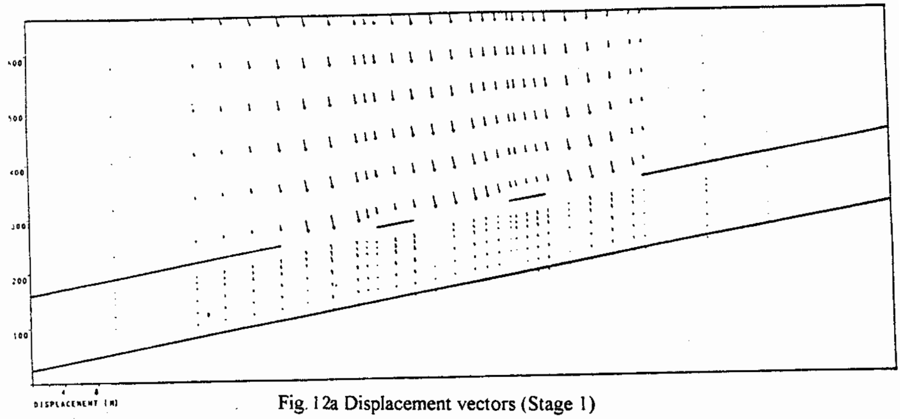


Fig. 12a Displacement vectors (Stage 1)

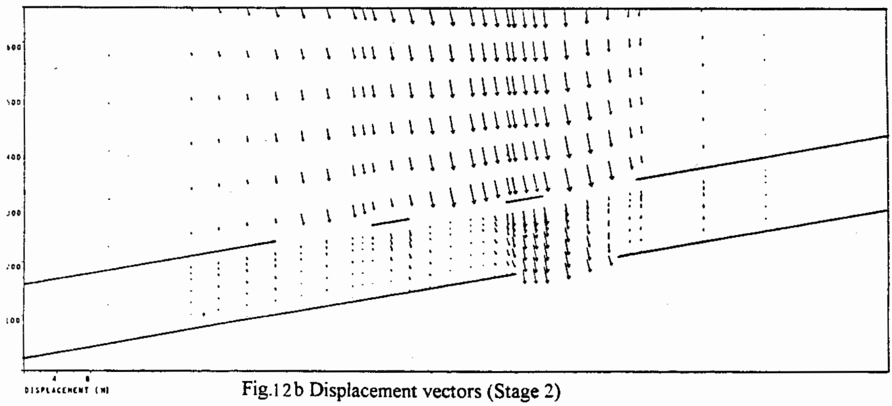


Fig. 12b Displacement vectors (Stage 2)

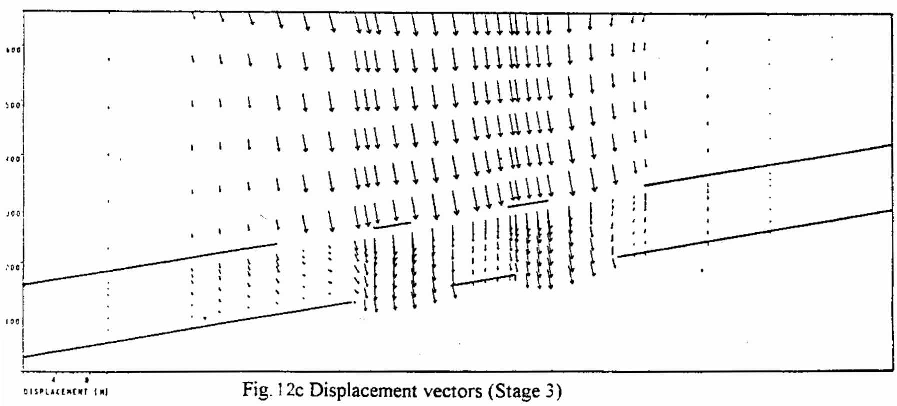
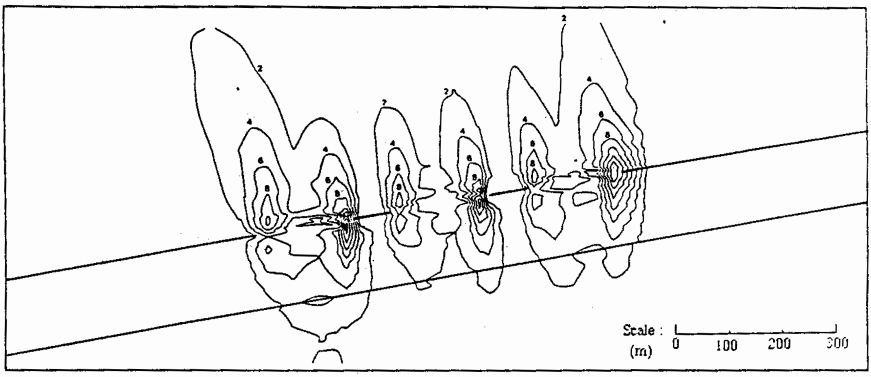
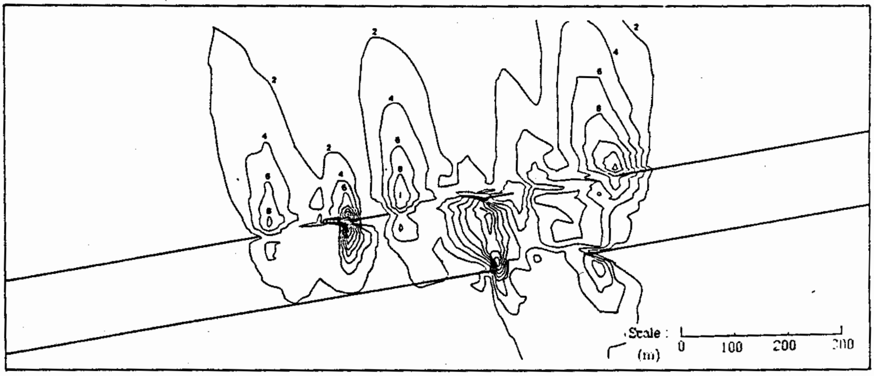


Fig. 12c Displacement vectors (Stage 3)



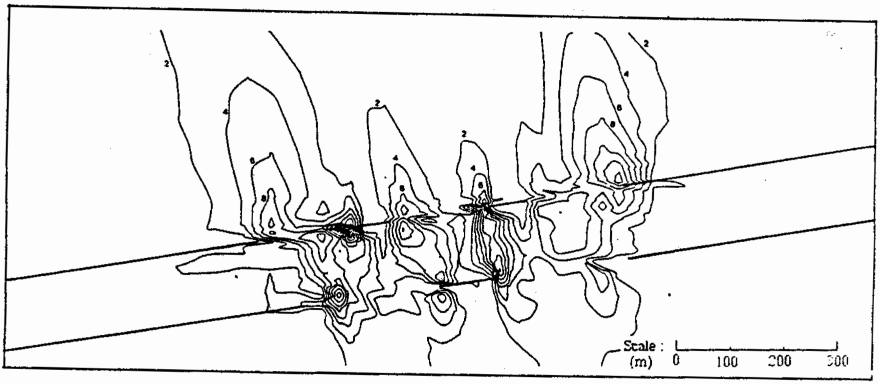
Data from 0 mm/m to 16 mm/m with a contour interval of 2 mm/m

Fig.13a Major Principal Strain Levels (Stage 1)



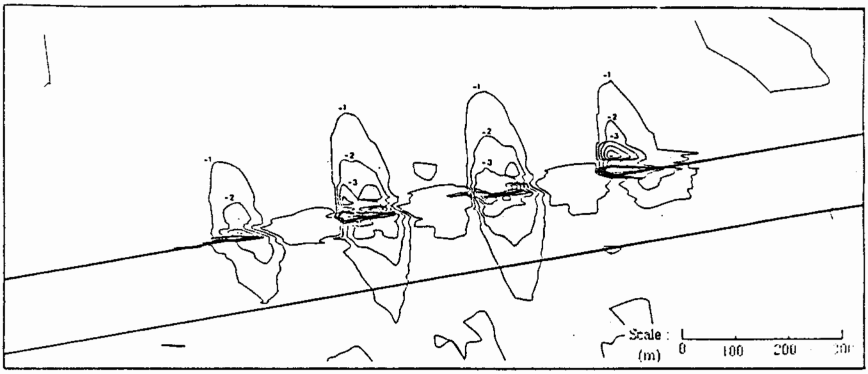
Data from 0 mm/m to 20 mm/m with a contour interval of 2 mm/m

Fig.13b Major Principal Strain Levels (Stage 2)



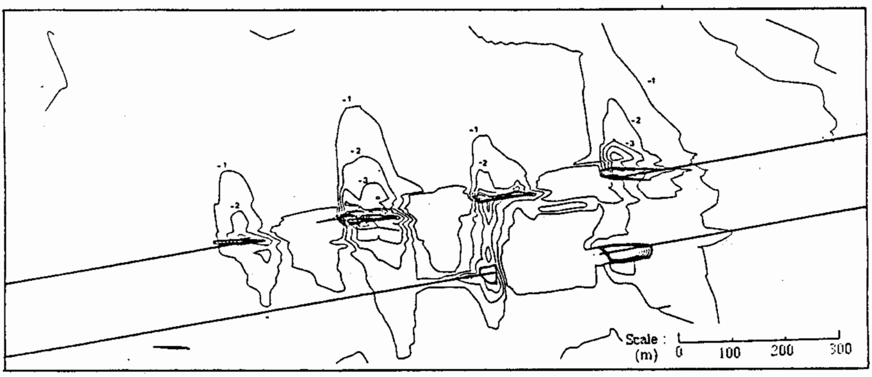
Data from 0 mm/m to 20 mm/m with a contour interval of 2 mm/m

Fig 13 c Major Principal Strain Levels (Stage 3)



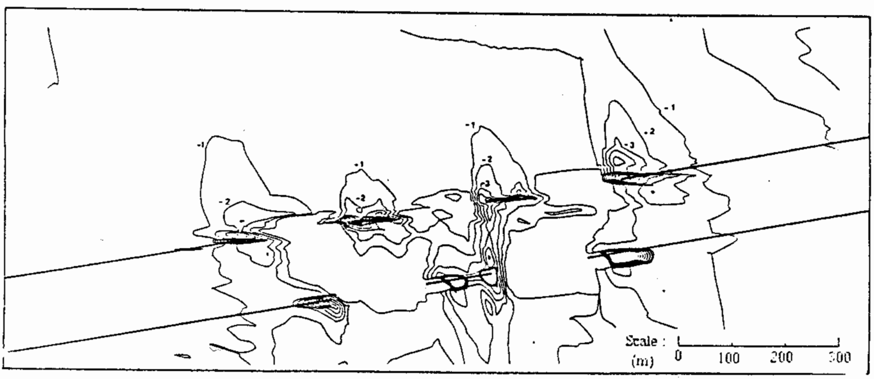
Data from -7 MPa to 0 MPa with a Contour Interval of 1 MPa

Fig. 14aMinor Principal Stress Levels (Stage 1)



Data from -9 MPa to 0 MPa with a Contour Interval of 1 MPa

Fig 14b Minor Principal Stress Levels (Stage 2)



Data from -10 MPa to 0 MPa with a Contour Interval of 1 MPa

Fig.14 c Minor Principal Stress Levels (Stage 3)