

# Mine Design and Planning Aspects: Undermining Aquifers and Surface Water Bodies

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## ABSTRACT

The paper discusses the development of fractures associated with underground mining operations. Physical modelling test results are compared with field observations and assessed by finite element and image analysis techniques. General comments are made regarding the influence of geological factors such as lithology, rock strengths, and hydrogeology in relation to the design and planning aspects of underground mines.

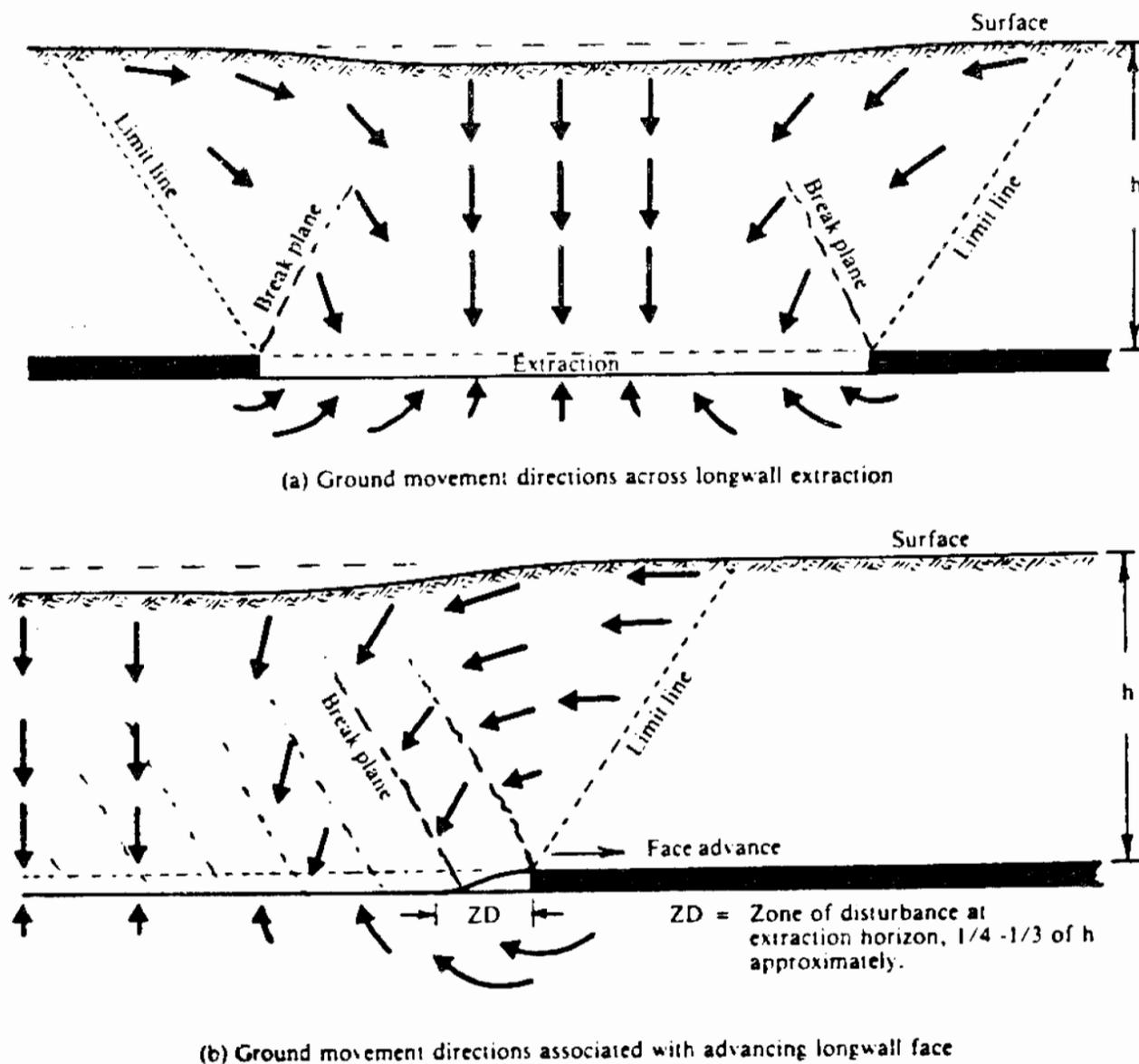
## INTRODUCTION

The longwall method of mining extraction involves the systematic removal of mineral from a tabular deposit followed by caving of the immediate overburden which induces subsidence and ground movement. This process normally involves caving of the overburden above the mineral deposit, but in some circumstances stowing of the mined out void is carried out for the purpose of controlling the propagation of fracture development from the mining extraction. Stowing is rarely carried out owing to the costs involved in providing fill material for such operations. In UK coalfields it is normal practice to cave the rocks above the longwall excavation, whilst controlling the magnitude of caving and subsidence by limiting the extraction width between purposely designed pillars of mineral.

In many situations in the UK coalfields aquifers overlie coal seams and can result in water gaining access to the mine workings. As a consequence, detailed exploration and evaluation of the geological setting in relation to water occurrence risks forms part of the preliminary assessment. From knowledge of the geological setting and the depth and mining dimensions, an assessment can be made of the response of the overburden to the mining operations and subsequent caving/subsidence processes. Several techniques have been applied to make such assessments ranging from empirical models through to physical modelling and computer based models. The present paper is concerned with making evaluations of the effect of caving/subsidence on the overburden above coal seams in UK Coal Measures which comprise of relatively weak to medium strength sedimentary rocks. The research techniques employed to evaluate such effects consist of physical models constructed of sand/plaster to simulate the geological setting and portray the fracture development phenomenon. This work has been supported by finite element stress analysis and image analysis techniques.

**LONGWALL CAVING AND SUBSIDENCE BEHAVIOUR**

The removal of mineral from a tabular deposit during longwall mining induces a redistribution of the stress field, and if the roof rocks are sufficiently weak, caving of the immediate roof. The caving process involves collapse of these rocks in proximity to the mined-out area, but importantly fractures develop at the ribsides of the longwall and can propagate extensively into the overburden. The caving process and stress redistribution effects result in the manifestation of vertical and lateral rock displacement occurring towards the mined-out area. The magnitude of the resulting subsidence is a function of the strength of the overburden, the extraction thickness, width and development extent of the longwall, and the depth below the surface.



**Figure 1:** Ground movements around a longwall extraction after Whittaker and Reddish<sup>(1)</sup>

Of special significance in the longwall caving process is the occurrence of fracture zones around the mining extraction. Although, the maximum subsidence and main caving effects are associated with the centre region of the longwall extraction, it is the edges of the longwall at the mining horizon which experience the most intensive development of fracturing. Attention is required to be given to the likely effects of such fractures penetrating aquifer horizons overlying the longwall extraction.

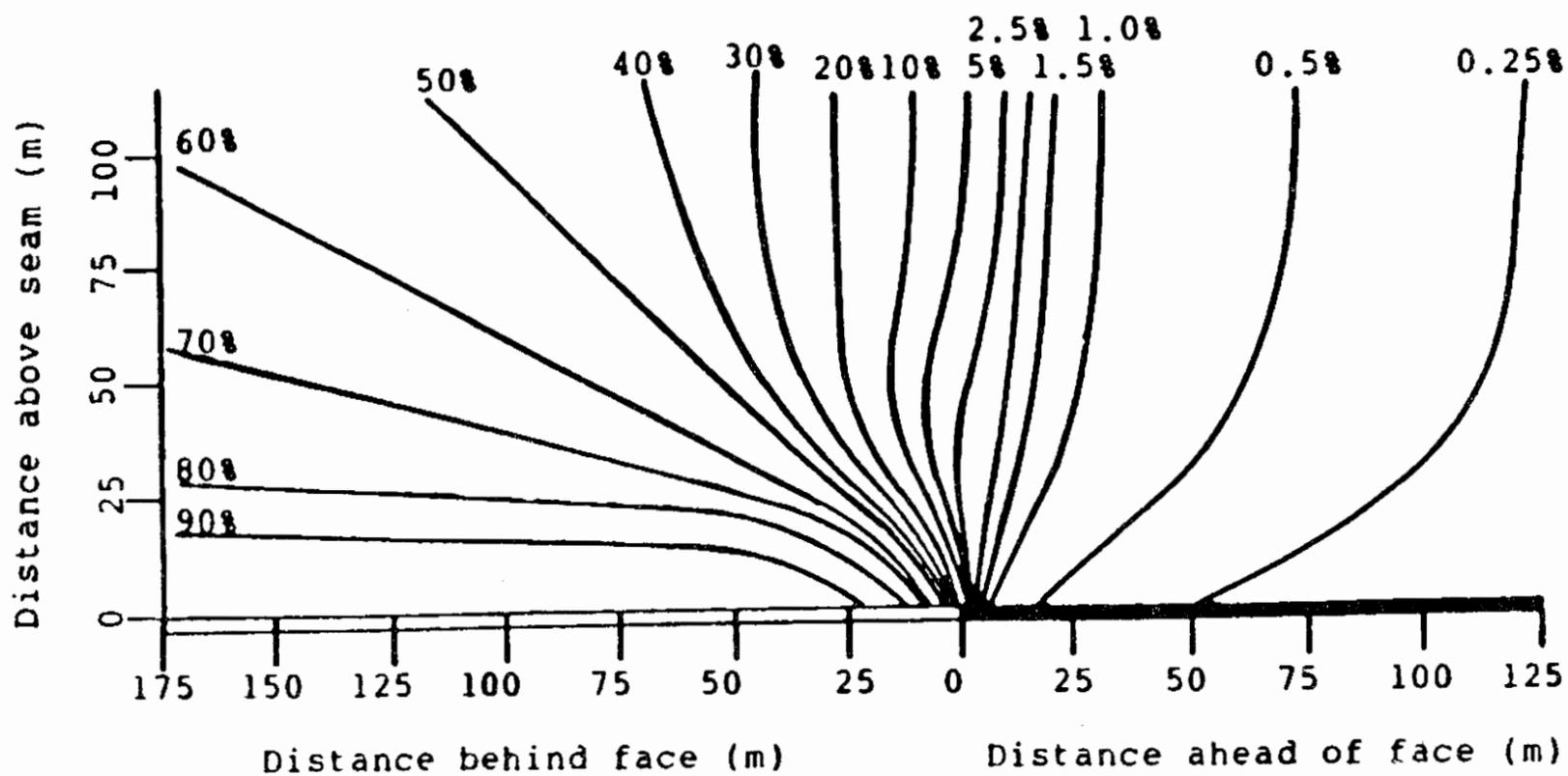
Figure 1 shows the strata displacement pattern associated with a longwall extraction. The displacements tend to rotate about the ribsides of the extracted area, see Figure 1 (a), and as a consequence give rise to a characteristic break plane which is essentially a fracture development zone. Figure 1(b) shows the strata displacement pattern around the face-line of

## Whittaker, Reddish & Sun - Mine Design and Planning Aspects when Undermining 201 Aquifers and Surface Water Bodies

a longwall extraction. The fractures occur as a series of parallel break planes and can subsequently close after cessation of the caving phenomenon. The fracture planes which occur behind the longwall face are of a temporary nature since their duration is dependent upon face advance and the accompanying caving process.

The authors have been concerned with research into ground movements around longwall extractions and have reported on previous investigations<sup>(2,3,4)</sup>.

The general movement of strata around a longwall face has been discussed by Potts<sup>(5)</sup>. His interpretation of the pattern of rock displacement which occurs during caving and subsidence is shown in Figure 2. He shows vertical movements to be taking place ahead of longwall face and a relatively uniform transition around the face region.



**Figure 2:** Vertical displacements of ground movement associated with a caved longwall extraction (vertical displacements expressed as a percentage of extracted seam height) after Potts<sup>(5)</sup>

### EFFECT OF INCREASING LONGWALL WIDTH ON FRACTURE DEVELOPMENT AND STRAIN PATTERN

It is recognised that the width of the longwall extraction plays a major role in influencing the extent of caving and fracture development above the extraction. Previous work at the University of Nottingham has investigated this aspect of longwall design and results are presented in Figure 3 which show physical model results obtained with a self-body-loading type of model which caved and subsided following creation of the longwall extraction. The physical size scale was 1: 156.25 whilst the strength scale was 1 : 214.

Figure 3 shows the effect of taking a 5.6 m extraction height in a seam of depth 137.5 m below the surface. Coal Measures sedimentary rocks were simulated in the overburden above the longwall extraction. The longwall width was established initially at 128 m and the caving behaviour observed; as is seen in Figure 3(a) a significant bed separation formed at the boundary between the caved zone and the competent (uncaved) rock spanning the extracted

202 Whittaker, Reddish & Sun - Mine Design and Planning Aspects when Undermining Aquifers and Surface Water Bodies

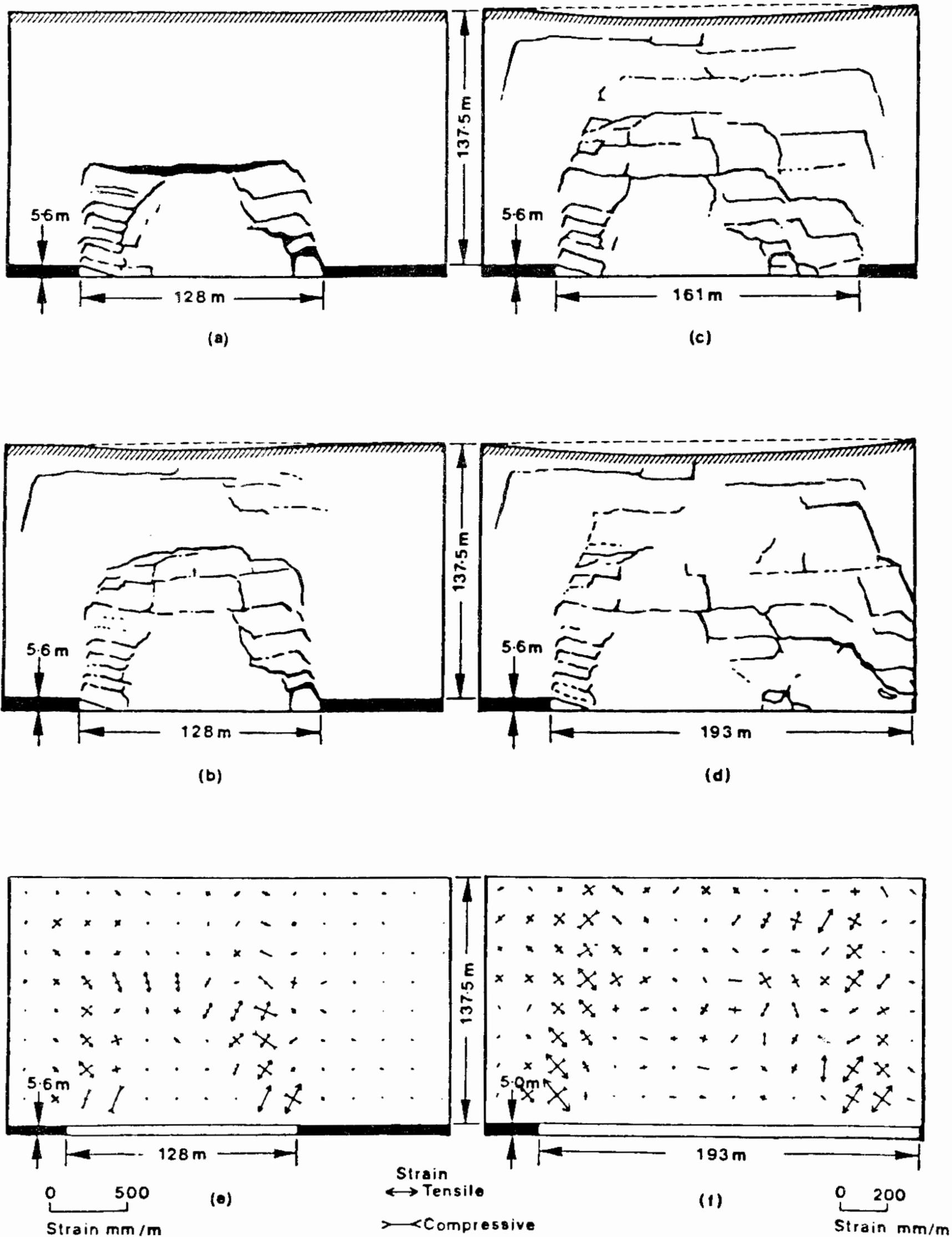


Figure 3: Fracture development pattern and strain vectors for increasing width of longwall extraction after Whittaker et al.<sup>(6)</sup>

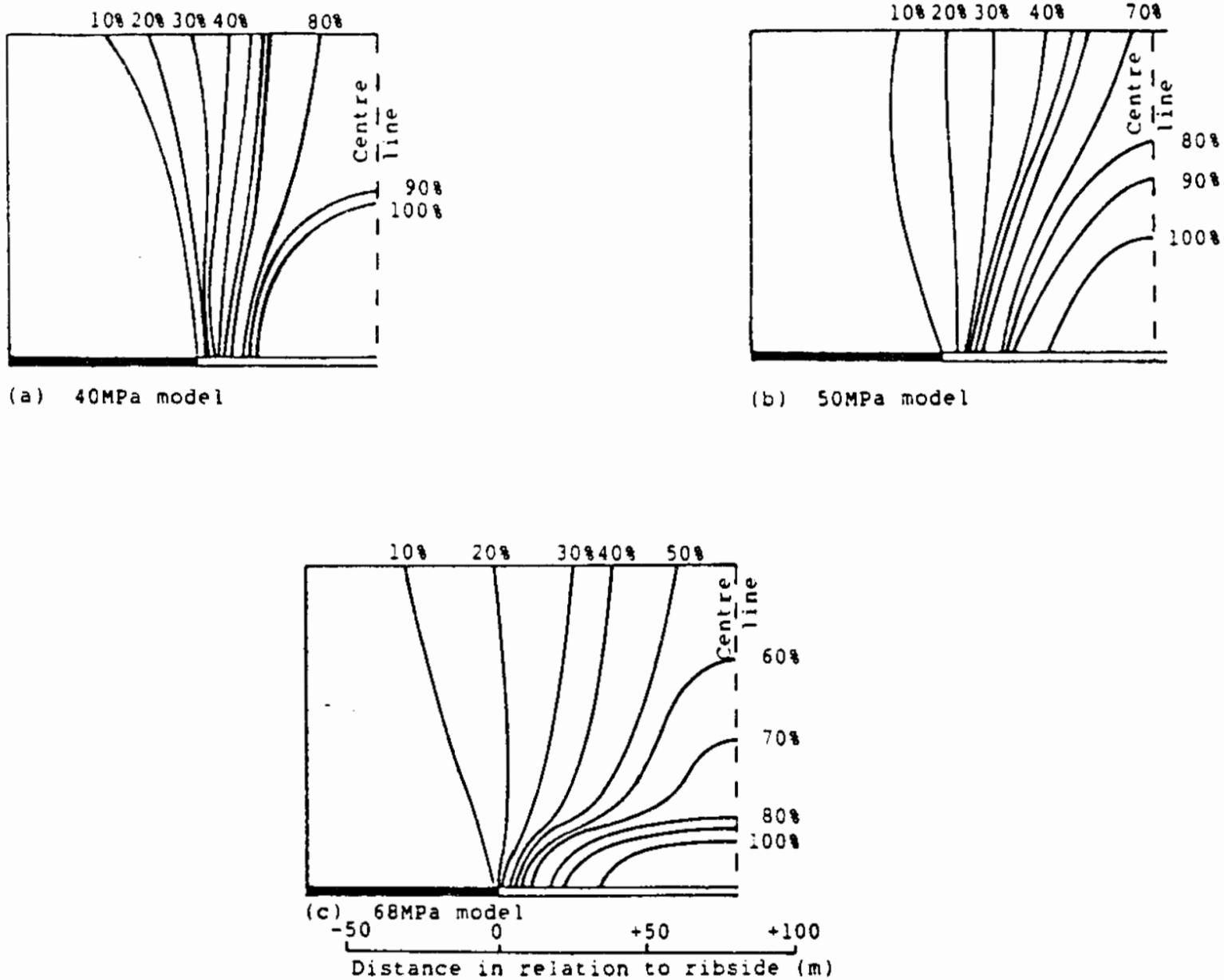
**Whittaker, Reddish & Sun - Mine Design and Planning Aspects when Undermining 203  
Aquifers and Surface Water Bodies**

area. The caving process progressively increased vertically and eventually choked itself at a height about equal to the extraction width; subsidence developed at the surface after the caving process was transmitted through the overburden. The large bed separation which occurred as an early feature (see Figure 3 (a)) is of special importance to those situations which contain aquifers in the overburden since this size of bed separation can create drainage and the formation of a large body of water which could seep or rush into underlying mine workings.

Increasing the longwall width to 161 m and 193 m demonstrates fracture development towards the surface, but without the occurrence of significant bed separations. The influence of the ribside in creating a significant zone of fracture development is clearly illustrated in all these situations. The central region of the caved ground is less affected by fracturing than the edges of the longwall extraction.

Figure 3(a) illustrates a measure of symmetry in its caving behaviour. As the longwall width was increased (by extending the extraction on the right-hand side of the model, whilst keeping the left-hand side static) the caving angle became shallower over the advancing face side (RHS).

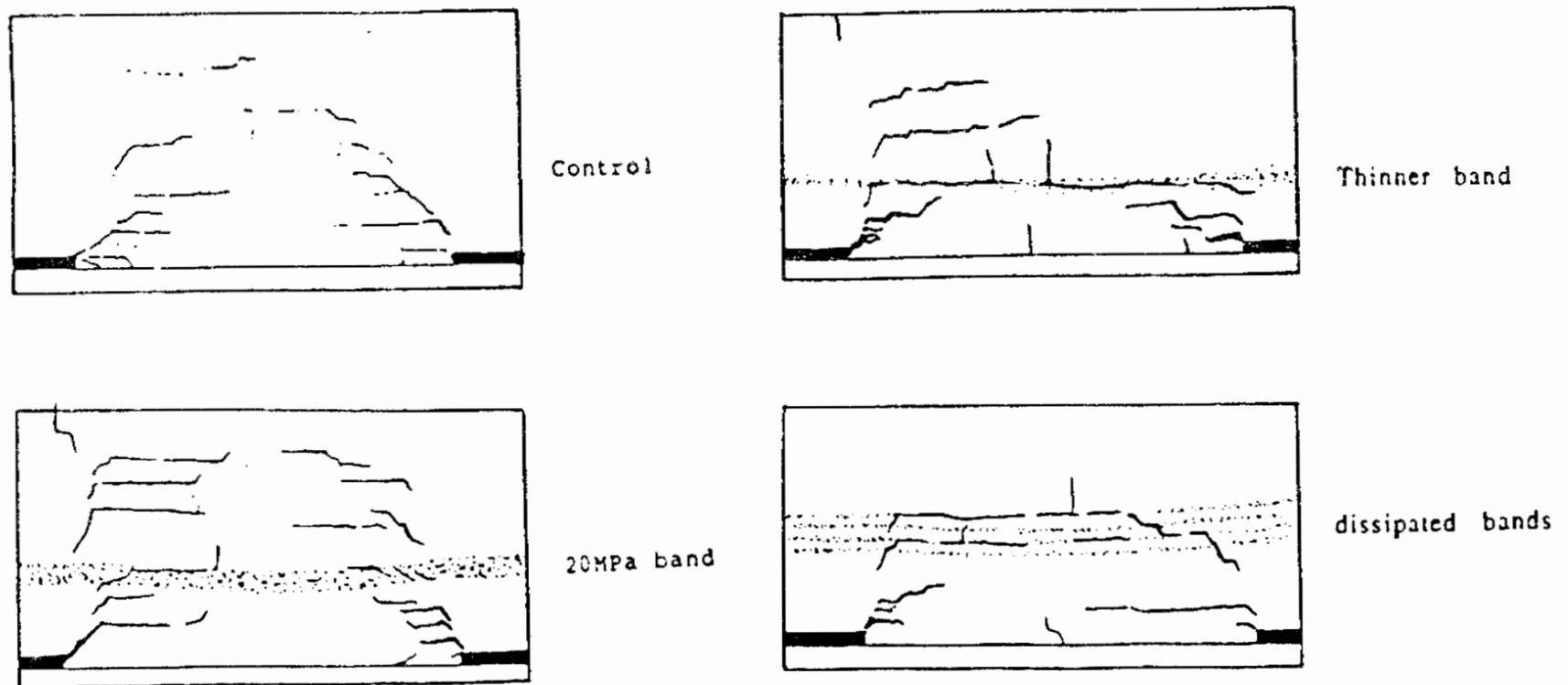
Strain vectors are shown in Figure 3(e) and (f) for longwall extraction widths of 128m and 193 m respectively, and these illustrate the high intensity of strain around the solid ribside and the low intensity around the centre of the caved zone. The strain vectors show the existence of compressive and tensile components (although at right angles) at various points.



**Figure 4: Influence of overburden uniaxial compressive strength on subsidence development above a caved longwall extraction**

### INFLUENCE OF INCREASING STRENGTH OF OVERBURDEN ON SUBSIDENCE DEVELOPMENT

Increasing strength of overburden influences the subsidence behaviour of rocks overlying the longwall extraction. Figure 4 shows results for three values of overburden uniaxial compressive strength. The results clearly show how even with substantially increased longwall width of extraction, the resultant surface subsidence is significantly reduced as the average overburden strength increases.



**Figure 5:** Effect of weak band on fracture development in overburden (seam thickness = 2.8 m, longwall width = 181 m, depth = 105 m)

### EFFECT OF WEAK BAND OF ROCK WITHIN OVERBURDEN

The effect of the presence of a weak band of rock within the overburden above a caved longwall extraction has been investigated and results are presented in Figure 5. A control model was used for purposes of comparing the results. The weak band of rock was incorporated in the model in three different forms: a thick band; a thin band; a dissipated series of thin bands.

The results show that a weak band can influence fracture development, and it tends to discourage fracture propagation. The several thin bands situation encourage repeated separation of the beds and tend to inhibit upward propagation of fracturing.

### TENSILE STRAIN MAGNITUDE IN RELATION TO DEPTH BELOW THE SURFACE

The physical model results have been employed to investigate the change in magnitude of the tensile strain vectors between the surface and mining extraction horizon. Figure 6 shows magnitude of the principal tensile strain vector in relation to depth, whilst Figure 7 shows a rationalised presentation of the results. The latter illustration employs a multiplying coefficient

# Whittaker, Reddish & Sun - Mine Design and Planning Aspects when Undermining 205 Aquifers and Surface Water Bodies

for  $M/h$  to yield the principal tensile strain using a similar approach to that employed in the British coal industry's subsidence handbook<sup>(7)</sup>. Both Figures 6 and 7 demonstrate a significant change in the tensile strain magnitude within the lower quarter of the depth below the surface.

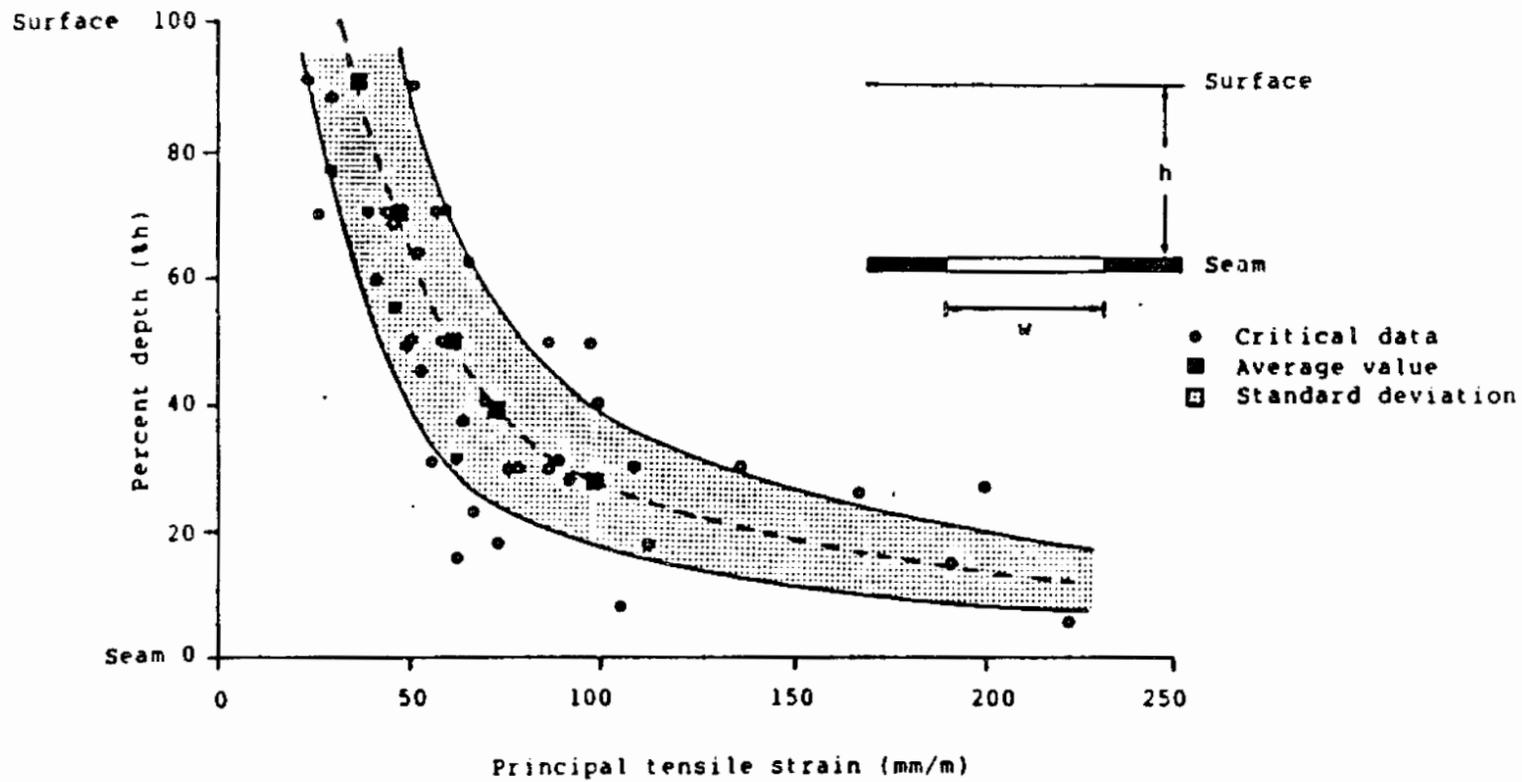


Figure 6: Principal tensile strain vector value in relation to depth below surface

## TENSILE STRAIN MAGNITUDE RELATED TO FRACTURE CONTINUITY

Fracture occurrences in the physical models have been analyzed and related to the magnitude of the tensile strain vector. Figure 8 shows a generalised presentation of the results for a longwall ribside in relation to the tensile strain magnitude. The results were obtained by visual examination of several physical models.

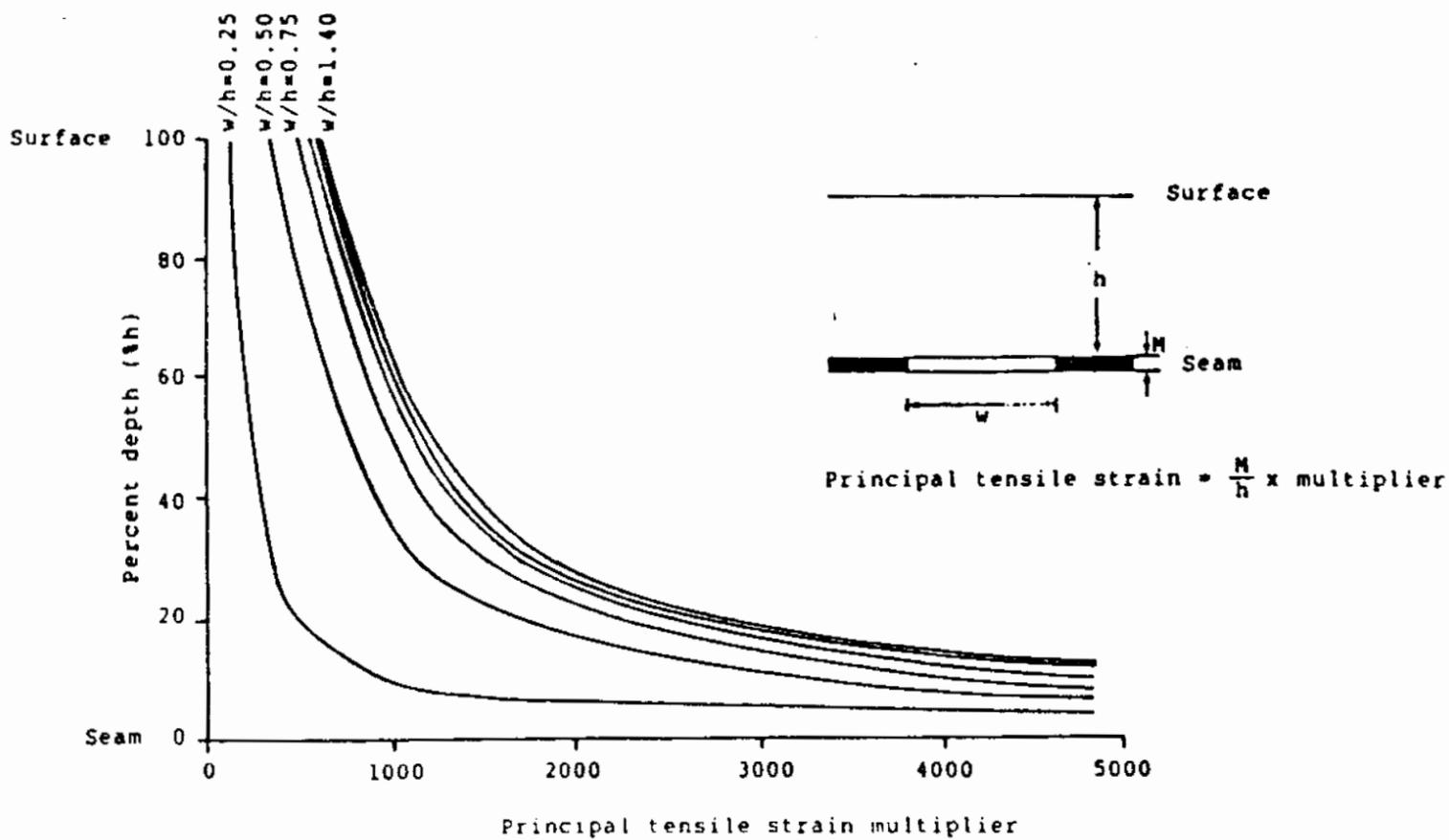


Figure 7: Principal tensile strain multiplier in relation to depth below surface for different w/h ratios

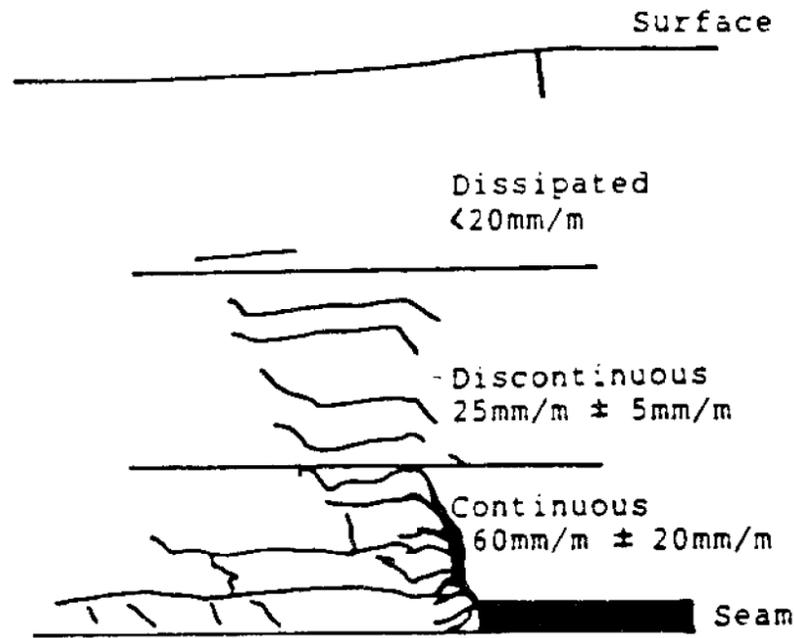


Figure 8: Fracture continuity in relation to the magnitude of the tensile strain vector for a longwall extraction ribside

### FINITE ELEMENT STRESS ANALYSIS RESULTS

The finite element method is a computer based mathematical modelling technique that assumes continuum mechanics and elastic behaviour. The method can, however, be adapted to simulate failure using what are described as nonlinear techniques. A nottingham University finite element model has been developed for mining subsidence analysis.

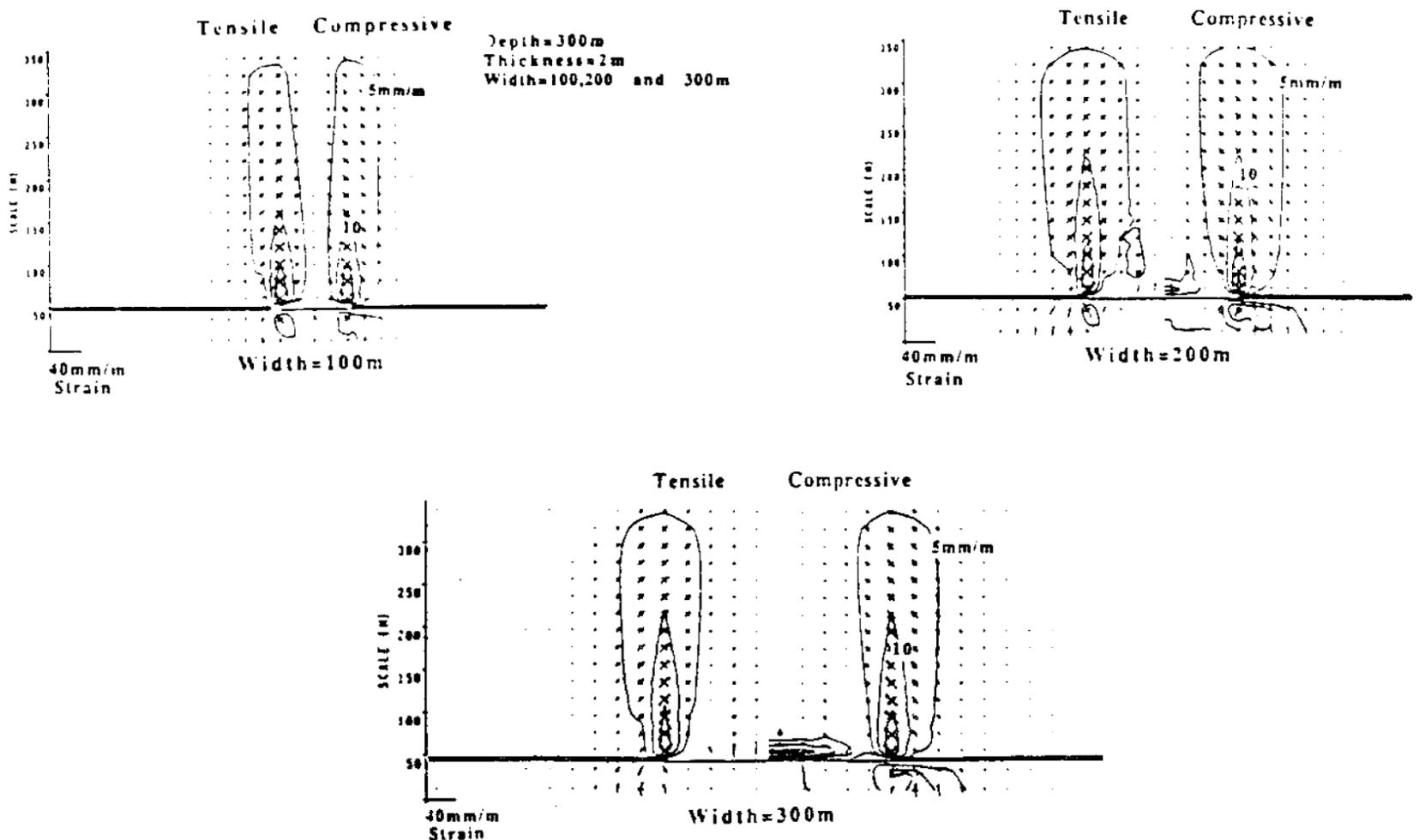
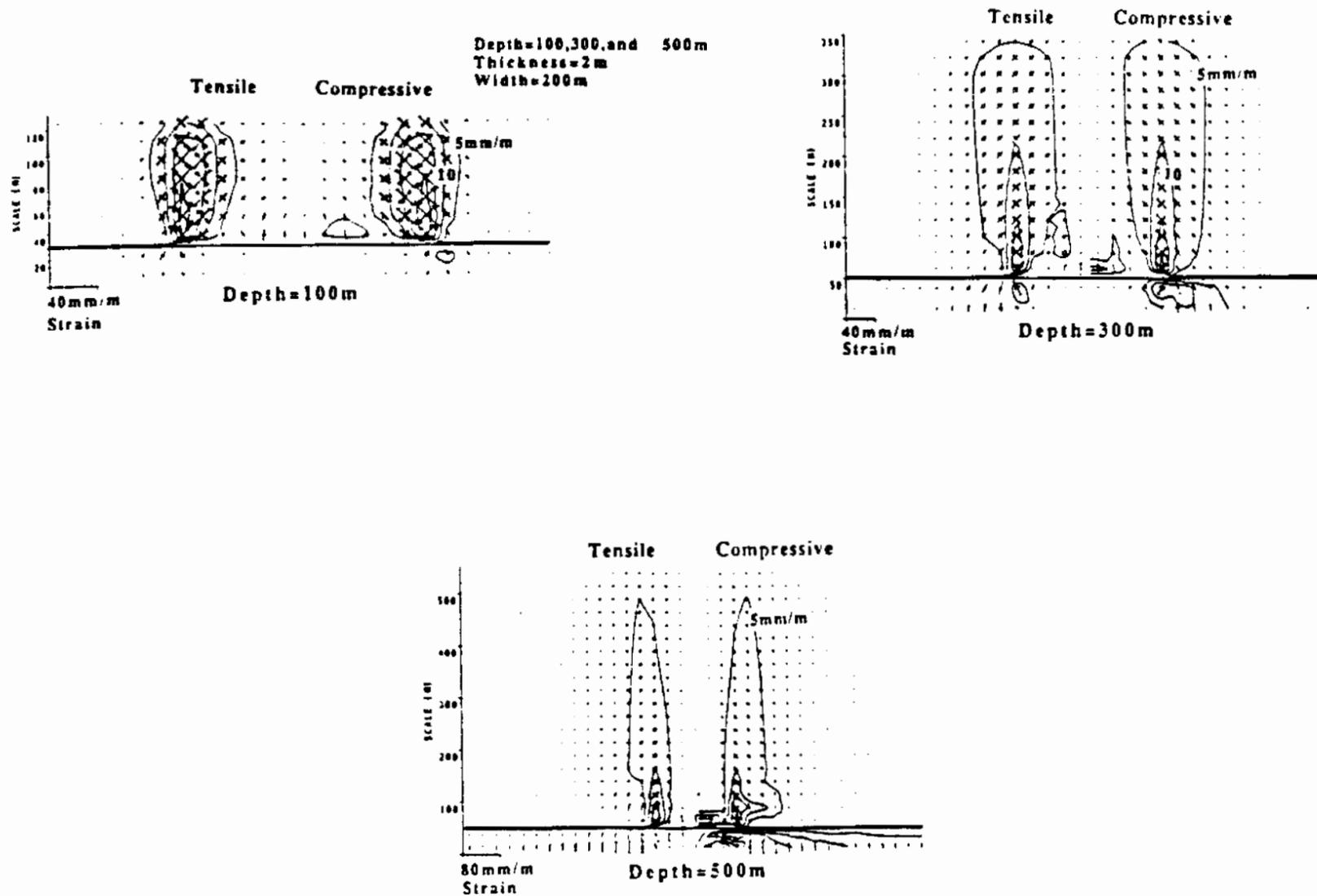


Figure 9: Induced principal strain vectors for various panel widths

# Whittaker, Reddish & Sun - Mine Design and Planning Aspects when Undermining 207 Aquifers and Surface Water Bodies



**Figure 10:** Induced principal strain vectors for various longwall mining depths

Nonlinear modelling requires the determination of a point at which material behaviour changes. For rock this point is that at which failure occurs and is normally determined by a failure criterion in the form of an equation. The finite element model employed here uses a modified Mohr-Coulomb criterion.

The finite element model has been applied to a range of mining longwall situations at different depths below the surface, various extraction widths and for different extracted seam heights. The model has been refined and calibrated to the NCB Subsidence Engineers' Handbook for a full range of mining geometries using one set of overburden material properties.

Figure 9 shows the configuration of induced principal strain vectors at 300 m depth, 2 m extraction height of longwall extraction widths of 100 m, 200 m and 300 m. The results show the progressive development of strain areas with increasing panel width. The most significant regions of strain concentration are seen to be localised around the ribside edges.

Figure 10 shows finite element principal strain vector results for mining depths of 100 m, 300 m and 500 m below the surface for an extracted seam height of 2 m and longwall extraction width of 200 m. The results show the characteristic change in the strain patterns for increasing depth.

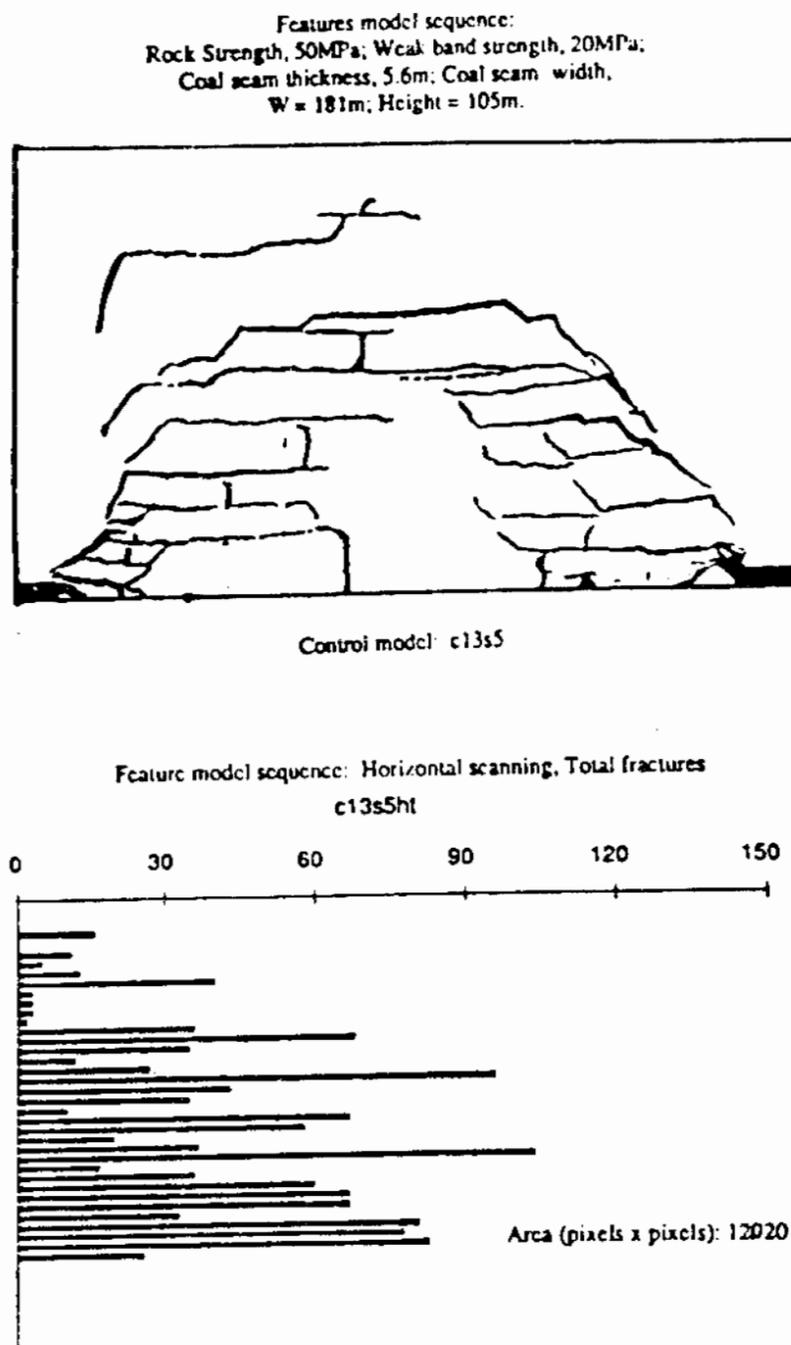
**IMAGE ANALYSIS RESULTS**

Image analysis has been applied to the physical model fracture patterns observed during the mining process. Measurement has been made of the fracture density distribution, which has been further divided into total, horizontal and vertical fracture density distribution by means of numerical filtering.

An example of the results as applied to a fracture model is presented in Figure 11 which shows a processed fracture image with a vertical distribution of total fractures as achieved by horizontal scanning.

The image analysis results show the general increase in fracture density towards the mining horizon. This permits quantification of the fracture intensity, and allows non-subjective comparison of models.

Image analysis of subsidence models is a useful method of comparing different fracture patterns in longwall situations.



**Figure 11:** Image analysis results for fracture pattern above longwall extraction

## CONCLUSIONS

### Physical modelling

The physical models have allowed a number of important potential failure mechanisms to be examined, and have strengthened current knowledge in this important area. The physical modelling technique has the major advantage over others in providing fracture patterns visually and in relation to forming the extraction. Fracturing is a key phenomenon concerning changes in permeability. Various geological and geometrical factors, which affect the fracture patterns, can be readily investigated. The results from the physical modelling provides first-hand information, which can be further studied in a systematic and quantitative manner. This greatly helps in the understanding of flow path potential, and provides guidance with due regard to geological and mining factors. The physical model results presented here clearly demonstrate their usefulness in this respect.

### Numerical modelling

The finite element results have shown similar patterns to the physical modelling results on comparable problems. The technique however shows some changes in strain areas with increased depth. The increased flexibility and repeatability of the finite element technique make it highly attractive as a modelling tool. The interpretation of finite element results in terms of permeability changes and fracture potential is however difficult due to a lack of the physical modelling studies can greatly assist in the interpretation of strains calculated by finite element method.

### Image analysis

The use of the image analysis technique has shown a promising improvement in model results interpretation. It serves as a useful supporting tool for subsidence and fracture pattern evaluation.

## ACKNOWLEDGEMENTS

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## 210 Whittaker, Reddish & Sun - Mine Design and Planning Aspects when Undermining Aquifers and Surface Water Bodies

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