SUBSURFACE FRACTURE DEVELOPMENT DUE TO LONGWALL MINING AND ITS INTERPRETATION USING IMAGE PROCESSING TECHNIQUES

by

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ABSTRACT

This paper presents the physical modelling results of subsurface fracture development associated with longwall mining operations and an application of image processing techniques to interpretation of the results. Physical modelling results have been obtained by employing a large sand and plaster model loaded purely by gravity as a means of fracturing the subsurface strata above the longwall excavation. The results have shown fracture development and crack propagation as a longwall face advances and demonstrated that the strength of stratified rocks, the presence and position of a weak band, and the extraction thickness, have significant effects upon the overall fracture patterns above the excavation.

Binary images of fracture patterns were scanned from the black and white photographs of the tested models using an image analyser coupled to a video camera. These images were manipulated by a custom written C program which allows the images to be processed in both vertical and horizontal direction. The images were filtered to quantitively differentiate between vertical and horizontal fracture intensities. The vertical fracture intensity is particularly important as vertical fractures are considered to provide the main avenues for surface and subsurface water inflow into the excavation. The use of the image analyser techniques has shown a promising improvement in image enhancement and in model results interpretation in a quantitative manner. The numerical nature of the image analyser results will allow further statistical comparison with other modelling techniques to be undertaken and significantly increase the scope for use of the modelling technique results.

INTRODUCTION

Potential water problems within existing and proposed coalfields have prompted a more detailed study of the mechanisms associated with longwall mining and caving. Although the mechanism resulting in surface subsidence is well understood with many different prediction models available, based on field measured data. The difficulty in measuring the subsurface strata movements has led to a shortage of knowledge upon the mechanisms involved in the collapse of strata above a longwall face before it reaches the surface. This is as a result of the inaccessibility of the subsurface strata, and therefore there is little reliable data available to be able to build up a comprehensive picture of subsurface strata movements. However, the study of surface-ground movement is of vital importance in relation to surface and sub-surface water inflow into the excavation. One approach to this problem has been the direct monitoring of strata movement and permeability changes from the surface to the mining horizon from boreholes drilled either from surface or from coal seams adjacent to the coal face being worked. The monitoring has usually taken the form of multi-axial extensometers, however, geophysical methods have been used with limited success. The cost of such methods has proved to be a limiting factor in their use, and therefore effective low cost methods are required to be developed. This has led to the development and application of various modelling techniques.

Modelling techniques can take many forms from purely mathematical models to empirical and even physical models. In the past years these modelling techniques have been developed at Nottingham University to simulate strata behaviour over longwall panels (e.g. Aiston, 1982; Reddish, 1984; Whitaker et al, 1985; Fitzpatrick, 1987; Gaskell, 1989; Whitaker and Reddish, 1989). The use of different modelling techniques has allowed comparisons to be made between different types of results with resulting improvements to the understanding of these various techniques. Physical modelling has a major advantage over other methods in that it is able to illustrate fracture and failure patterns visually, whereas numerical modelling has the advantage of perfect repeatability and precision.

However, the approach with the physical and numerical modelling techniques has been similar, sequences investigating the influence of major mining parameters width, depth, thickness, and rock strength having been investigated (Gaskell, 1989; Whitaker et al, 1991). Further more detailed work upon the influence of weak strata bands upon fracture continuity has also been undertaken. In particular, composite models with multiple seam extractions and with the in situ geological conditions at the Asfordby Mine site have been successfully accomplished. This modelling featured physical modelling, numerical modelling and case studies. The approach is particularly augmented by the development of image analysis techniques to quantitatively interpret the results from the physical modelling. This makes possible a non
subjective quantitative comparison between different models. The research results to be presented in this paper, however, concentrate on the following two situations. Firstly, the application of the physical modelling techniques to investigate the influence upon fracturing of a thin weak band located in various positions in the overburden of a longwall panel. Secondly, to contribute to the development of image analysis techniques for the interpretation of the physical modelling results. The physical models have been comprehensively validated by comparing the models' surface subsidence with the Subsidence Engineers' Handbook's (SEH, 1975) empirically predicted profile.

PHYSICAL MODELLING TECHNIQUES

The physical modelling approach adopted in this study is based upon the laws of similitude which allow the calculation of an equivalent model strength for a full scale situation. Dimensional analysis and the laws of similitude are achieved by applying Buckingham's Theorem stating that complete equations can be reduced to a functional relationship between a complete set of independent dimensionless products. By using the technique of dimensional analysis a geometry scale factor and a strength scale factor can be determined, which are then used to construct the physical models. A detailed discussion of the dimensional analysis regarding the physical modelling technique can be found in Whittaker et al. (1985). In this study the geometry scale factor and the strength scale factor were determined as 156 and 214 respectively. It is important to note, however, that the in situ rock strength is approximately determined by dividing the strength obtained in the laboratory by a factor - in situ rock strength reduction factor, which can be found in Wilson (1982). This reduced in situ rock strength is then used to calculate model strength based on the strength factor.

The models were constructed using a damp sand/plaster mixture cast in distinct lcm layers into a 3m x 1.5m x 0.15m test rig. A measured quantity of fine sawdust was spread evenly between each layer cast to simulate stratified rock. The proposed extraction was achieved by removing laminate blocks inserted during casting. The effect of extraction thickness was simulated by removing a number of blocks of different thicknesses, known as extraction stages. In this study, five extraction thicknesses (0.7, 1.4, 2.8, 4.2 and 5.6m) were simulated. A thin weak band with a thickness of 4mm was introduced with three locations known as higher (47m), medium (31m) and lower (15m) position with respect to the excavation. Full details relating to the geometry and strengths of the physical models are shown in Fig.1. The model is allowed to cave under the influence of gravity alone, measurement of displacement being taken on the surface at each stage of extraction. Fracture patterns were obtained from photographs and evidence, which can be used for subsequent study employing image analysis techniques.

The main emphasis of the physical modelling has been to evaluate fracture community and distribution around longwall panels, with a view to quantify risks associated with undermining aquifers. The models have been validated by comparing the models with an idealised reality. The surface boundary of the model and the surface in reality are the only places where direct comparison of model and reality is reasonably achieved. Many observations at the surface have allowed a statistically reliable surface subsidence model to be developed in the SEH (1975). The physical models have been compared at surface with the SEH and have shown close agreement. Surface subsidence results for all the models have been compared with the SEH as routine practice.

PHYSICAL MODELLING RESULTS

The results from the model tests are presented in two categories, firstly as surface subsidence profiles and secondly as line diagrams visually showing the fracture patterns. Surface subsidence profiles for the two extreme cases of the weak band in lower and higher positions are plotted in comparison with the SEH predicted and are shown in Fig.2 for the five extraction thicknesses. The profiles are fairly consistent with SEH predicted profiles. In Fig.2, the effect of band position upon the surface subsidence is apparent. A general trend of a decrease in surface subsidence with the height of the weak band position above the seam is clearly indicated. Fig.3 shows the extraction thickness effect on the profiles, illustrating the progressive nature of subsidence development. Good agreement with SEH predictions at all stages is again observed. Fig.4 illustrates the change in shape of the subsidence trough with increasing extraction thickness. It is seen that the model with the weak band in higher position shows a flatter and wider subsidence profiles than the model with the weak band in lower position which gives a steeping and narrowing of the subsidence profiles.

The fracture patterns for the sequence of extraction thickness (1.4m-5.6m) are illustrated in Fig.5, showing the effect of extraction thickness upon the fracture development. The fracture patterns for the weak band sequence with an extraction thickness of 5.6m (i.e., the final stage only) are illustrated in Fig.6(a). This sequence shows the influence of the weak band position upon the fracture development. The following features on the fracture patterns have been noted:

1) At earlier stages of extraction (smaller extraction thickness), similar features on the fracture patterns for all the three cases are observed, indicating the position of the weak band shows similar effect. By increasing extraction
thickness, the fracture pattern became more defined and continuous. Although the extent of fracturing is constant for all cases, the surface tension effects become more apparent. Noticeable is the surface fracture penetration which increases considerably as extraction thickness increases. Finite element analysis of the subsidence models have shown that an increase in extraction thickness results in an increase in strain magnitude in the lower part of the models (see for example, Gaskell, 1989; Whittaker et al., 1991).

2) Small but numerous fractures are developed in the model with the weak band in lower position when compared to the other two cases, showing the fracturing to be more dissipated.

![Graphs showing subsidence profiles compared with SEH predictions.](image)

**Fig. 2** Surface subsidence profiles compared with SEH predicted

3) The presence of the weak band within the model causes an apparent reduction in overall model strength indicated by steep break angle, extra surface subsidence, and surface tension fractures. The position of the weak band as a parting plane for a steep initial break seems to be important. Good parting planes were indicated to have some control over the angle of break in the lower sections of the model. The fracture break angle between the extraction and the band base is almost vertical, indicating the effective span for the overburden in this location is greater than for a model without any weak band (The control model). This in turn has caused the model to have a greater effective span at the band and is probably the reason for better subsidence development, and more dissipated and generally displayed weak nature of fractures throughout the banded models series. This feature in turn leads to more comprehensive failure in the upper sections of the models.

4) The sequence of models investigating the influence of weak bands upon the propagation of fractures, has demonstrated fractures to be refracted by the weak band. The refraction of the fractures has tended to reduce the potential inflow paths. The position of the weak band however, has been shown to have only a minor influence upon the degree of refraction in the band itself but the overall failure pattern is different. Fractures travelling into weak bands have been shown to be deflected in such a way as to reduce their potential for fluid inflow. This effect is important in explaining the beneficial effects of
weak mudstone bands in the overburden at certain collieries in the U.K. This section has demonstrated an interesting feature suspected by geologists at a number of collieries. The combined effect of fracture reactivation and the sealing properties of weaker rock types (greater tendency towards plastic behaviour, and production of expanding clays on contact with water) is to seal overlying aquifers from workings in conditions that would normally cause water problems.

The above analysis of the distribution and intensity of fracturing has been relatively subjective. To improve results interpretation in a quantitative manner the use of an automated image analysis technique has been adopted. The following section describes the image analysis technique.

**IMAGE ANALYSIS TECHNIQUES**

**BACKGROUND**

The sand/glasser physical modelling method provides valuable information on surface subsidence profiles and subsurface fracture characteristics and development. In order to investigate the effects of fracture distribution on the likelihood of surface and subsurface water inflow into longwall workings, it is felt important to analyse the photographic records obtained from the physical modelling in a systematic and quantitative manner. A quantitative presentation of features allows for detailed comparisons between different models so that less subjective conclusions can be drawn with respect to the water inflow into the workings.

Recent advances in automatic image analysis have initiated interest in the potential use of this technology in the interpretation of the results from the physical modelling.

The image analysis techniques have been used frequently for the measurement of the size distribution of fragmented materials with considerable success. These techniques combine the best aspects of advanced computers and optical instruments. The main facility for this analysis is an IBAS 2000, which includes an extensive, fully automatic software driven control system. The IBAS 2000 system consists essentially of an image processing unit which is controlled by a XSI host microcomputer. A keyboard, data monitor and colour monitor are supplied for access, control, and visual representation of the measurement process, with a digitizing tablet and cursor supplied for interactive work. In addition, a video camera and macro-stand are included for the direct analysis of photographic media.

The application of the image analysis techniques to
the analysis of subsurface fracture patterns is extensive and complex and requires careful consideration, but generally speaking, this process consists of the following three stages: sample preparation, image acquisition and the image analysis itself. A brief description of these three stages is given below.

**SAMPLE PREPARATION**

Sample preparation is concerned with the photographic acquisition of the initial images from the physical model tests, which includes the whole fracture pattern to be analysed. During this preparation extreme care is taken to obtain good quality images in the form of black and white photographs. Black and white photographs are sufficient as the analysis system works upon grey levels rather than colour. This includes careful photographic techniques, such as controlling the exact location of the camera (distance and angle from the model, height to the ground). exposure time, consistent and good lighting, focus and clear contrast. These parameters must be standardized for all images taken for all excavation stages and all models such that direct comparisons can be made without external influencing factors.

**IMAGE ENHANCEMENT**

Image enhancement concerns the processing of raw images into ones that only include the fracture pattern, this involves appropriate editing techniques. The image enhancement is conducted purely on the IBAS 2000 system.

The image is captured by a process of automatic digitisation, i.e., by scanning the well-prepared black and white photographs of the tested models through a video camera and monitor with a screen resolution of 640 x 512 pixels. The image is divided into an array picture of points (pixels), each one being assigned a brightness, or grey level value (0, black to 255, white) according to the strength of signal detected. Special attention is required to minimize the subsequent editing processes so as not to exclude any minor or partly closed fractures.

This can be achieved by the utilization of a scale marker on the photograph or by directly observing common features from the image on the screen. This ensures that different images have their fracture patterns scanned at approximately the same size. It is important to ensure however that no fractures are missed out (particularly the two tensile fractures at the two extreme sides). This process is important to ensure a pixel to have the same equivalent fracture area for all images.

After an image is input and scaled, the desired image is then stored as a binary image in the memory for further editing. The final binary image is achieved by the removal of grid lines, the band and other unwanted objects by the use of their differing grey levels. The separate objects in the binary image are then the patterns comprising only the fractures. These binary images are stored onto floppy diskettes as two dimensional binary arrays which are ready for subsequent further processing. All the above image filtering is achieved on the IBAS 2000 system. The next stage of analysis is conducted on an IBM PC.
(a) Fracture patterns for the weak banded models
Extraction thickness $M = 5.6$ meters

(a.1) Lower position (15 meters above seam)

(a.2) Medium position (31 meters above seam)

(a.3) Higher position (47 meters above seam)

(b) Total fractures for horizontal scanning

(b.1) Lower position (15 meters above seam)

(b.2) Medium position (31 meters above seam)

(b.3) Higher position (47 meters above seam)

Fig. 6 Fracture patterns and fracture distributions for horizontal scanning
Fig. 6 Fracture patterns and fracture distributions for horizontal scanning (continued)
Fig. 7 Fracture distributions for vertical direction scanning

**IMAGE ANALYSIS**

Image analysis refers to the measurement of fracture density distribution, which is further divided into total, horizontal, and vertical fracture density distribution by means of filtering. An additional useful parameter, the relative fracture area, is found useful to characterize and compare fracture patterns for different models.

Standard image analysis functions were found to be insufficient for the very specific analysis required, and most of the analysis took place on an IBM PC using custom-written software to manipulate the images.

Each image was scanned twice horizontally and once vertically. Horizontal scanning of the image provided fracture distribution along the vertical direction (from top to bottom) to show fracture density variation relative to the distance from the roof of the excavation. In this case, the image is scanned line by line (horizontal) from the top to the bottom.
(c) Vertical fractures for vertical scanning

Vertical scanning of the image, however, provides fracture distribution along the horizontal direction (from the left to right) to illustrate the fracture density variation with the position of the working face. In this case, the image is scanned line by line (vertically) from the left to the right of the image and the fractures encountered by the vertical lines are accumulated as the total fractures for those lines.

Filtering of the image was undertaken for each scanning direction by introducing a cut point of 10 pixels to quantitatively differentiate between vertical fractures and horizontal fractures, and an index may be defined accordingly. The 10 pixels cut point was determined after trials on results of a large number of different cut points. The 10 pixels cut point results were found to be the most satisfactory in splitting vertical and horizontal fractures. The fractures encountered by a scan line are considered as objects of different sizes (chords in pixels). For example, when horizontally scanning if the fracture chord length (in pixels) is less than 10 pixels then the fracture is regarded as a vertical fracture which is then added to the vertical fractures. If the fracture chord length is larger than 10 pixels then this fracture is considered as a horizontal fracture which is then accumulated to the horizontal fractures. The same principle applies to the vertical scanning, but in this situation the fractures with chord lengths less than 10 pixels are regarded as horizontal fractures, and was used. Therefore, for each scanning direction three figures are obtained, i.e., total fractures, horizontal fractures and vertical fractures.

For each image six fracture distributions are then achieved with three from each scanning direction, that is, for both horizontal and vertical scanning directions, there are total, horizontal and vertical fracture distributions. To make the image clearer and easier to follow, for each scanning direction, every 10 pixels wide bands (10 lines) rather than single lines were grouped and mean values of the fractures (total, horizontal and vertical) for the group were used to plot the fracture distributions. Standardised scales and the plotting of the complete model series on a single sheet help to ease comparison of the plotted distributions.

### IMAGE ANALYSIS RESULTS

The image analysis was conducted on two sequences, firstly an extraction thickness sequence and secondly the weak band position model sequence. Due to the limited amount of space, the results for the latter sequence only are illustrated in Fig.6(b) - 6(d) for the horizontal scanning and in Fig.7 for the vertical scanning. The position of the weak band and the two fracture levels of 15 pixels and 20 pixels respectively are also shown on the figures for easy comparisons of the fracture distributions. The fracture areas (total, horizontal and vertical) are calculated and shown on the figures. The fracture area is an important parameter indicating the total amount of fractures. An index of vertical to horizontal fractures can be determined accordingly, which is also another important parameter reflecting the proportion of vertical fractures. The density of vertical fractures is considered to be probably directly related to the risk of water inflow into workings. Fractures constitute the greatest potential for inflow and therefore their density is critical to quantification of water inflow into mine workings.

A number of features can be observed from the image analysis results.

Firstly, Fig.6(b), 6(d) and Fig.7 illustrate the...
following general characteristics of the fracture patterns for the weak banded models: the quantity of fractures generally increases from the model surface towards the coal seam; fracture distribution is symmetrical about the centre of the panel. Horizontal fractures are significantly more developed than vertical fractures as expected since most fractures are developed along bedding planes. The majority of vertical fractures are developed close to the two ends of the excavation with few fractures in the central area over the excavation.

Secondly, the presence of the weak band shows a significant influence upon the fracture intensity: the quantity of fractures decreases with increasing height of the weak band with respect to the coal seam - fracture area is largest for the weak band in lower position and smallest in higher position. The lower weak band position would appear to encourage greater fracturing area. The vertical fractures are greatest for the higher position and smallest for the lower position. A higher band position would appear to encourage more vertical fractures. The absolute quantities of fractures provide a useful general guide for interpretation of the fracture patterns, however, they are unable to accurately quantify the paths for water inflow into the workings. However the study of two fracturing levels, namely dissipate fractures, and continuous fractures can provide valuable information relating to water inflow into the working. This will be discussed in more detail in the following section.

The image analysis results undertaken on the image sequence to investigate the effect of extraction thickness on the fracture pattern have demonstrated that fracture areas (total, horizontal and vertical) increase with extraction thickness and linear relationships have been obtained. The ratio of vertical fractures to horizontal fractures decreases with increasing coal seam thickness. As the extraction thickness increases the proportion of horizontal bed pairings increases.

Further analysis of the image analysis results was undertaken based on fracturing levels defined from previous experience. The fracture levels shown in the six distributions relate to the particles (amount of fracture) intersected in the image. From experience in earlier physical and numerical models, two critical levels of fracturing have been assessed and utilized with the first being a level of 15 pixels and above, equivalent to dissipate fractures with some potential for water inflow, and level 20 pixels and above for continuous fractures with very significant potential for water inflow. These cut points were derived from the fracture level definition described in detail in Gaskell (1989) and Whitaker et al (1991). It is relatively easy to determine what percentage of the fractures are above a certain intensity level in any distribution, and this approach has been applied to the image analysis results to simplify them into the data summarized in Table 1 for the series of three models all at a 5.6 metre extraction thickness. The simplified data are presented as fracture areas and the percentages of fracturing in vertical and horizontal directions for the two critical levels. The fracture areas and percentage continuity allow direct comparative comparison of the real situations. This table of data has been derived from manual processing of the raw image analysis results as shown in Fig.6(b) - 6(d) and Fig.7.

Although the information in the table is complete showing distributions vertically and horizontally for total, vertical and horizontal fractures. The most important factor concerning water penetration is almost certainly the vertical distribution of vertical fractures followed closely by the vertical distribution of horizontal fractures. The larger figure provided in the table is the scanned area of fractures which provides a useful additional comparison between fracture stress. A 100 percent figure would indicate complete connection in that direction. Conversely, a zero percent figure would indicate no connection in that direction.

The model with the weak band in higher position is seen to be consistently better than that with the weak band in lower position. For example, the vertical distribution of vertical dissipate fractures are 44 and 66 percent respectively, illustrating the model with the weak band in higher position is some 22 percent better. The vertical distribution of continuous fractures are 24 and 66 percent respectively illustrating the model with the weak band in higher position is some 42 percent better. Almost the same conclusion can be drawn from the vertical distribution of horizontal fractures. The condition for the model with the weak band in medium position is between them.

It is important to note, however, that the information in Table 1 is based on a 5.6 metre extraction and thus is exaggerated to some extent. In order to allow a better understanding of the potential fracture levels the information needs adjusting for extraction thickness equivalent in the real situations. Each model is ideally scanned at different extraction thicknesses, and these can be used to determine the relationship between fracture percentage continuity and extraction thickness. It has been demonstrated that linear relationships between extraction thickness, fracture continuity percentage and fracture area for the different scanning approaches were obtained. Based on these relationships the results in Table 1 can be adjusted to those for real situations with reduced extraction thickness. Full details regarding this derivation is given in more detail in Whitaker et al (1991).

CONCLUSIONS

PHYSICAL MODELLING RESULTS

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 excavation. Fracturing is a key phenomenon concerning changes in permeability. Various geological and geometrical factors, which affect the fracture pattern, 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 inflow 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.
<table>
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<td></td>
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<tr>
<td>Total Fractures</td>
<td>Mean total fractures of both scanning directions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percentage of fracture levels in terms of total fractures for horizontal scanning</td>
<td>91% 80% 62% 52% 71% 59%</td>
</tr>
<tr>
<td></td>
<td>Percentage of fracture levels in terms of total fractures for vertical scanning</td>
<td>67% 62% 75% 62% 67% 53%</td>
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<tr>
<td>Vertical Fractures</td>
<td>Mean vertical fractures of both scanning directions</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>Percentage of fracture levels in terms of vertical fractures for vertical scanning</td>
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<tr>
<td>Horizontal Fractures</td>
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<td>Percentage of fracture levels in terms of horizontal fractures for horizontal scanning</td>
<td>73% 67% 56% 56% 48% 30%</td>
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<td></td>
<td>Percentage of fracture levels in terms of horizontal fractures for vertical scanning</td>
<td>66% 66% 33% 33% 44% 24%</td>
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</table>

Table 1 Dissipated and continuous fracture levels associated with extraction thickness of 5.6m

**IMAGE ANALYSIS RESULTS**

The processing language of the image analyser is powerful and flexible and allows a wide range of processing and data screening techniques to be applied to the image. Discussion of the most significant fracture features concerning water inflow is important in terms of targeting the processing technique. The prepared black and white fracture image is far superior in quality to the hand prepared images presented in earlier results. Further analysis of the image analysis results provide valuable information in relation to water inflow into the excavation.

The use of the image analysis technique has shown a promising improvement in image enhancement and in model results interpretation in a quantitative manner compared with the convolutional method. Another more complex processing technique could also be developed in that the image could be analysed into a series of vectors representing fracture length, direction and width. The statistical distribution of particular fracture parameters could then be assessed, but this approach would involve considerable development work.

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