The Numerical Analysis of Subsurface Deformation in Relation to Minewater Ingress at Wistow Colliery

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ABSTRACT

In July 1983 an influx of water occurred on the first Barnsley face at Wistow Mine in the Selby Coalfield. At its peak the estimated inflow exceeded 120 l/s (1600 gpm), the source of the water was from Permian aquifers which were present between 75 - 85m above the Barnsley seam. This paper describes the mining background, together with the geological and hydrological controls thought to be responsible for the water ingress that persisted over four of the first six faces at Wistow. Within two years of the first influx mining personnel at the colliery eliminated the inflow of water on adjacent faces by the application of horizontal strain criteria which had successfully been employed in the North East Coalfield when mining coal below the Permian and the North Sea. Wherever possible within the "A" block district, the mining layout was modified to reduce the apparent maximum horizontal tensile strain to less than 10 mm/m.

As a further consequence of the influx a research programme was sponsored jointly by British Coal and the European Coal and Steel Community, to evaluate the principle factors that control mine water ingress onto longwall faces from overlying aquifers. One of the primary objectives of this research was to develop a numerical model capable of predicting the subsurface strata deformation which occurs following the extraction of coal by longwall methods. The model has been developed by Golder Associates and has been applied directly to the Wistow situation. The results have confirmed the presence of bed separations immediately below the Permian unconformity, which were in direct contact with the overlying aquifer. The magnitude of the principal strains resulting from the development of horizontal bed separations are, considerably lower than those predicted using the empirically derived criteria from the North East Coalfield where the sea bed is able to act as a free surface.

INTRODUCTION

Within the mining industry a sudden unexpected influx of water from an overlying aquifer can, at worst, lead to loss of life but will more commonly result in the total disruption of coal production, the loss or damage to longwall mining equipment that can cost several million pounds to replace, and the sterilisation of thousands of tonnes of coal reserves. Steady state inflows, while not necessarily being so catastrophic can be a constant nuisance, creating poor working conditions that reduce the efficiency of the mining equipment and morale of the work force.

Guide lines controlling the safe working of coal below a known aquifer at statute level are clear. Her Majesty's Inspectorate of Mines forbids the mining of coal within

45m of a known aquifer. However, at the present time, there are no clear guide lines or design methods available to a mining engineer to assess the likely risk of mining coal up to this 45m metre cover line.

Within the United Kingdom, guide lines that do exist are based on local, empirically derived criteria, mainly from the North East of England. Risk assessment criteria have been generated from this coalfield for coal workings below the sea bed and under high permeability Permian and Coal Measure aquifers. The criteria have developed from a combination of local mining experience passed down through the years, calibrated with strain criteria derived from the Subsidence Engineers Handbook(1). The criteria assumes that the sea bed or base of a confined aquifer can be regarded as a free surface. A proposed mining layout is deemed "safe" when the maximum horizontal tensile strain, induced on the base of the aquifer by its geometry and seam extraction height, does not exceed 10 mm/m. A further statistical study conducted by Garritty(2) suggested, that for certain geological sections, this safe limit should be reduced to 6 mm/m.

In the coalfields of Yorkshire and the East Midlands, the exhaustion of coal reserves in the western exposed coalfields over the last 20 years, has necessitated the exploitation of coal underlying Permo-Triassic cover rocks containing high permeability aquifers under artesian pressure. The development of the Selby coalfield in the mid 1970's is one such project. Wistow Mine is one of five mines within the Selby complex. It is the shallowest of the mines both in terms of depth of coal below surface and the interval to overlying Permo-Triassic Strata. Wistow "A" block in the Barnsley seam contained the first production face in the coalfield.

This paper describes the mining background, together with the geological and hydrological controls, thought to be responsible for the occurrences of a substantial water ingress that persisted over four of the first six faces. The paper describes the application of a numerical model to the Wistow case history which is able to predict the subsurface strata deformation induced on the immediate overlying Coal Measures and Permo-Triassic aquifer, by the longwall extraction of the Barnsley Seam.

MINEWATER INGRESS AT WISTOW

A graphic section showing the geology in the immediate area is given in Fig 1. The thickness of intervening Coal Measure strata to the Permian is between 75 - 80m. The Coal Measures contain about 80% of competent strata (siltstone and sandstone) in units up to 20m in thickness. The Permian sequence consists of 3 - 7m of weakly cemented Basal Permian Sands [BPS] which are overlain by 61m of Lower Magnesian Limestone [LML].

The permeability of the intervening Coal Measure rocks in this area is very low, of the order of 1×10^{-10}m/s. The BPS and the LML are both highly permeable, confined aquifers with artesian pressures of up to 10m above surface. The permeability of these two formations is 5×10^{-5}m/s and 2×10^{-4}m/s respectively. The LML in the immediate vicinity of "A" block is characterised by the development, over its lower 10m, of a highly vuggy texture that dramatically reduces the in-situ strength of the formation.

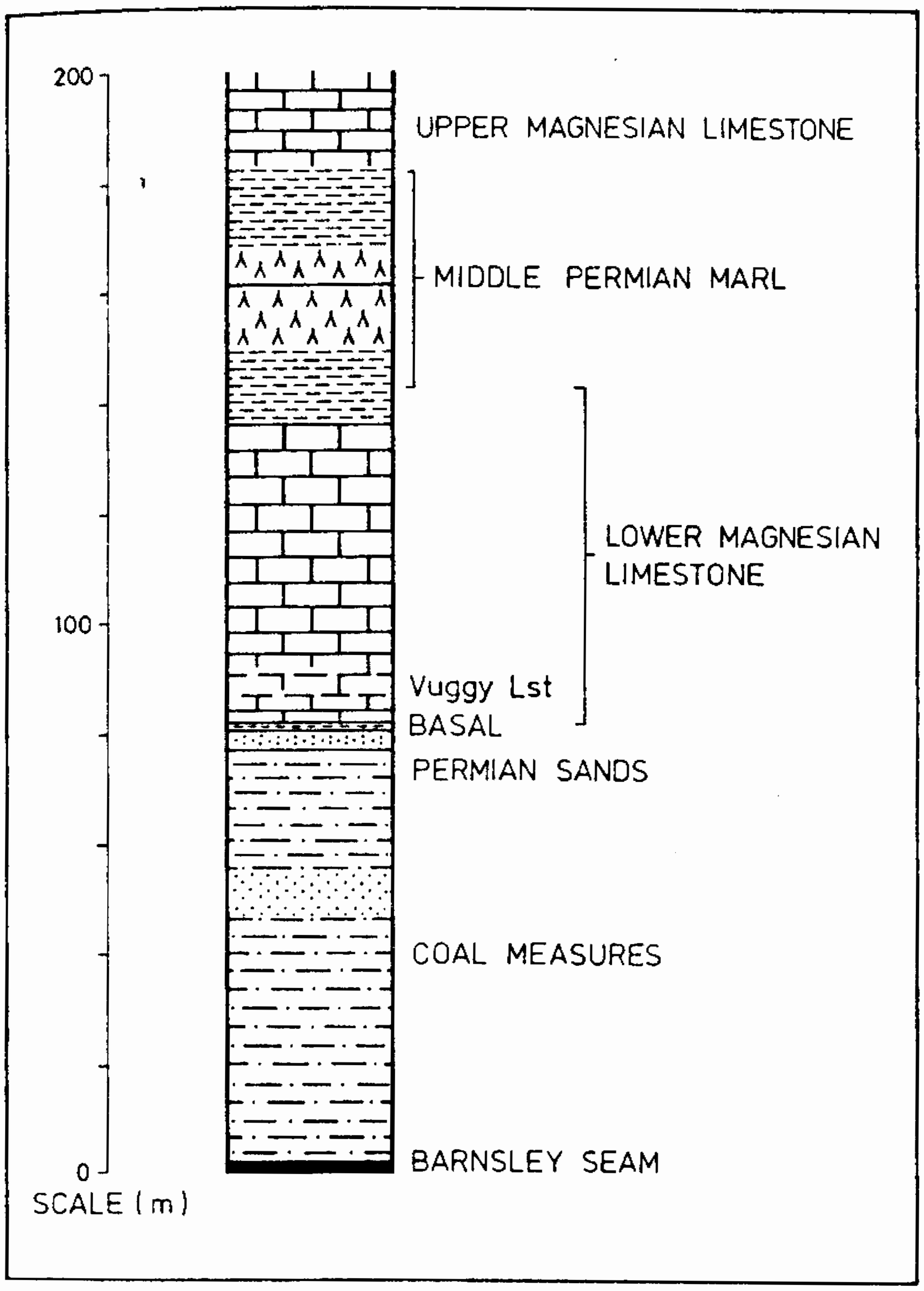

Fig.1 Section of strata above A1's face. Wistow

A plan showing the mining layout of "A" block is given in Fig. 2. Of the first six faces in "A" block four were wet. The nature and mode of water inflow was very similar on all of the wet faces. To illustrate the pattern of water inflow, the following section describes, in some detail, the initial water influx that occurred on A1's face.

Water on A1's face

The width of A1's face was 135 m, the height of extraction was 2.4m and the depth of workings below surface was 330m. When the face had retreated back almost to the square position a major inflow of water occurred from the goaf, which has been estimated to be in excess of 120 l/s (1600 gpm). The inflow was associated with a major weighting that damaged face equipment towards the centre of the face. Chemical analysis quickly determined the source of the water to be from the LML. After a period of 5 weeks, the face was restarted and the water make reduced to less than 40 l/s (500 gpm). At this time, a series of three surface boreholes (Bleak House Nos 1 - 3) was drilled into the LML in a line at right angles to the direction of mining retreat.

The purpose of the boreholes was to monitor the distribution and magnitude of the effective drawdown in the aquifer as a result of the inflow. A series of plots illustrating these changes is given in Fig. 3. With face advance, the inflow rate into the mine reduced sharply to less than 4 l/s (50 gpm). This reduction was mirrored in the boreholes, where water levels rose some 12m from -12m O.D. to surface. A further water flush occurred on the face on the 1st October, which was reflected in a 3m drop in water level in the overlying aquifer. Good face advances were achieved in October with inflow rates reducing to 4 l/s (50 gpm) . A number of weightings regularly occurred every 30 - 40m of retreat with no increase in inflow onto the face. A drop in water level on the 25th October was associated with a weighting, but there was no increase in inflow onto the face.

On the 31st October a large weighting occurred on the face that was associated with a second major inflow in excess of 90 l/s (1200 gpm). It is interesting to note from Fig. 3 that the water level in the LML began to drop several hours before the inflow occurred underground. Indeed, this phenomenon was to be repeated on subsequent faces, the early drop in water level being used as an early warning device to the colliery. This pattern of inflow persisted on A1's face until it was abandoned in March 1984 after only 460m of retreat.

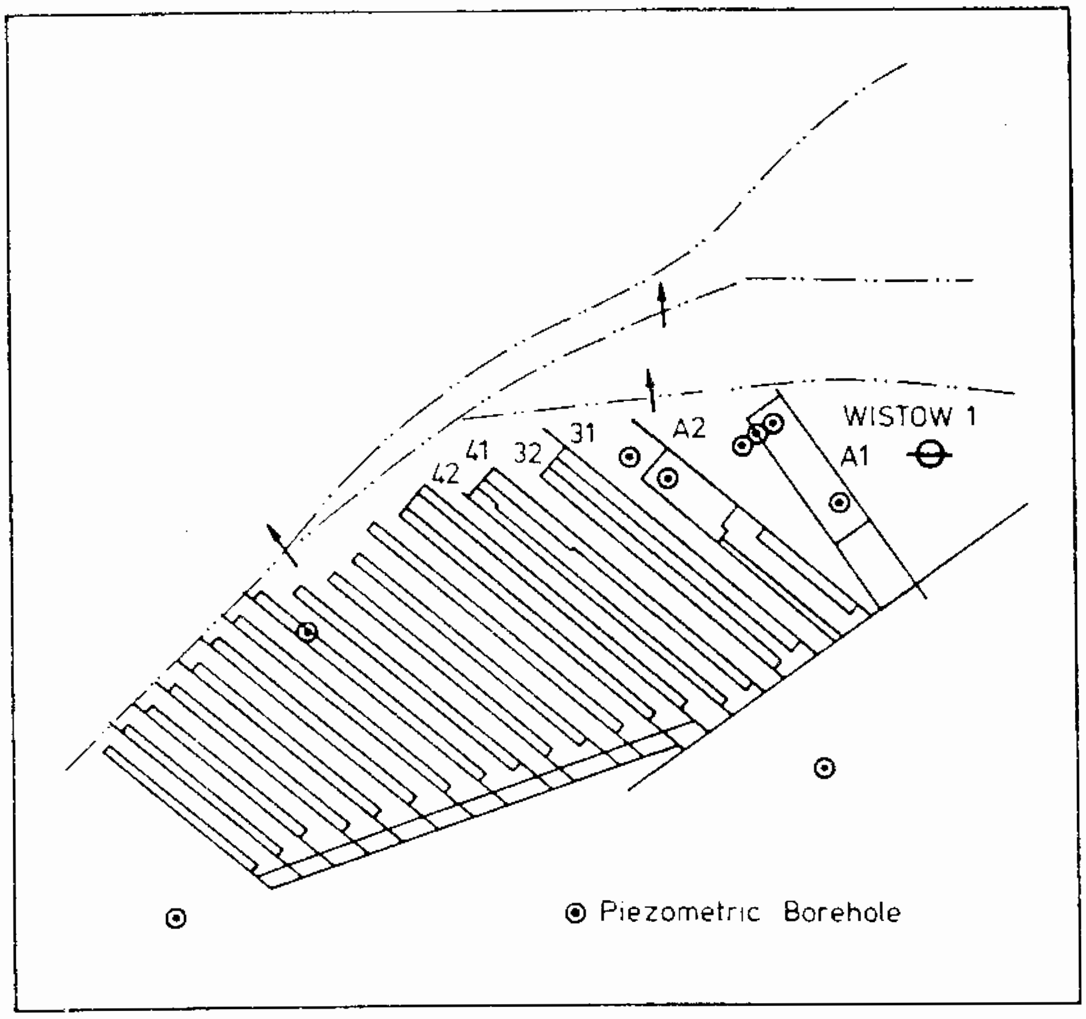

Fig.2 Mining layout of 'A' Block

Water on Successive Faces

Initially, the principle cause of the influx was thought to be related to the presence of a fault that haded over the A1's face start line. Subsequent developments for A2's face were shortened to some 210m away from the fault. Unfortunately after 92m of retreat a weighting occurred with an associated water inflow. This pattern repeated until the face was abandoned after 230m away of retreat.

After the initial influx on A2's it became clear that the inflow was not related to the presence of faulting. In an effort to control the situation, mining personnel at the colliery began to apply the empirically derived strain criteria developed in the North East coalfield. The current mining layout, according to the Subsidence Engineers Handbook, induced maximum horizontal tensile strain in the order of 21 mm/m on the base of the Permian, a factor of two greater than that practiced in the North East.

For the next two faces, A31's and A32's, the face width was reduced to 45m and the height of extraction to 2.2m. The maximum horizontal strain estimated on the base of the aquifer was reduced to 12 mm/m, a figure much closer to the North East working criteria. Indeed, in the short term all was well, both faces were dry and the next two faces, A41's and A42's, were designed with similar mining dimensions. On A41's and A42's, after face retreats of 350m and 80m respectively, an influx of 45 l/s (600 gpm) occurred. After this occurrence, mining personnel decided to adhere strictly to the North East criteria and slightly reduced the mining section, and the face width to 38m. With an intervening coal pillar of 55m the revised mining layout induced, on the base of the Permian, estimated principle strain levels of 10 mm/m. Since the adoption of this design

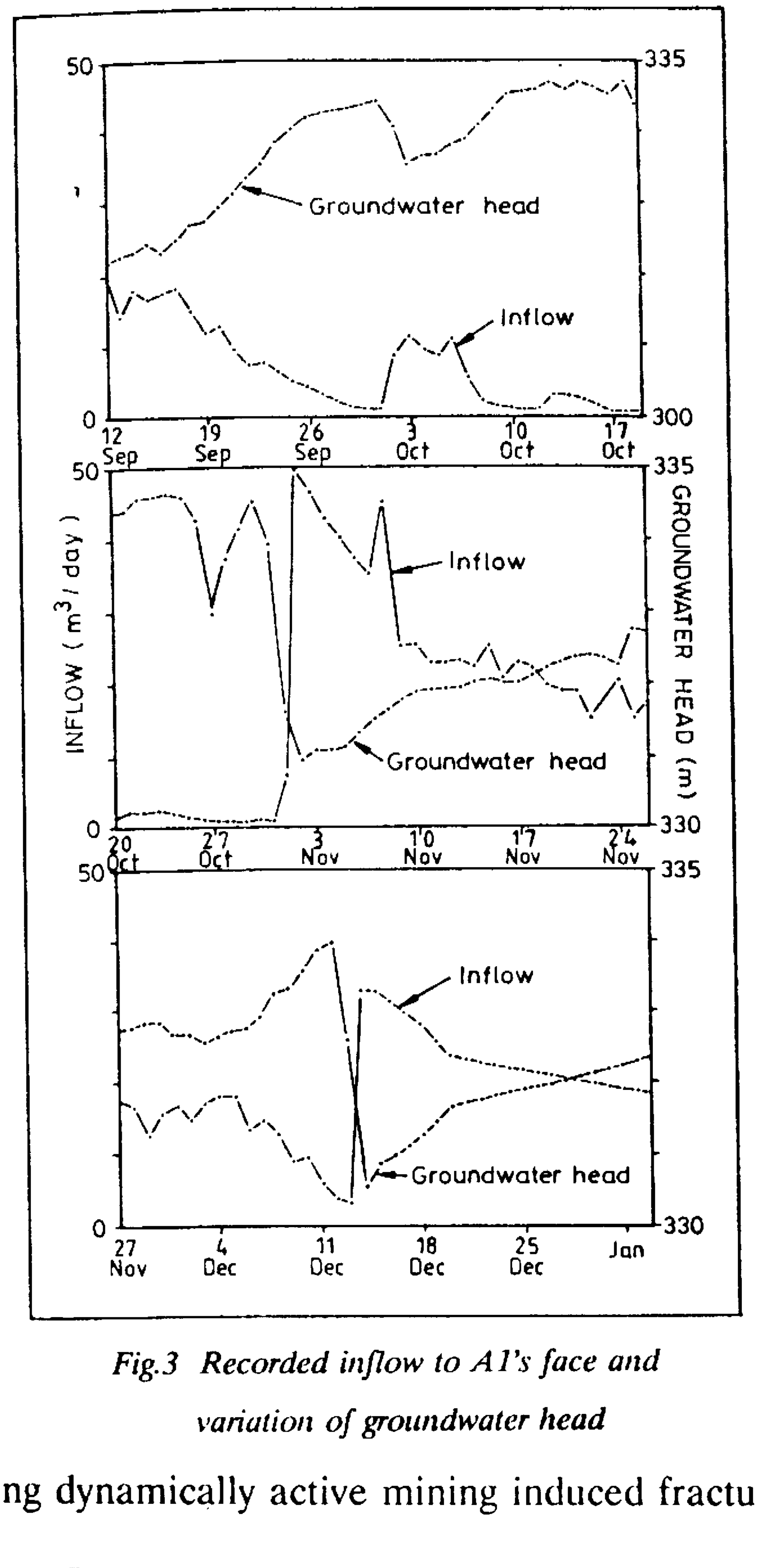

Fig.3 Recorded inflow to A1's face and variation of groundwater head

criteria, a further 19 single entry faces were mined in "A" block with no subsequent occurrence of Permian water.

DISCUSSION

In an effort to explain the inflow characteristics on to the "A" block faces the following conceptual model is proposed. The nature of the inflow, according to Lloyd et al(3) can be divided into two principle types:

1. *Steady State Inflow:* this flow regime is inferred as being as a result of permanent sub-vertical fractures induced through the intervening strata into the Permian.

2. *Time Variant Inflow:* this flow regime dominated the inflow characteristics on all "A" block faces. It is proposed that there were two modes of time variant inflow in operation; bed separation dewatering and fracture flow along dynamically active mining induced fractures.

The contribution from the rapid dewatering of sub-horizontal bed separations is thought to be responsible for the bulk of the initial water flushes. An illustration of this is clearly shown in the lower plot in Fig. 3. Immediately after the initial influx has occurred, a time variant flow regime is seen to dominate for several days, with inflow rates rapidly falling against an equally rapid rise in water level. These observations can only be modelled and explained by a release of water from storage.

For a bed separation zone to have any effect on ground-water inflows onto a longwall face, it has to satisfy three fundamental requirements:-

1. There must be a source of stored water.
2. A connection from the source of water to the bed separation is required.
3. A further connection must exist from the bed separation to the coal face.

The final connection must occur only after the initial connection with the aquifer.

If this is not the case, then the bed separation will not fill and will have only a very limited effect in directing inflow.

The evidence for the presence of zones of bed separation is unambiguous. The regular occurrence of weightings on the face, as a result of the dynamic caving characteristics of the strong roof measures, was periodically associated with a loss of ground water head in the aquifer with no increase in inflow rate on to the face. The sudden loss in hydrostatic pressure can only be a consequence of an inflow of water into an area of increased storage.

The high percentage of competent strata within the Coal Measures interval would suggest that the position of the bed separation must be quite high and remote from the immediate roof of the coal seam, either in the Coal Measures or within the aquifer itself.

In an effort to measure the position of a bed separation zone overlying A2's face, repeat geophysical logging was undertaken in Long Lane No. 3. monitoring borehole. The results of the geophysical logging before and after mining are illustrated in Fig. 4. Before mining, the borehole was logged to its full depth of 241m. After mining, the lower part of the hole had collapsed and could only be logged down to 220m. This horizon coincides exactly to the upper contact of the vuggy limestone. A comparison of the geophysical logs reveals the following points:-

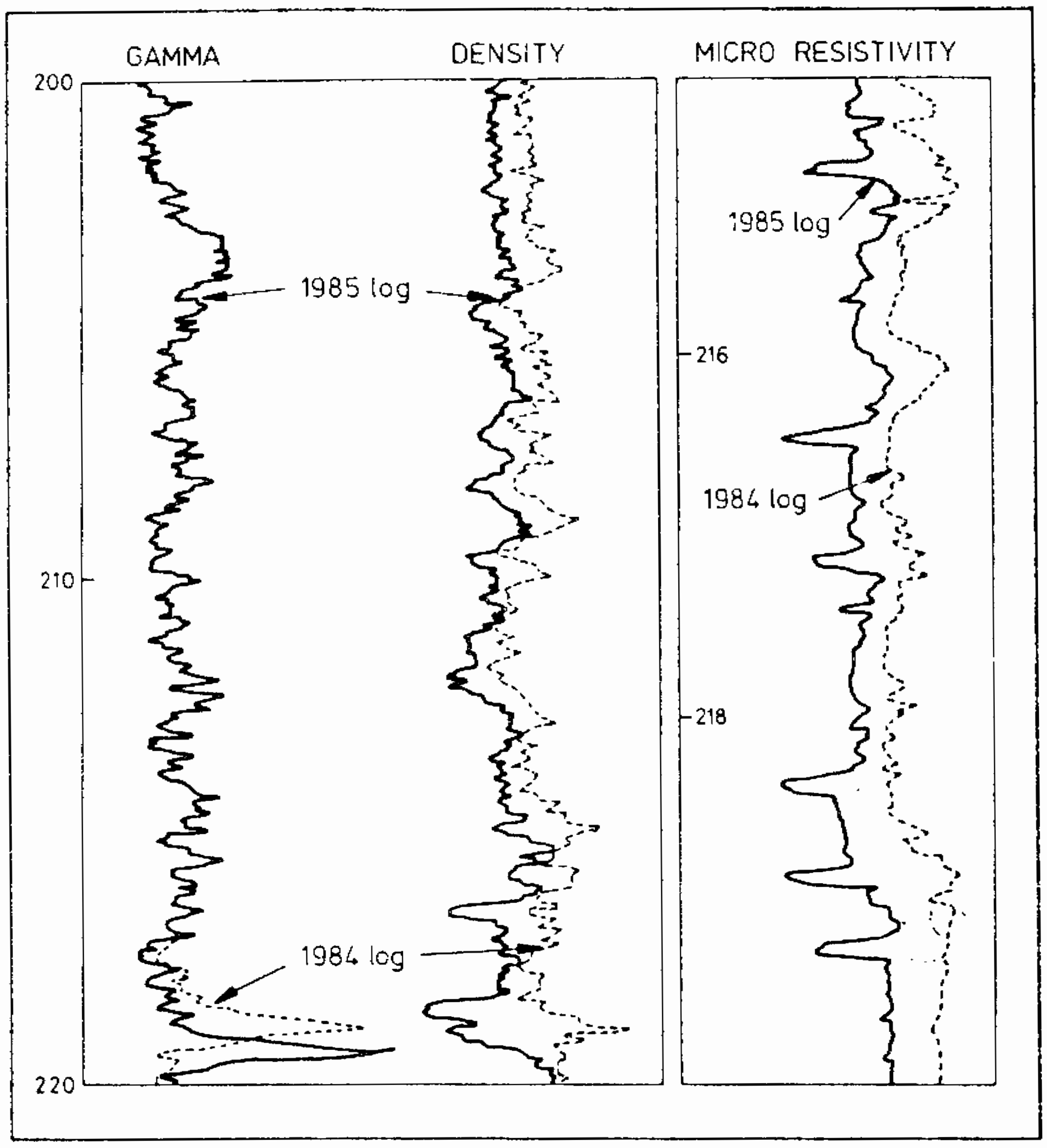

Fig.4 Geophysical logs - Long Lane Nº 3

1. Vertical displacement above the top of the Upper Magnesian Limestone is negligible.

2. There was less than 10 cm movement above the top of the LML.

3. The gamma log shows a 40 cm downward displacement of a mudstone bed at 219m, with no significant displacement noted above.

4. Areas between 215 - 220m which were originally high density have become low

density, indicating bed separation. This was confirmed by micro-resistivity logging also conducted.

These observations were taken as conclusive evidence that bed separations occurred in the LML and there had been collapse of the lower vuggy limestone.

With the benefit of hindsight the development of a conceptual model to fit this case history is academic. The successful application of the 10 mm/m strain criteria in this area and its likely significance in other mining sites is one that must be addressed. At a first glance, the relationship between horizontal tensile strain (acting in a vertical plane) and zones of bed separation, which are generally assumed to be sub-horizontal, is not clear. On the narrow faces, where no water occurred, bed separations did not appear to cause any problems. This raised a number of questions to which answers were sought:

1. Were bed separations formed over the narrow faces?
2. If bed separations were formed, were they not intersected by sub-vertical fractures?
3. How relevant is the application of the strain criterion in areas of different geology?

Collieries in the Midlands have worked multiple seams in weaker sequences of Coal Measures up to 45 m below highly permeable, high pressure aquifers with no water inflow. The apparent horizontal strain development at the base of the aquifer in these cases is in excess of 25 mm/m, using the Subsidence Engineers handbook method.

There is an obvious relationship between strong geology, vertical fracturing and horizontal tensile strain which is relevant to the Wistow case history. In an effort to quantify this relationship more clearly, the application of a recently developed geomechanical numerical model to Wistow "A" block is discussed.

NUMERICAL MODELLING

Golder Associates was commissioned to develop a computer based numerical model for the calculation of strata deformation around a longwall face. The model was required to provide a better estimate of the strain in the vicinity of potential aquifers than was possible from the current method. A well proven non-linear finite element program, which had been in use for several years for geotechnical modelling, was used as the foundation for development. The version which is now in use for longwall modelling is fully non-linear, in-homogenous and specifically designed to deal with layered strata. Three separate failure criteria are utilized;

i) the σ_1/σ_3 rock strength,
ii) the frictional strength of ubiquitous bedding, and
iii) the tensile rock strength.

The manner in which the pre and post-yield deformation properties are handled by the program has been designed to permit the modelling of transverse isotropy in bedded strata. It is this aspect of the program which is responsible for the success that has been achieved it duplicating surface subsidence, mostly to within 90% of the observed value and always better than 80%.

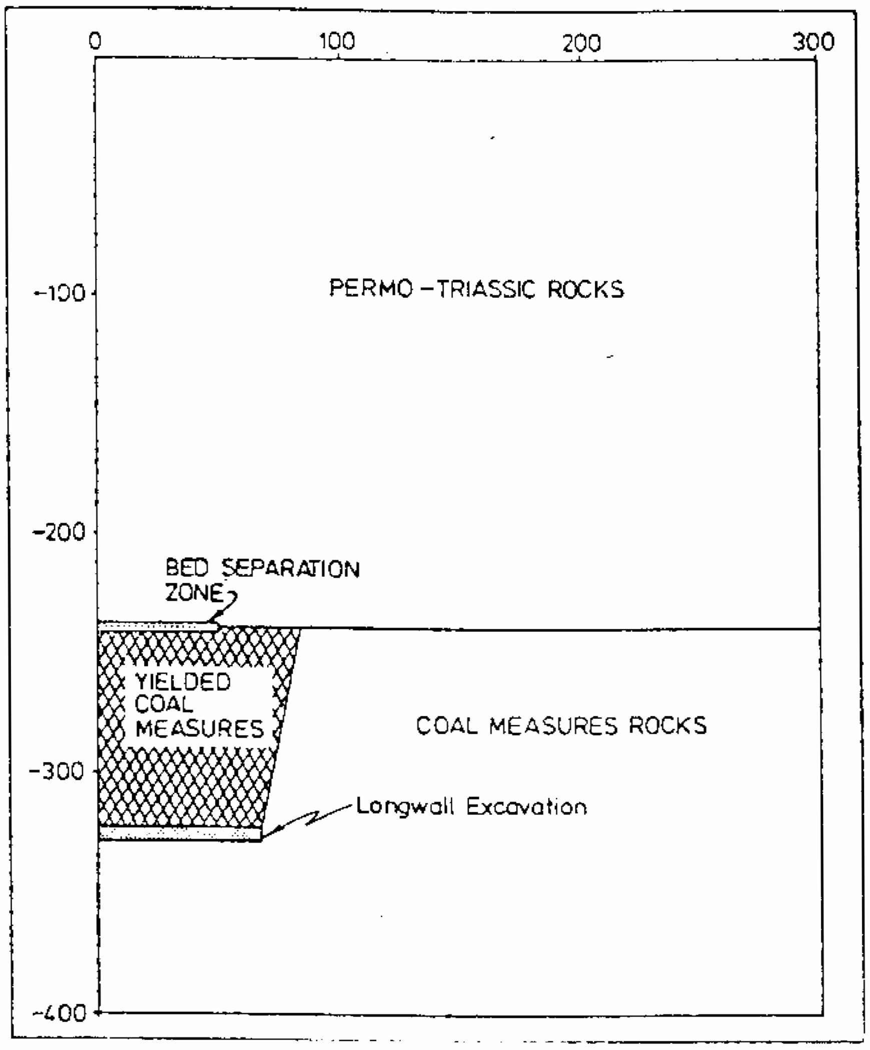

Fig.5 Strata Yield Zones

The results of the finite element analysis of Wistow "A" block showed that the Coal Measures strata above the longwall had yielded and that the yield zone extended up to the base of the Permo-Triassic strata. This is illustrated in Fig. 5 where the angle of draw (or limit angle) is shown to be about 10° from the vertical. The Permo-Triassic rocks showed no yield and bridged over the yielded Coal Measures beneath. The calculated surface subsidence was only about 100 mm, over the panel centre-line which agreed well with the observed subsidence. This was very low compared with the 900mm predicted by the SEH. In the model, vertical tensile stresses were indicated at the base of the Permo-Triassic strata following the development of yield in the Coal Measures. The rock mass tensile strength was considered to be close to zero which led to the formation of a bedding plane dislocation of about 100 m horizontal extent. At the panel centre-line an opening of 440 mm was indicated in the bedding dislocation.

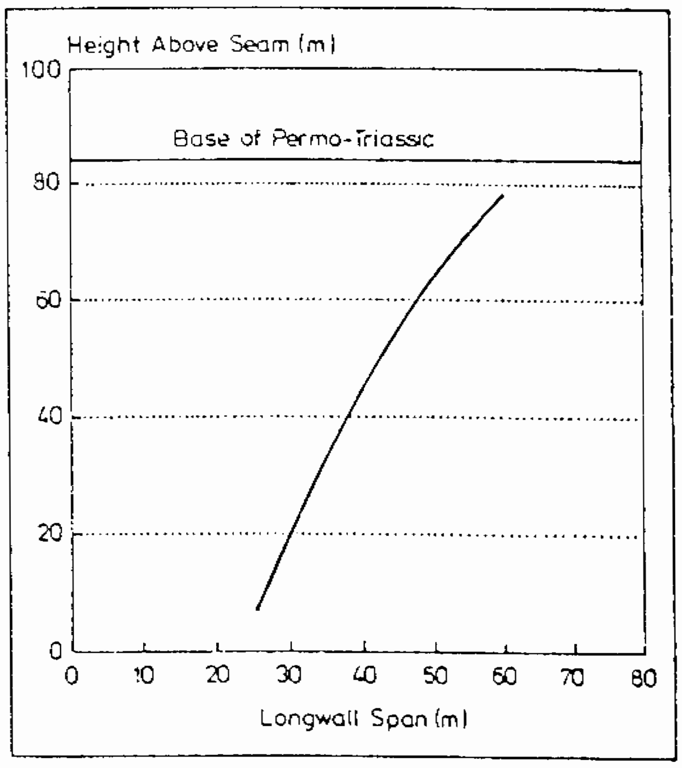

Fig.6 Height of Yield Zone v Width of Face

The finite element results confirmed the observational data that the upward migration of strata yield had been arrested by the strength and competence of the Permo-Triassic strata, which resulted in only minimal surface subsidence occurring. The loss of volume within the rock mass, caused by the coal extraction, was taken up by the development of a distinct strata dislocation at the base of the Permo-Triassic rocks and the amount of opening calculated was very close to that suggested from the geophysical logging. As a consequence of the bridging of the Permo-Triassic rocks, the compaction of the rubble goaf (gob), which results from the downward deflection of the yielded rock, was limited to only 15% of the extracted seam thickness. This compares with some 85% modelled elsewhere.

In response to the initial inflows, the Management of the Colliery had successfully reduced the water to manageable quantities by reducing the face widths of later panels. To investigate why the narrower faces were dry, the finite element program was used to determine the sensitivity of strata behaviour to the width of the longwall face. The analysis showed that there was a significant relationship between the height of the yield zone and the width of the face, as illustrated in Fig 6. If the yield zone created by the longwall does not reach the base of the Permo-Triassic strata, then no bedding dislocation will occur at the base of the aquifer, thus confirming a link between face width and potential water flow at Wistow "A" block. Assuming an error band for the location of the base of the Permo-Triassic strata and for the calculated curve, it can be seen that bedding dislocation in close proximity to the aquifer can be expected after the face width exceeds about 50 m.

Once the finite element analysis had produced a plausible mechanistic model which accorded well with the observed strata behaviour, attention was turned to the levels of strain which were calculated. The principal strain tensors show that neither tensor lies in the plane of the stratification, see Fig. 7. The magnitude of the largest principal strain is of the order of 9 mm/m at about 20 m below the bedding dislocation and dips at about 60°. Contours of strain showed that maximum vertical tensile strains of about 4 mm/m were calculated perpendicular to bedding, see Fig. 8, and horizontal strains on the base of the aquifer were 0.5 mm/m compressive over the excavation and tensile over the solid abutment. These strain results called into question the applicability of the Subsidence Engineers Handbook for the prediction of strains on specific sub-surface planes, and also the validity of the strain levels proposed by this method.

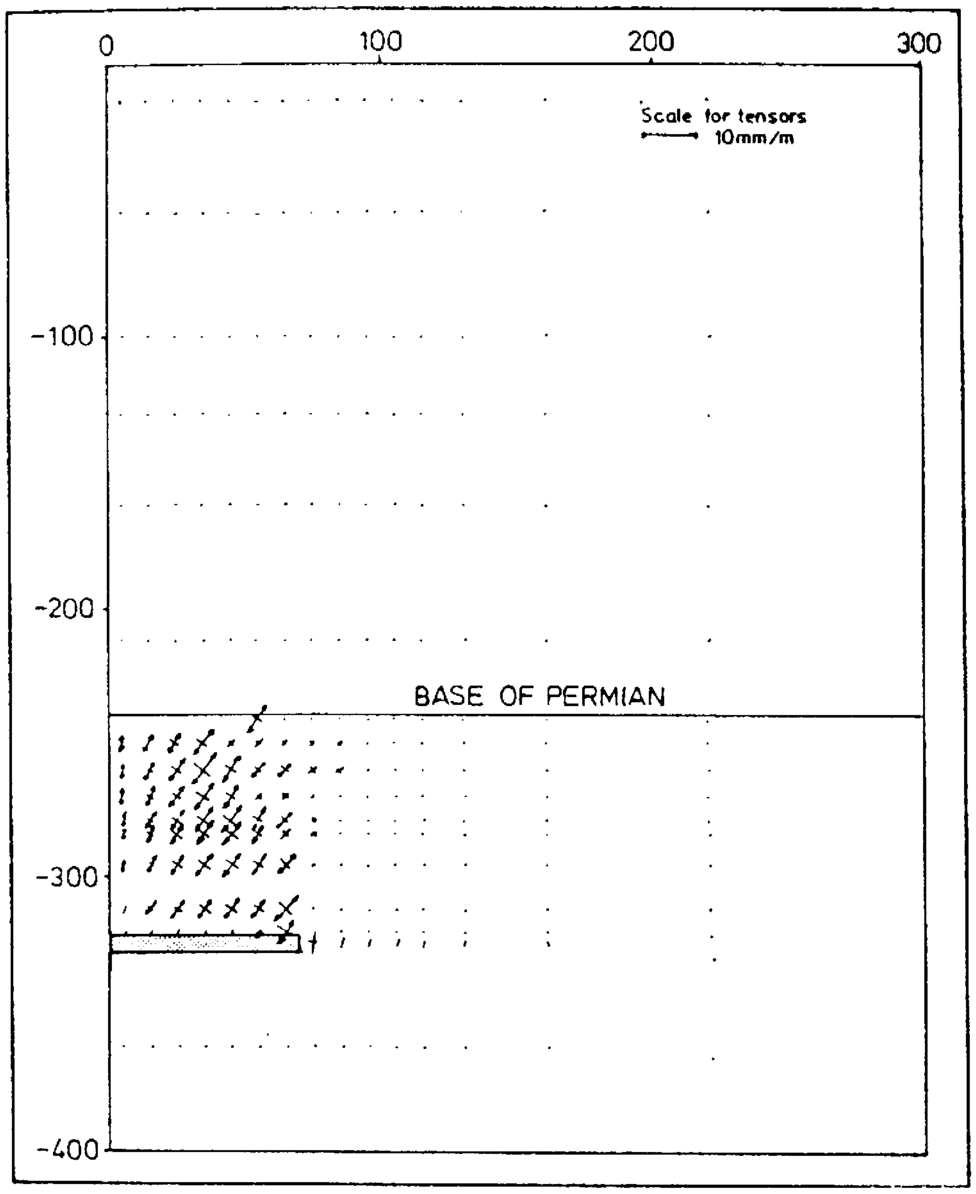

Fig.7 Principal Strain Tensors

Recently, Bai et al (4) have proposed strain criteria which appear to be suitable for the prediction of strata failure above longwall excavations in Britain. The method uses the horizontal and vertical strain components and sets limits of compressive and tensile strain above which bed separation and rock fracturing will initiate. The strain levels proposed are tabulated below. Based on these thresholds, strains of 1 mm/m tensile and 2 mm/m compressive have been used to indicate zones of potential compressive and tensile strain failure at Wistow "A" block, see Fig. 9.

STRAIN FAILURE CRITERIA			
Type of Failure	Strain mm/m		Orientation
	Tensile	Compressive	
Fractured Zone	> 2	> 4	Horizontal Strain
Potential Fractured Zone	> 1	> 2	Horizontal Strain
Bed Separation Zone	> 2		Vertical Strain
Potential Bed Separation Zone	> 1		Vertical Strain

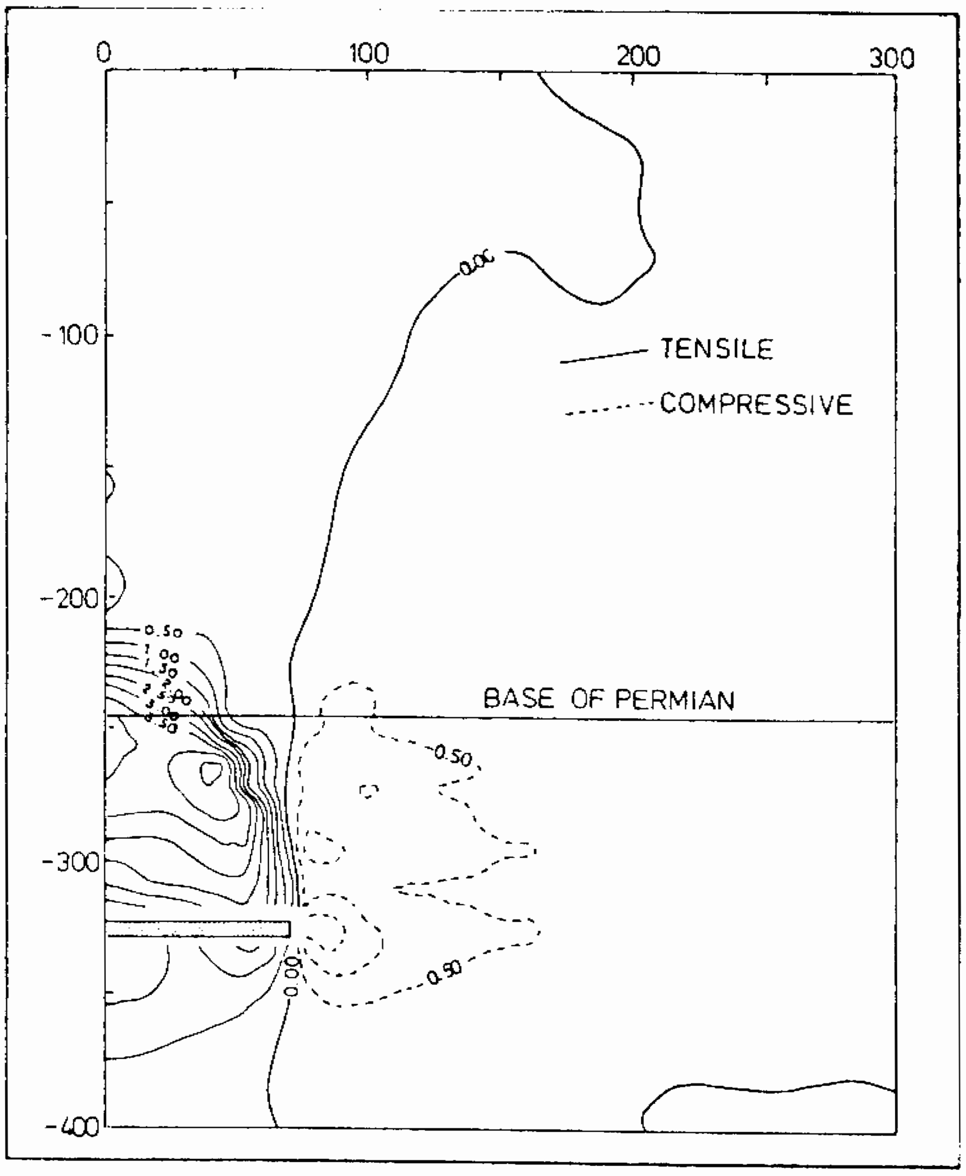

Fig.8 Contours of Vertical Strain

The zone of >2mm/m vertical tensile strain indicates that bed separation will occur throughout the Coal Measures and into the lower 25m of the Permo-Triassic strata.

Above the immediate goafed zone horizontal tensile strains between 0 and 1 mm/m are shown, which result in an area above the longwall where both the horizontal and vertical strains are tensile.

CONCLUSIONS

This case history indicates that there is a useful relationship between the risk of water on a longwall face and the strain developed in the strata. In the past, the Subsidence Engineers Handbook has been used as a method of assessing the likely sub-surface strain on the base of an aquifer. This method is questioned because it relies on the incorrect assumption that a sub-surface horizon behaves in the same way as the unconfined ground surface and takes no account of lithological variations. At Wistow "A" block the water influxes were attributed, at least in part, to the occurrence of large scale bed separations and the use of a horizontal strain criterion is unlikely to be useful in predicting the development of bed separation in horizontal strata.

The numerical model of "A" block shows that the principal strains are not orientated parallel to the stratification but dip at about 60° to the bedding and the values indicate a maximum strain of about 9 mm/m. The maximum horizontal and vertical tensile strains calculated at the base of the Permian are about 4 mm/m and 0.5 mm/m respectively. These values are considerably less than those estimated using the

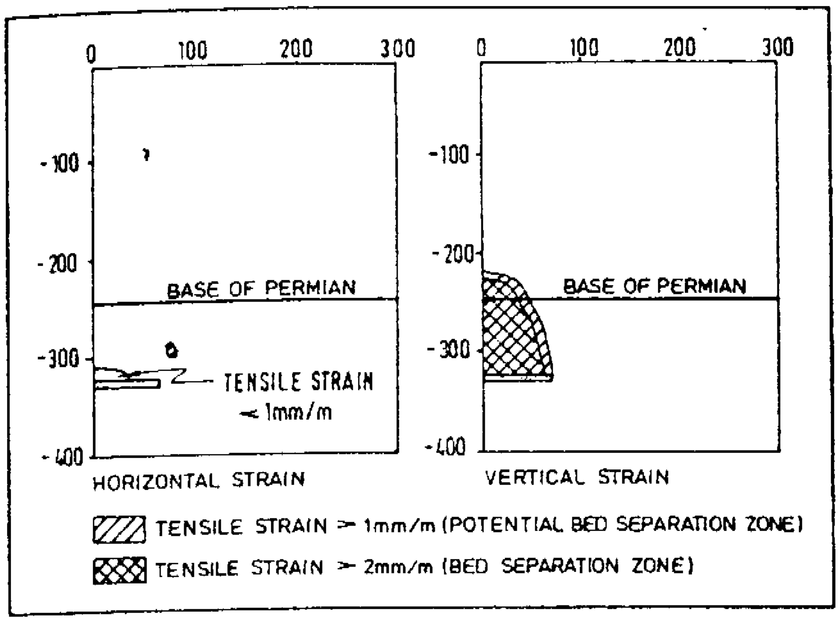

Fig.9 Zones of Critical Strain

Subsidence Engineers Handbook method. The modelling results also confirmed that the face width of 38m, ultimately found to be free of water problems, was sufficiently narrow to prevent the strata yield zone extending to the base of the aquifer.

Bai et al have proposed critical horizontal and vertical strain criteria for strata failure, including the occurrence of bed separation. These criteria seem to be applicable to this case history, where large areas of bed separation are indicated in the model which extend through the quite competent Coal Measures into the Permian strata. However, the proposals of Bai et al do not address either the importance or the significance of the attitude of the principal strain tensors with respect to the bedding. This aspect of the calculated strain requires further investigation, together with the importance of variations in lithology.

The use of a non-linear numerical model which can accurately predict the behaviour of strata of different geotechnical properties throughout the succession and model the surface subsidence, appears to be a very promising tool in the assessment of water risk on longwall faces. The finite element method used in this study is capable of predicting strain throughout the strata, from which the propensity for small scale and large scale bed separation can be determined. The application of these results can then greatly assist in the assessment of the risk of water inflow onto specific faces from a knowledge of the hydrogeological characteristics of the strata. Further calibration studies will be required to determine the applicability of the critical strain levels proposed and their sensitivity to the site geology.

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