GROUND FRACTURES DUE TO LONGWALL MINING SUBSIDENCE

BY
B N WHITTAKER
D J REDDISH
D J FITZPATRICK

Department of Mining Engineering
University of Nottingham
University Park
NOTTINGHAM
NG7 2RD
United Kingdom

ABSTRACT

The paper discusses experimental results of a large model employed to study fracture development in the ground overlying longwall mining operations. The model utilizes gravity loading only as the means of developing caving and fracturing of the ground above the longwall excavation. The results show fracture development and caving propagation as a longwall face develops from its starting point. The effect of rock strength in the immediately overlying roof is discussed in relation to subsidence development. Special attention is focussed on subsidence development to aquifer horizons. The thickness of cover between the mine horizon and overlying bodies of surface water eg: rivers and the sea, is considered in relation to underground excavations. The paper concludes with a general discussion on guidelines for undermining aquifers and surface water bodies with special reference to longwall operations.

INTRODUCTION

Longwall mining is the predominant method of extracting coal seams in Europe, and since caving of the roof behind the longwall workings is the main practice, knowledge on the effects of caving and subsidence is frequently sought. There are many situations where the coal reserves are overlain by significant aquifers; in some cases major surface water bodies including the sea, lakes, rivers need to be taken into consideration when planning underground mining layouts. Longwall mining creates a disturbance to the overlying beds of strata between the extraction horizon and the surface. It is the significance of such a disturbance as caused by caving and subsidence that prompted this research investigation. Whilst it is appreciated that the caving zone is a localised effect in close proximity to the longwall mining horizon, the propagation of subsidence movements towards the surface induces cracks and fissures, separations, relative slipping and opening of pre-existing geological weakness planes such as faults. The resulting effect can be to cause water inflow into longwall workings. This particular study has been directed towards examining the effect of mining subsidence on inducing fracture pattern development between the mining horizon and the surface. The research programme involved the use of a body-weighted model whereby mining was carried out progressively and accompanying displacements and fracture pattern development observed. The situation modelled corresponded to a depth of 105 m below the surface, which is the minimum amount of cover required in the UK for longwall extraction in under-sea workings.

MINING SUBSIDENCE

There are several methods of predicting subsidence and surface strains above longwall mining operations, see Fig 1, but little work has been done studying the effects of mining on the strata between the surface and the extraction horizon. For example in the UK the National Coal Board (1967,1975) publication, the Subsidence Engineers Handbook (SEH), has been used and verified as a reliable means of predicting surface displacements and strains above a longwall panel; however in this publication prediction of sub-surface effects is not considered mainly owing to lack of reliable data. In the context of physical modelling, however in order to ascertain these effects the SEH plays an important role as a means along with dimensional analysis, of validating the results. If the surface effects of the model are confirmed by the SEH, and the dimensional analysis is meaningful, then it is reasonable to assume that the results obtained are realistic.

The major interest in the development of mining-induced fissures arises from the resultant changes in permeability particularly when undermining aquifers and/or surface bodies of water. In the UK mining under the sea is controlled by the

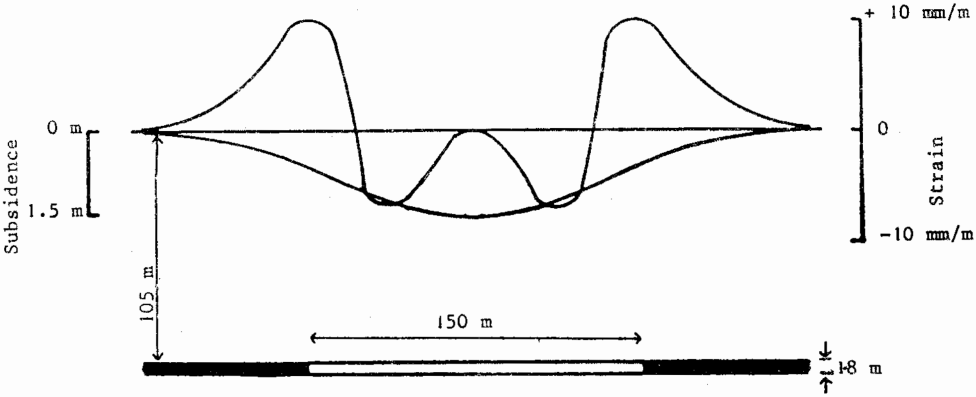


Fig 1 Transverse subsidence and strain profiles

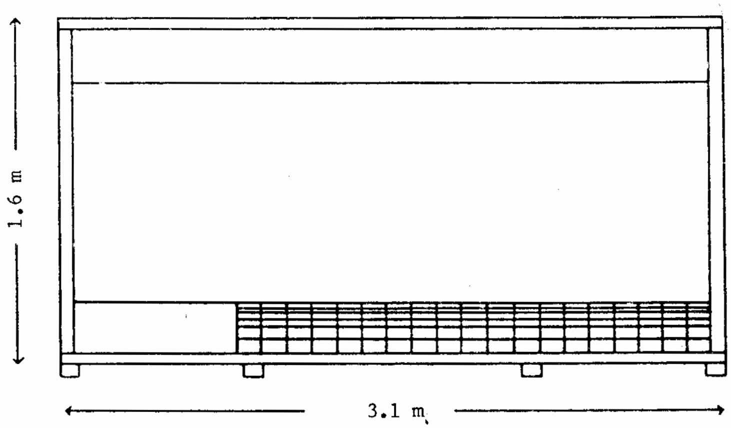


Fig 2 Test rig

NCB, PI (1968).

In the case of longwall operations in under-sea workings, two particular aspects are referred to here: (a) the minimum cover between the seabed and the mining horizon must be at least 105 m of which 60 m must be Coal Measures strata, (b) the maximum tensile strain at the seabed must not exceed 10 mm/m.

The UK coal industry guidelines for under-sea working have been compiled on the basis of judgement of many years experience, particularly in mining coal seams around the coasts of Britain, particularly the North East Coalfield. The incorporation of a subsidence limiting parameter regarding under-sea working is a unique feature in such guidelines when considering practices in other countries. The research investigation described here was aimed at providing an improved understanding of the inter-relationship between depth of cover, magnitude of subsidence and surface tensile ground strain and the accompanying fracture pattern developments between the mining horizon and the surface.

SUBSIDENCE MODELS

Empirical subsidence models are used widely for prediction of anticipated effects of longwall mining on the surface and associated surface structures. The NCB, SEH subsidence prediction procedures are used in many countries and in the case of UK coalfields give surface subsidence predictions with a marked degree of accuracy. It is used widely for comparing various other types of subsidence models.

Profile function and influence function methods give no measure of intermediate strain and cannot easily be adapted to do so. This is because they do not attempt to describe the mechanism of subsidence and rock failure, but produce a surface fit only.

Elastic modelling and finite element techniques suffer from a similar problem in that subsidence and, in particular, rock failure is not a purely elastic phenomenon. As a consequence, these methods suffer in their capability to produce the exact subsidence and strain curves as observed in mining practice. Non-linear finite element techniques provide more scope in producing results which match more closely to those observed in practice.

By a process of elimination, this leaves physical modelling which has the advantages of the effects being visible during all stages of development, incorporation of complex stratigraphics, and variation of mining parameters.

At an early stage in the research, it was decided to employ only gravity as the applied load as this obviated the need for a stronger and more complex experimental test rig. Fig 2 shows the test rig.

EXPERIMENTAL TEST RIG

The internal dimensions of the rig are 3 x 1.5 x 0.15 m. The extraction is simulated by progressive removal of blocks from the bottom of the model. In the first model these extended only for the centre half of the model in order to give a transverse profile and were subsequently altered so that they could extend all the way across the right hand side as shown.

The model is constructed by fixing boards to the front and back of the model and casting 1.25 cm layers of plaster sand mix with intermediate layers of sawdust. Dyed layers were used at intervals to ease photographic comparisons. The entire model casting operation takes 2 days and the finished model is allowed to dry for 24 hours after removal of the front casting boards. A suitable grid (10 cm square) is then drawn on the model prior to commencement of the test.

DIMENSIONAL ANALYSIS

The laws of dimensional analysis were applied to the design of the subsidence model. Using this technique all the variables of a particular problem are expressed in terms of the fundamental dimensions, usually mass, length and time (but occasionally force, length and time). The dependent variable can then be expressed, if necessary, in terms of all the independent variables.

Subsidence is judged to depend on the following parameters:

(i) The face geometry = G (metres)
(ii) The rock's tensile strength = T(N/m^2)
(iii) The rock's compressive strength = C(N/m^2)
(iv) The rock's Youngs modulus = E(N/m^2)
(v) The rock's Poissons ratio = ν (dimensionless)
(vi) The rock's unit weight = W(N/m^3)

There are others of less significance of course, but in order to simplify the analysis, only the parameters that will be controlled during modelling have been considered.

Using the above parameters it would be possible, although difficult, to find an expression for subsidence thus:

$$S = f(G,T,C,E,\nu,P)$$

However, the use of Buckingham's theory simplifies the process. This states that "a complete equation can be reduced to a functional relationship between a complete set of independent dimensionless products". It is clear that such a relationship would have to hold for both the model and reality, and this enables the production of the various scale factors involved.

Variable	Dimensions
S	L
G	L
T	$ML^{-1}T^{-2}$
C	$ML^{-1}T^{-2}$

E	$ML^{-1}T^{-2}$
ν	
W	$ML^{-2}T^{-2}$

Using Buckingham's theory, the dimensionless relationship becomes

$$\frac{S}{G} = f(T/C, E/C, \nu, WG/C)$$

As mentioned above this should hold for both the model and reality which means that for

$$\frac{Sm}{Gm} = \frac{Sr}{Gr}$$ (subscript m refers to model, r to reality)

Then $\frac{Tm}{Cm} = \frac{Tr}{Cr}$, $\frac{Em}{Cm} = \frac{Er}{Cr}$, $\nu m = \nu r$ and

$$\frac{WmGm}{Cm} = \frac{WrGr}{Cr}.$$

These can all be rearranged to give

$$\frac{Sr}{Sm} = \frac{Gr}{Gm}$$ the geometric scale factor

and $\frac{Tr}{Tm} = \frac{Er}{Em} = \frac{Cr}{Cm} = \frac{WrGr}{WmGm}$

Poissons ratio is considered to have little effect and so can be ignored.

$\frac{Gr}{Gm}$ is easily calculated from the size of the model, and in this case it represents 105 m.

Thus $\frac{Gr}{Gm}$ for the model = $\frac{105}{1.0795} = 92.27$

The ratio $\frac{Wr}{Wm}$ is also known as it is just the ratio of the densities. Assuming typical Coal Measures strata to have an average density of 2.35 Mg/m^3 then

$$\frac{Wr}{Wm} = \frac{2.35}{1.711} \doteq 1.37$$

Thus the scale factor for Young's modulus and the strengths (as they have the same units, they must have the same scale factors) as given by

$$\frac{WrGr}{WmGm} = 133.26$$

The Young's modulus and compressive strength values of the model material were determined and the following results obtained:

Sample	Young's Modulus ($x10^6 N/m^2$)	Compressive Strength ($x10^6 N/m^2$)
1	7.384	0.0821
2	8.636	0.0706
3	6.78	0.0856
4	7.04	0.0867
Average	7.384	0.0821

Thus the model was representative of a rock having the following properties:

UCS	10.94 MPa
Youngs Modulus	0.984 MPa
Density	2.35 Mg/m^3

The UCS value seems a little low but it is widely accepted that laboratory measurements of strength can be as much as 5-10 times larger than the in situ strengths and when this is taken into account, the value appears reasonable.

PRELIMINARY RESULTS

Transverse profile

The first model (M1) to be constructed, extraction performed and subsidence developed was that of a geological situation representing a sequence of fairly strong sandstones (50-100 MPa, UCS) overlying the longwall. The width/depth (w/h) ratio was 1.3. Additionally a further model (M2) was tested using the same mining geometry but with the equivalent of strong siltstone strata (about 30-60 MPa, UCS) overlying the longwall. The extraction height (m) in both cases was equivalent to 3.4 m with a depth of cover 105 m.

Both models illustrated progressive caving from the mining horizon but with decreasing span, which developed to a height whereupon large scale bed separations became the predominant feature.

Fig 3 illustrates the nature of large-scale bed separations over the longwall extraction whilst Fig 4 shows additional failure characteristics due to subsidence.

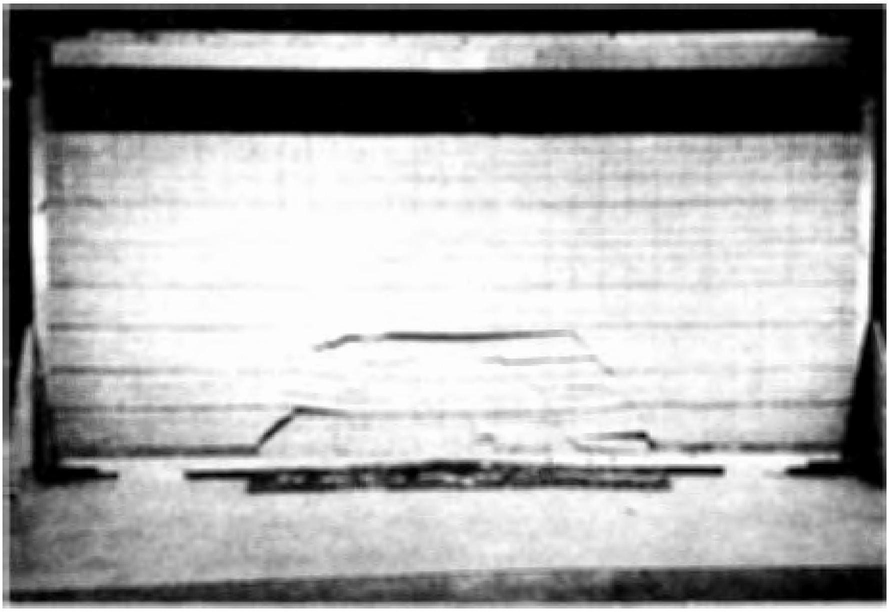


Fig 3 Transverse section across longwall extraction showing development of subsidence and fracturing.

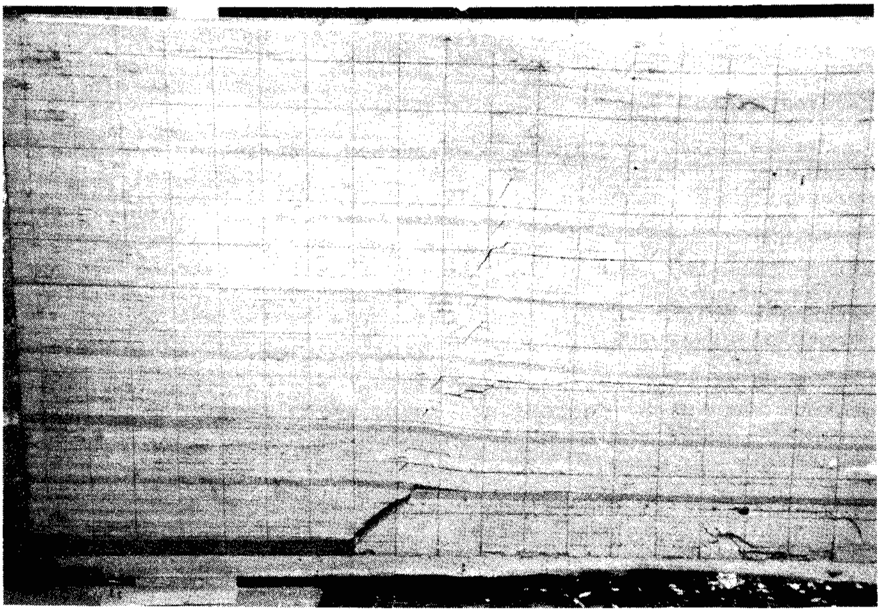


Fig 4 Longitudinal section of longwall extraction showing fracture occurrence above solid ribside.

Fig 5 shows the transverse subsidence profiles for models M1 and M2 compared to that predicted by the SEH method. Model M1 which represents a very strong overburden resulted in about 10% (m) maximum subsidence whilst model M2 gave about 20% (m). The corresponding SEH prediction gave 40% (m). The combination of shallow depth and fairly strong overburden undoubtedly inhibited the development of more subsidence at the surface.

The SEH results have been established from case histories taken mainly in the depth range of 300-800 m, with very few shallower than 200 m. Consequently, the effect of averaging was to partially mask the effect of very shallow depths on subsidence development. Results from subsidence observations in USA, Australia and India having shallow conditions and very strong cover rocks tend to indicate maximum subsidence values of a similar order to those obtained with models M1 and M2. The tendency for bridging to occur across the models with strong overburden supports general observations and previous findings made in similar mining situations.

Longitudinal profile

Extracting models M2 and M3 to the edge of the test rig allowed longitudinal profiles to be produced; the longitudinal profile obtained corresponded to a half-critical transverse profile. Fig 6 shows subsidence results for models M2, M3(a) and M3(b) compared with the SEH profile. There is a close degree of correlation between all the profiles, although maximum subsidence with the models was generally about 10% greater than that predicted by SEH. This feature is probably due to the idealised nature of the subsidence model.

The preliminary results indicated that the subsidence models provided a meaningful basis for conducting more detailed investigations into fracture development in relation to extraction height, depth of working and surface tensile strain.

TEST RESULTS RELATING SUBSIDENCE TO FRACTURE DEVELOPMENT

This model was constructed specifically to investigate the influence of extraction height on fracture development. The seam height was modelled to be equivalent to 10.8 m extracted in six lifts which gave a surface ground tensile strain variation between 6.5 and 62 mm/m.

Subsidence aspects

As with the other models, a check was made to ensure that the surface subsidence profiles were in close agreement with SEH (Fig 7); the first five lifts are shown in these results.

Fig 8 again shows general agreement between the subsidence model and SEH for extractions up to 3 m in particular. The SEH was constructed using data mainly from 1-3 m extractions and extrapolation of this data for 8m or 9m extractions is unrealistic.

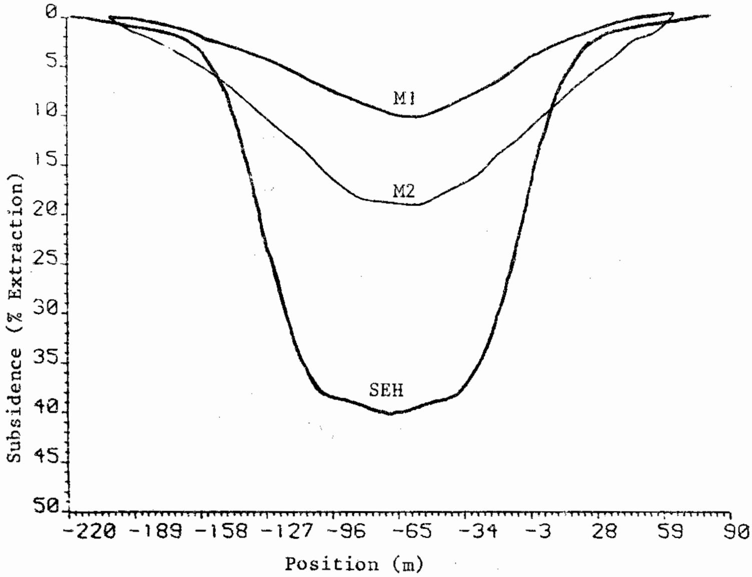


Fig 5 Preliminary results - Transverse

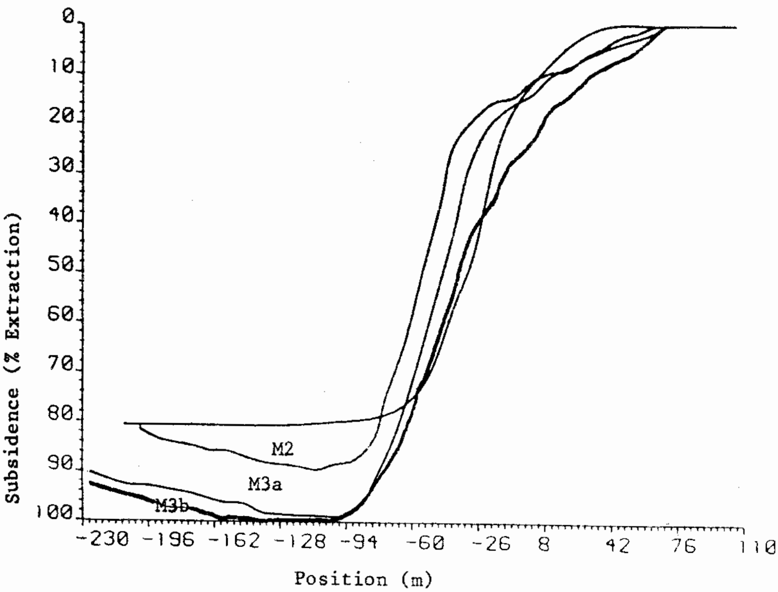


Fig 6 Preliminary results longtitudinal

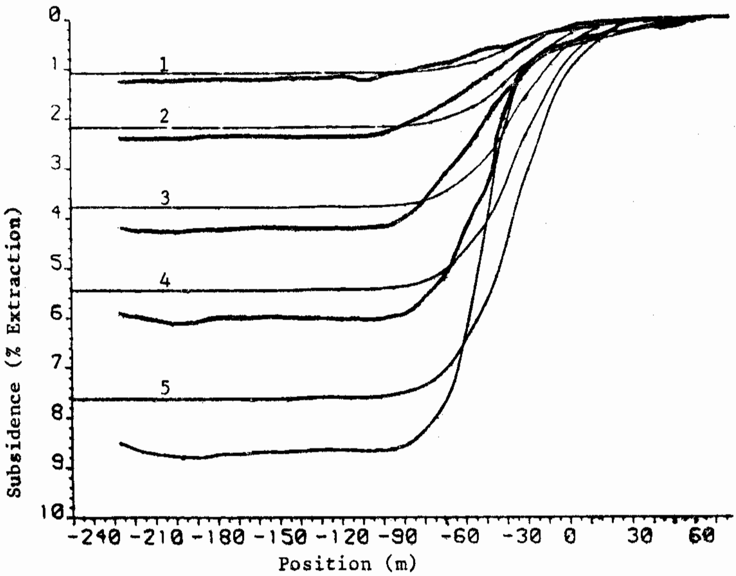


Fig 7 SEH Comparison

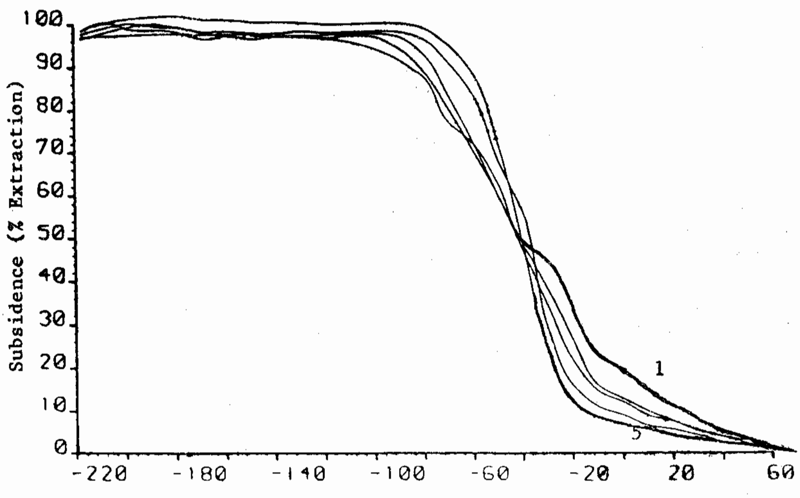


Fig 8 Half profile results for increasing extractions

A further interesting point that becomes apparent when the subsidence curves are plotted with subsidence as a percentage of the extraction is illustrated in Fig 8. There is a definite trend in the gradient of the curve about the transition point in that as the extraction increases, the gradient also steepens. This again points out an omission in the SEH which considers the curves to be identically shaped, varying only in magnitude.

The satisfactory surface fit with these results permits valid deductions to be made regarding the subsurface features. Fig 9 shows the subsidence along intermediate layers. This shows as expected, the steepening of the curve in closer proximity to the extraction horizon.

Fracture development

Fig 10 shows the progressive development of fractures with increasing extraction height. The major fracture development is associated with the ribside; and consequently if mining dimensions permit, the face-line also becomes an origin of major fracture development. The fractures occur in a regular progression and appear to be related to the predicted tensile strain (+E) at the surface especially in the range 0 to +30 mm/m; most cracks are of similar nature and magnitude. Above +30 mm/m maximum tensile strain, a second line of development of cracks is produced parallel to the first line and displaced over the goaf by a distance varying from h/3 - h/3.5, and general crack widening and connecting up continues.

A first analysis of the crack propagation patterns shown in Fig 10 indicates that zones of crack development can be identified and expressed in relation to the maximum tensile strain at surface (+E). This has been carried out and the results are shown in Fig 11. The crack development zones considered are firstly the maximum height extended by cracks which appear to definitely interconnect from the extraction horizon, and secondly the extent of appreciable crack development above the mining horizon but which do not necessarily interconnect. This first zone would appear to indicate where free flow from an overlying aquifer would readily occur, whilst the second could indicate where there might be a risk of water inflow seeping from an overlying aquifer. Essentially, these results indicate that crack development from a ribside gradually decreases in significance, rather than showing an abrupt change in conditions. It is concluded here that local geology and depth of mining will play major roles, especially in influencing the significance of the second crack development zone which is regarded as posing a risk to water inflow. Obviously, the presence of an aquiclude in such a zone could be a major controlling factor.

The results shown in Figs 10 and 11 indicate that for +10 mm/m maximum tensile strain at the surface, crack propagation approaches the surface to a height of around h/3 for crack interconnection and h/2 for maximum influence of crack development in the case of the model used to investigate a depth (h) of 105 m. This represents a geological situation which readily promotes crack development, and in actuality the occurrence of pliable mudstone rocks would inhibit the extent of cracking above the ribside. These results indicate that an acceptable factor of safety is incorporated in the UK guidelines for longwall operation in undersea workings.

Fig 12 shows a photograph of the model after six lifts have been extracted at the mining horizon. During extraction of each lift the cover beds over the longwall were naturally fractured during caving and cracks reopened during extraction of subsequent lifts. On completion of mining each lift, however, there was general closing of major cracks and compaction of the caved material at the extraction horizon. Fig 12 shows the state of the model particularly crack location after completion of mining and a most important feature exhibited is the integrity of the beds immediately over the central region of the extraction; whilst the ribside shows large scale crack development, the caved and subsided region over the extraction indicates marked restoration of its ability to restrain water inflow from any overlying aquifers. Any inflow in such conditions would occur mainly from the ribside fracture zone.

This model resulted in major cracking at the surface after +30 mm/m (+E) and the maximum depth to which such cracks penetrated downwards was around 7.5 m indicating that surface cracking is essentially a local effect and has no deep-seated significance in normal longwall mining operations.

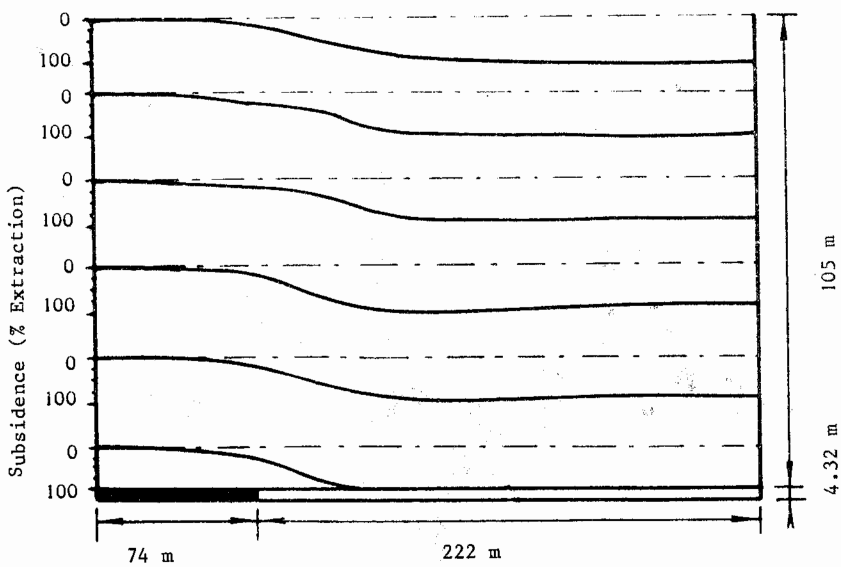


Fig 9 Subsurface Subsidence Profiles Model 4

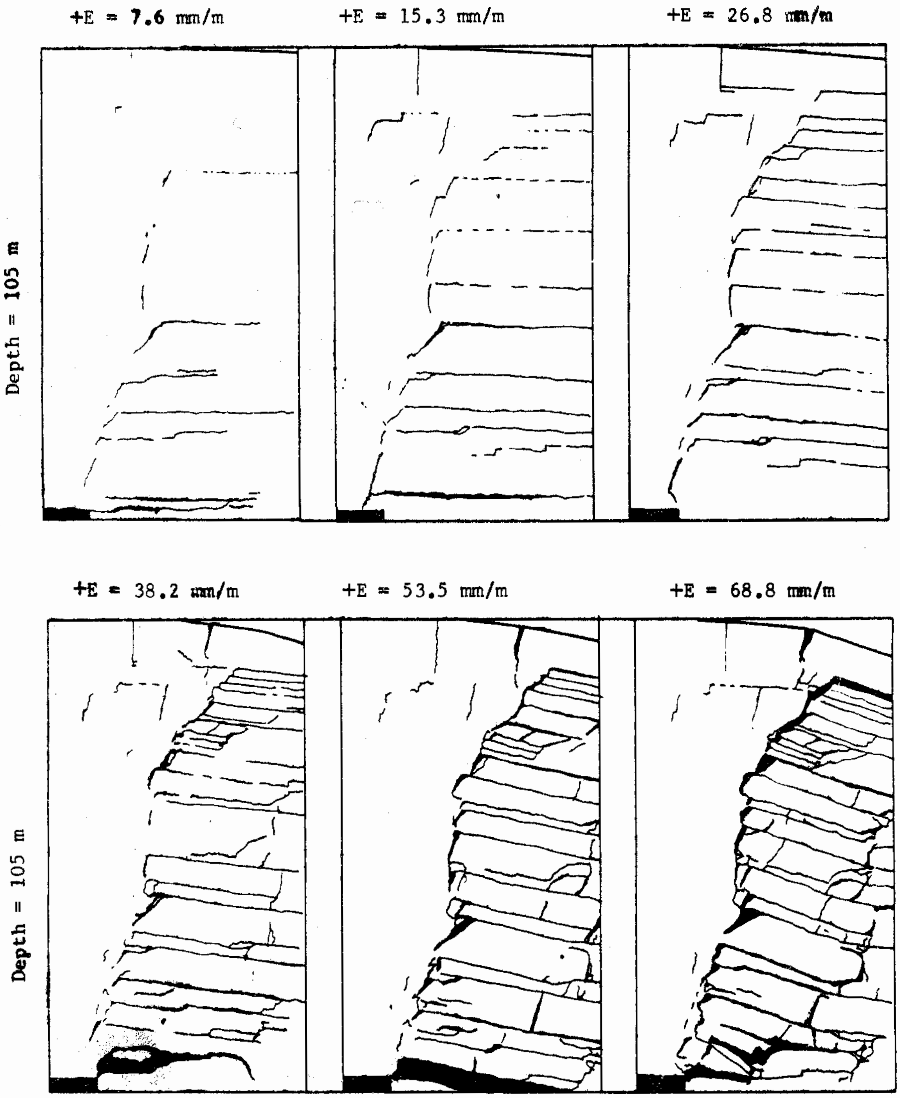
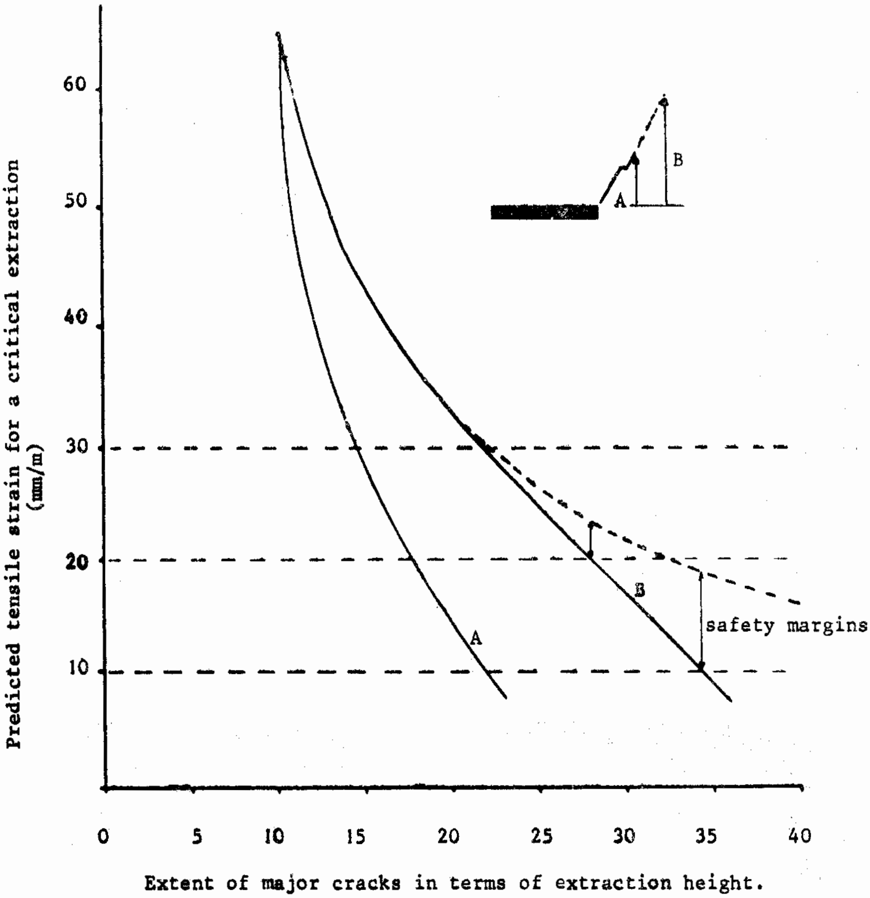


Fig 10 Fracture pattern development over ribside of longwall for progressive magnitudes of extraction height.



Lines A and B depict direct and possible levels of connections between cracks towards surface.

1. At 10 mm/m strain
   direct connection is 31% of the way to surface
   possible connection is 53% of the way to surface

2. At 20 mm/m strain
   direct connection is 49% of the way to surface
   possible connection is 86% of the way to surface

3. At 30 mm/m strain
   direct connection is 66% of the way to surface
   possible connection is 98% of the way to surface

Fig 11 Extent of fractures above longwall extraction.

CONCLUSION

The form of physical modelling involving gravity loading a scaled simulation of a section of strata between the surface and mining horizon of a longwall extraction lends itself to investigation of the effects of caving, subsidence and crack propagation. Surface subsidence profiles produced by such models are consistent with those predicted by the NCB Subsidence Engineers' Handbook. The models give a detailed appreciation of the effects of mining under different types of strata and in particular can indicate the extent of crack development and the likelihood of disturbing overlying aquifers.

ACKNOWLEDGEMENT

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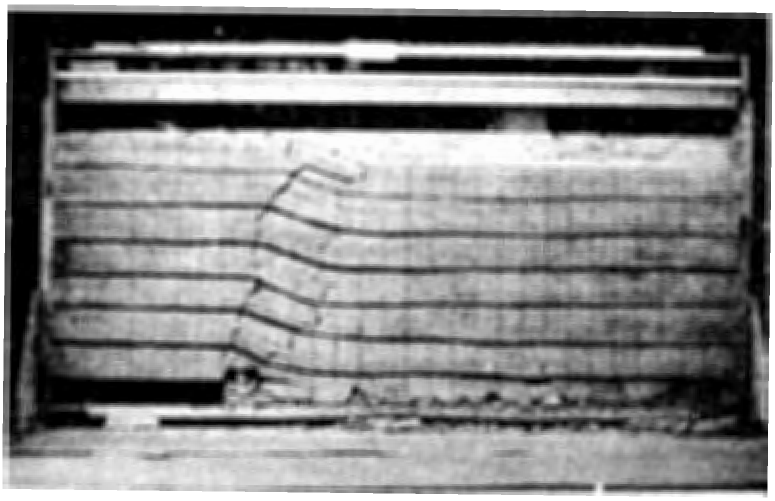

Fig 12 Demonstrating characteristic behaviour of caved goaf and closing of fractures after six successive longwall extractions.