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SURFACE SUBSIDENCE PREDICTION TECHNIQUES FOR UK COALFIELDS - AN INNOVATIVE NUMERICAL MODELLING APPROACH

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ABSTRACT

Extensive numerically based modelling has been conducted to simulate surface and sub-surface subsidence due to longwall mining in UK Coal Measure rocks. The results have been validated, against the Subsidence Engineer's Handbook (SEH) surface subsidence prediction method. A Rock Mass Classification Rating (RMR) has been used to derive pre and post failure input parameters for both strength and stiffness properties. RMR has been found to be the most acceptable approach through a thorough review of methodologies and approaches to the determination of numerical modelling input parameters. Longwall panels of 200m width and 2m extraction thickness at various depths have been simulated using Fast Lagrangian Analysis of Continua *FLAC (Version 3 3),* A strain softening constitutive model with user defined pre failure stifmess and strength parameters in the input data file, and post failure values for stifmess have been incorporated in a separate function that is activated by plasticity during the computer rua The final version of the model has been validated through a combination of the pattern of stress redistributed around longwall panels and the displacement distribution at the surface. Sequences evaluating the variation of subsidence with extraction thickness and panel width have been run for typical but idealised UK longwall excavations at 400m depth. An interesting relationship between depth and RMR has been explored and a modification to Serafim and Pereira's expression for in-situ rock mass Young's Modulus derivation has been suggested. Based on the experience in validating the model for UK Coal Measures it is proposed to adapt the model as a tool for surface subsidence prediction in various international coalfields having significantly different rock mass and subsidence characteristics.

1 INTRODUCTION

One of the important features of mining beneath Coal Measure rocks is the surface subsidence produced after a longwall panel has been extracted. The accurate prediction of the final subsidence profile at the surface caused by any such mining activity is of particular importance to help minimise surface damage and to optimise the mining method design. Previous research has already been carried out in this complex field at Nottingham in order to establish tools which can be used to forecast the amount and extent of any movement at the ground surface using empirical, physical, and limited numerical modelling techniques. (Reddish 1984, Yao 1992, Benbia 1995)

This research has established a series of numerical models, to simulate a 200 m wide longwall panel at a wide range of depths between 100m and 800m below ground with a 2m extraction thickness. Input values for the strength and stifmess parameters for the models were initially considered to be those of a typical UK Coal Measure rock mass (Yao et al 1993). A Finite Difference Method, Fast Lagrangian Analysis of Continua *{FLAC) Version 3.3* with a wide suite of constitutive relations were used in the analyses (ITASCA 1995). The Subsidence Engineer's Handbook (SEH) method was used as a reference to validate the surface results obtained from the numerical model (NCB 1975).

2 METHODOLOGY

2.1 Model Configuration

The numerical modelling programme was conducted utilising axi-symmetrical Finite Difference grids of l00m to 800 m depth by 800 m total width. The model grids contained some 10,000 elements, (Figure 1) A width of 800 m was found to be sufficient to model the full surface subsidence profile for one half of the 200m panel for the whole range of depths.

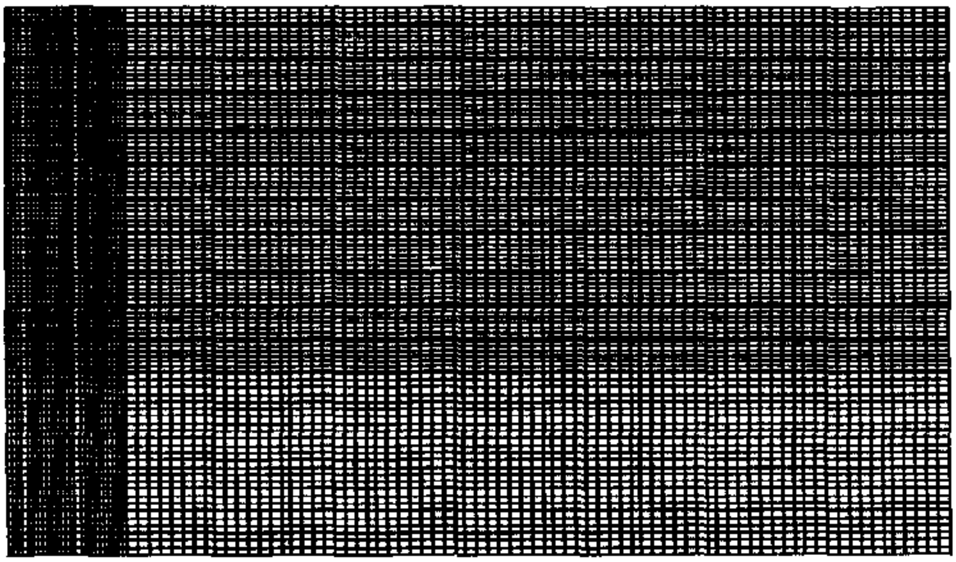
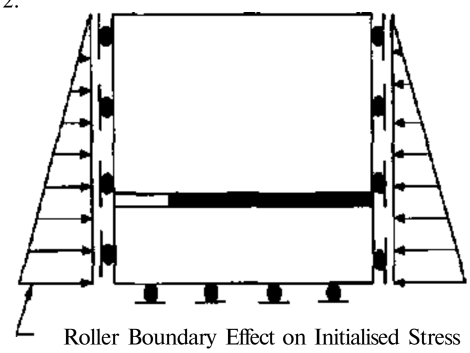


Fig lAxi-symmetrical Finite Difference grid comprising of 10,000 elements

The boundary conditions used are illustrated İn Figure 2.



Roller Boundary Effect on Initialised Stress

Fig 2: Model boundary conditions and load specificitions

2 2 Stress Conditions

Gravitational loading conditions were assumed to generate the virgin stress conditions using the following relationships, (Bigby et al 1992, Terzaghi and Richart 1952):

$$\sigma_v = \rho g h \qquad (1)$$

The vertical stress o_v throughout the grid was determined from equation (1).

where p — density of the rock mass = 2350 kg/m^3 (Yaoetall993)

g = acceleration due to gravity = 9.81 m/sec^2

h = depth

Horizontal stresses were determined from equation (2):

$$\sigma_h = \rho g h \frac{v}{1-v} \qquad (2)$$

where v- Poisson's Ratio of the rock mass was assumed to be = 0.2 (Yao et al 1993)

3 DERIVATION OF MECHANICAL PROPERTIES *OF* ROCK MASS

The elastic rock mass properties for model input into *FLAC* are defined in terms of Bulk (K) and Shear (G) Moduli derived using the following expressions:

$$K = \frac{E}{3(1-2v)} \tag{3}$$

$$G = \frac{E}{2(1+v)} \tag{4}$$

where E = Young's Modulus of rock

It has been well documented that in order to determine representative mechanical properties of a rock mass, a reduction in the value of laboratory test results on intact specimens of rock must be considered, (Bieniawskt 1978, Serafim & Pereira 1982, Nicholson & Bieniawski 1990, Mitri et al 1994).

In general the two most widely used methods to evaluate field mechanical properties are:

(0 Reduction of laboratory intact rock elastic modulus by a specific percentage to account for the influence of scale and the presence of discontinuities in the larger rock mass.

(ii) Apply rock mass classification principles to characterise the rock mass and utilise stiffness reducing expressions developed from a wide range of measured data.

3.1 Initial Modelling

For the base mode! at the initial stage of the modelling programme a reduction factor.İdeology wa adopted, based on work by Yao et.al (1993) and the following parameters were initial]) used within the model:

E_{ra},= 1200MPa
v = 0.2
UCS_m = E^/300 = 4 MPa
UTS„„= UCS.J10 = 0.4 MPa

where *E„„*= Modulus of Elasticity of Rock Mass
UCS„„= Uniaxial Compressive Strength of Rock Mass
UTS_m= Uniaxial Tensile Strength of Rock Mass

The strength parameters in terms of Cohesion (c) and Angle of Internal Friction (<D>) were derived from the inferred UCS^and UTS™.

The initial analyses were conducted using the base mechanical properties outlined above with the standard constitutive relations available within *FLAC* namely:

1) Elastic, Isotropic
2) Elastic, Transversely Isotropic
3) Non-Linear, Mohr-Coulomb Model
4) Non-Linear, Ubiquitous Joint Model
5) Non-Linear, Strain Softening Model

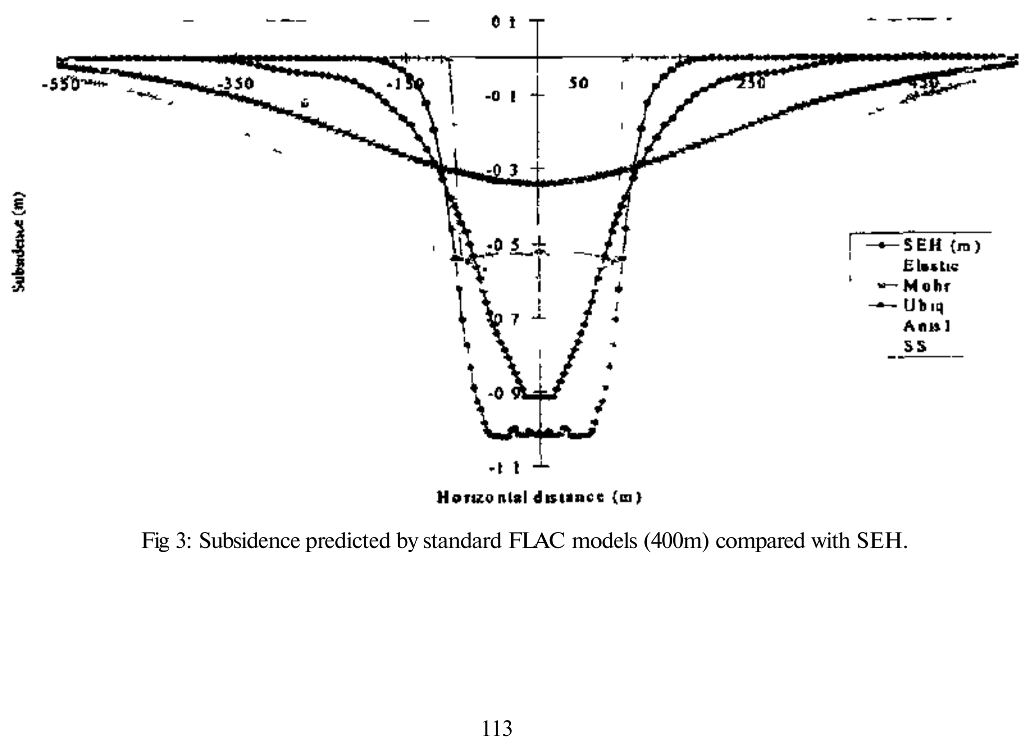


Fig 3: Subsidence predicted by standard FLAC models (400m) compared with SEH.

Figure 3 illustrates a representative example of the results achieved when the modelled surface subsidence was compared to that predicted by the SEH method for the 400m depth case. It was found that although the maximum modelled subsidence at the centre line of the 200m wide panel was relatively close to that predicted by the SEH method, there were serious deviations in the profile towards the outer ends. Where this end effect was eliminated by parameter adjustment the subsidence profiles simulated in the models did not accurately represent the predicted subsidence trough. After a large number of systematic adjustments to the mechanical properties and stresses input into the models it was concluded that the constitutive relations within *FLAC* could not accurately simulate surrace subsidence magnitude or model the subsidence profile predicted by the SEH method. It was concluded that the modelling package is sensitive to subtle changes in stiffness and strength parameters and therefore a detailed parametric study to determine accurate pre and post failure stiffness and strength parameters was essential for successful large scale modelling.

4 THE DEVELOPMENT OF ROCK MASS CLASS1FJCATJON BASED INPUT PARAMETERS

A wide ranging literature search was conducted to assess and evaluate the methodologies used to fine-tune mechanical properties for input within numerical modelling applied to sub surface rock engineering to accurately represent rock mass conditions, (Mohammad, et al 1997). Out of the hundreds of publications examined it was found that approximately 120 articles clearly stated the origin of their mechanical properties and where applied, the methodology utilised to fine-tune their input parameters to represent the rock mass scale. It was significant that some 60% of the numerical modellers did not mention the methodologies they adopted or used laboratory test results on small intact rock specimens within their models and applied no reduction to the stiffness or strength parameters to represent scale effects, me presence of discontinuities and the influence of mining in the third dimension. The other 40% of the numerical modellers however introduced reductions to their input parameters by the use of either a straight reduction to the stiffness and strength determined from laboratory tests on intact rock specimens or by utilising a rock mass classification within expressions based on in-situ measurement and empirical failure criteria, (Mohammad, et al 1997). The review conducted studied case histories and back analysed the input parameters separating the rock mass stiffness properties from the strength data. The model stifihess properties indicated interesting differences in the respective average reduction factors adopted by various researchers. Figure 4 presents the Young's Modulus results for laboratory rock tests plotted against the reduced \values used İn a wide range of rock mass environments, (Mohammad et al 1997). The stiffness values fine tuned to represent in situ conditions by the numerical modellers \aned considerably when compared in Figure 4 to intact stiffness for typical UK Coal Measure Strata (10,000 MPa to 25,000 MPa). Some researchers reduced stiffness for model input marginally from intact laboratory test results. Hence the average insitu stiffness illustrated in Figure 4 may be increased by this bias in the data. From the results of a numerical modelling sensitivity analyses it was concluded that much lower in situ stiffnesses than the average stiffness derived in Figure 4 was necessary for accurate simulation of UK Coal Measure rocks. The expressions that have been derived from in-situ measurement of deformation modulus and related to rock mass classification ratings suggest a much lower in-situ deformation modulus for UK Coal Measures (Figure 4). After an extensive parametric study Serafim and Pereira's (1982) expression was found to derive the best in-situ deformation modulus of UK Coal Measure rocks for the large scale subsidence modelling.

$$E = 10^{\frac{RMR-10}{40}} \quad \text{(GPa)} \qquad (5)$$

This expression was modified during the research to take into account the anomaly m the original expression that suggested a rock mass with a zero rock mass rating had a significant in-situ modulus The modified relationship was used within the anal>ses and is presented below:

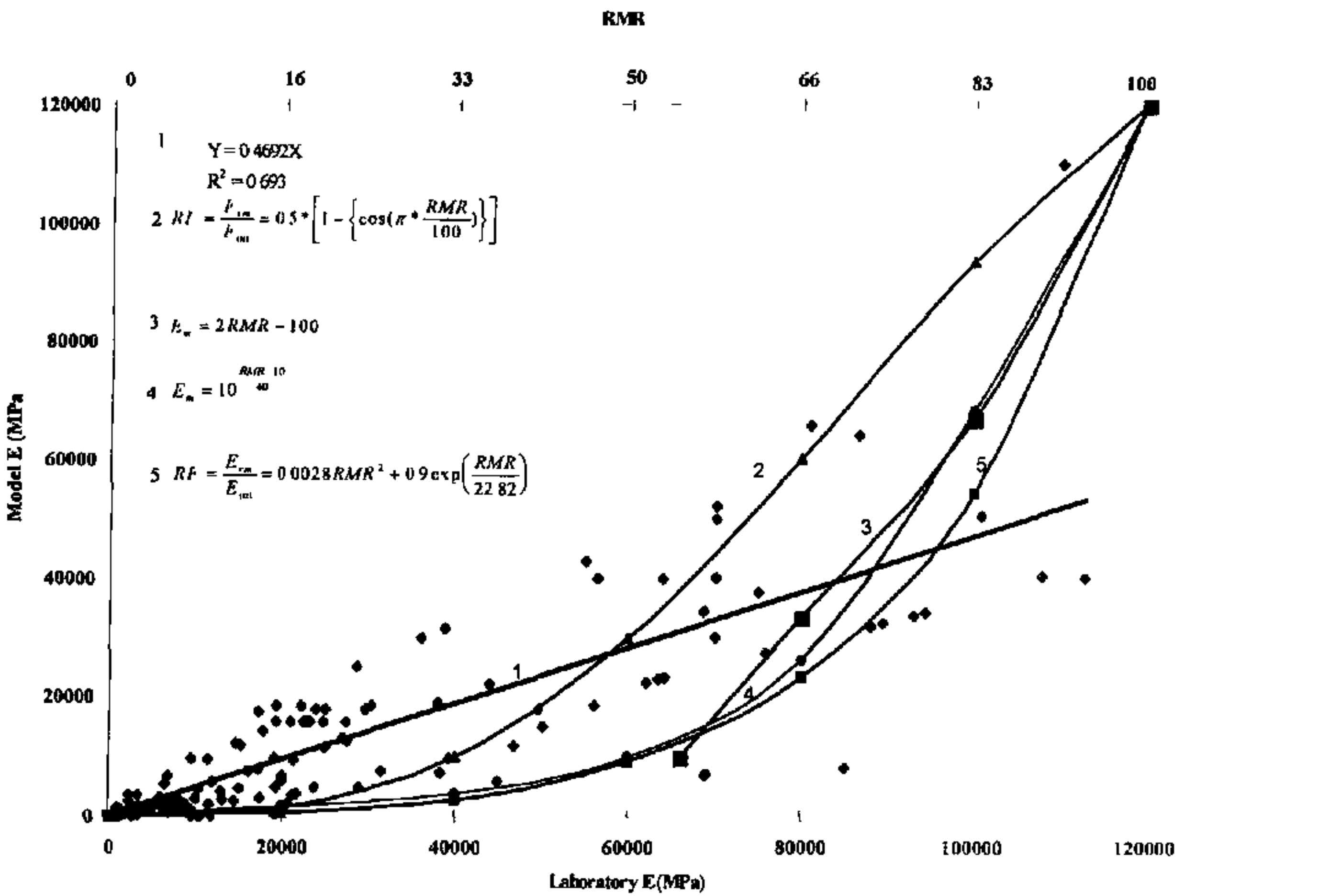


Fig 4 Young's Modulus from case histories for laboratory tests and numerical modelling input (Mohammad et al 1997)

$$E = 10^{\frac{RMR-10}{40}} - 0.562 \quad \text{(GPa)} \qquad (6)$$

During the *simulation* of the 200m wide longwall panel with a 2m extraction thickness the input parameters for bulk and shear moduli were determined from equations (3) and (4) utilising the rock mass deformation modulus obtained from Serafim and Pereira's relationship. A sensitivity analysis was conducted by varying the Poissons Ratio in the determination of these in-situ stiffnesses for model input. A Poissons Ratio of 0.2 was found to provide the optimum results in terms of the simulation of deformation processes that were reasonably valid when compared to reality for the full range of depths. Within the numerical models the deformation processes and surface subsidence induced by mining the 200m longwall panel at 2m extraction thickness at a depth range of 100m to 800m was determined by adjustment of the RMR value as a control for determining the pre and post failure stiffness properties, (Table 1).

4.1 Modelling of Extraction and Caved Waste

In order to model the propagation of a caved waste the model must be constructed to allow the development of an extensive yield and failure zone that can be considered representative of reality. However to literally imitate the actual deformation processes of a caved waste propagation and yield zone development would be unrealistic, - therefore a simplification of practice is essential when using numerical modelling techniques in these circumstances, (Starfield and Cundall 1988). Although complex this coold be achieved by defining a strain-stiffening caved zone and reduced input properties within the zone of influence above the extracted panel, (Lloyd 1995). The valid alternative that was adopted, was to extract the 2m high, 200m wide panel within the model allowing the roof and floor strata to converge (Reddish 1989). The introduction of post *failure* stiffness parameters would then be governed by yield and failure of the elements within the model. This methodology provided better results for subsidence prediction and displacement distribution within the models. Post failure stiffness properties were incorporated whliin the simulations as a straight reduction of the initial pre failure stiffness that was determined using RMR. After extensive evaluation the optimum reduction factor of 1/10th the pre-failure stiffnesses were specified within elements that had undergone varying degrees of yield and plasticity

Table 1 Summary of the stiffness parameters

Depth (m)	RMR	E* (GPa) Pre Failure	E* (GPa) Post Failure
400	40	5 0611	0 50611

E* is calculated according to the modified Serafim & Pereira expression (Eqn 6)

5 STRENGTH PARAMETERS

After a systematic series of Numerical Model runs, It was clear that the strain softening constitutive model provided the correct balance between stiffness and strength. Figure 5a shows the stress-strain relationship controlled by the elastic and plastic strain increment for the strain softening relation. Plasticity propagation was considered reasonably accurate when the failure mechanisms were assessed and evaluated using the authors monitoring experience of actual in-situ deformation processes.

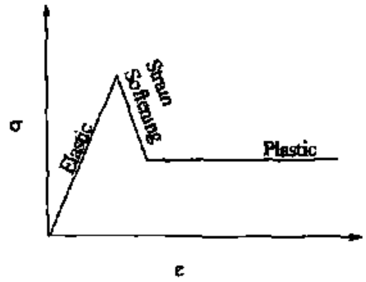


Fig 5a: Stress-strain relationship (strain softening)

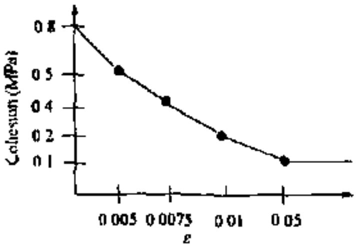


Fig 5b: Fine tuned SS parameters (cohesion)

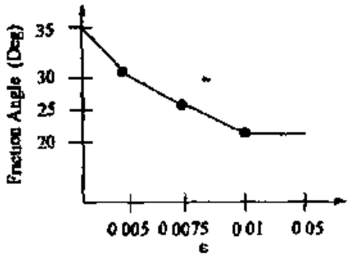
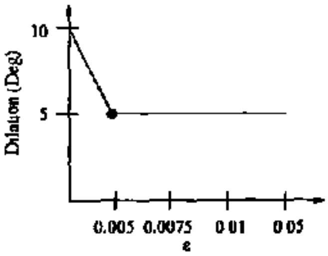


Fig 5c: Fine tuned SS parameter (friction)



FİR 5d: Fine tuned SS parameter (dilation)

The initial input properties for strength were determined using a modified coal measure rock mass failure criterion related to actual intact rock test data for UK Coal Measure rocks, fine-tuned for UK coal mine inshu conditions using a rock mass classification rating (Stace and Lloyd 1996). During the analyses it was further concluded that the strain increment specified was significant with respect to the full propagation of yield and failure within the model (Itasca 1995). After a thorough evaluation of the influence of the specified strain increment on model results the fine-tuned strain softening parameters and strain increments are presented İn Table 2;

Table *2:* Final strength parameters used in SS model with detuned strain increments.

Strain	Cohesion C (MPa)	Dilation d (deg)	Fric Angle ϕ (deg)
0	08	10	35
0.005	0 5	5	30
0 007S	0.4	S	25
0.01	0.2	5	20
0 05	0 1	5	20

The fine-tuned Strain softening parameters are illustrated İn Figures (5b). (5c) and (5d).

6 RESULTS

6.1 Validation of Model Depth Sequence

When the depth sequence was run for a particular RMR based input parameter set, the results displayed a certain pattern. When a low RMR was used good results could be obtained for shallower situations but deeper models gave a poor fit. Conversely when a high RMR was used the deep models produced a good fit but the shallower models underestimated. Fine adjustments İn the stifihess to strength balance could not start to overcome this fairly fundamental trend. As a result İt was felt that RMR and hence stiffness and strength must in some way change in the models with depth. Essentially deeper buried rocks of the same type appeared to be stifler. An alternative explanation would be that the gravitational stress field assumptions made were incorrect and vertical stress at depth is considerably reduced from that assumed. Some trials with increased horizontal stress also proved ineffective. The authors felt that the stiffening of rocks under higher stress and compaction was relatively logical and chose to investigate it further. Models were run at each depth and RMR and its associated properties adjusted until the best subsidence fit to the SEH validation model was obtained. The *FLAC* models were run for the full range of depths and were compared with results from the SEH surface subsidence prediction method, (Table 3): The RMR to determine the stiffness was the controlling parameter and was adjusted with depth until the subsidence profile simulated that predicted by SEH in tenns of limb profile and maximum subsidence magnitude. An error band of ±20% was considered reasonable for maximum subsidence (Whittaker and Reddish 1989, NCB 1975). It must be noted that the fine tuned Rock Mass Classification Ratings are presented in Table 3, since even relatively minor subtle changes in the RMR produced major differences in the maximum subsidence and subsidence profile shape.

Table 3 Summary of the FL AC and SEH results

Depth (m)	RMR	S_{max} SEH (m)	S_{max} FLAC(m)	Error %	E^* (GPa)
100	8	1.78	1 805	1 4	0 329
200	20	1.647	1.580	-4.07	1.216
300	28	1.291	1.372	6.27	2.256
400	41	0.913	0 932	2 08	5.394
500	47	0,678	0,679	0,15	7.852
600	54	0,4876	0.476	-2.38	12.027
700	57	0.371	0,349	-5 93	14.4
800	63	0 313	0 2928	-6 45	20 573

E^* is calculated according to the modified Serafim & Pereira expression(Equation 6)

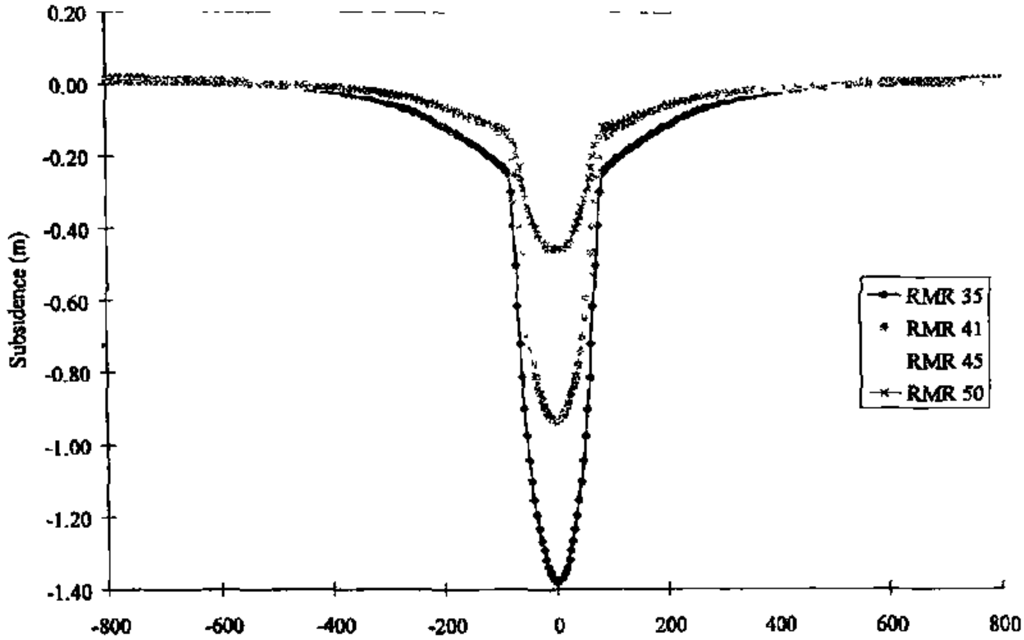


Fig 6: Sensitivity of the model towards RMR/ Stiflhess variation.

Figure 6 provides an indication of the affect of reducing and increasing the stiffness by variation of the RMR between 35 and 50 for the 400m depth case, the fine tuned value of 41 is also presented. The results of the sensitivity analysis suggested that relatively low variation in RMR (stiffness) produced significant differences in modelled maxinium subsidence and subsidence profile shape.

7 RESULTS ANALYSIS

7.1 Depth below Surface Variation

From the full range of model results displayed in Table 3, It was evident that the stiffiiess parameters of the rock mass appeared to increase with depth.

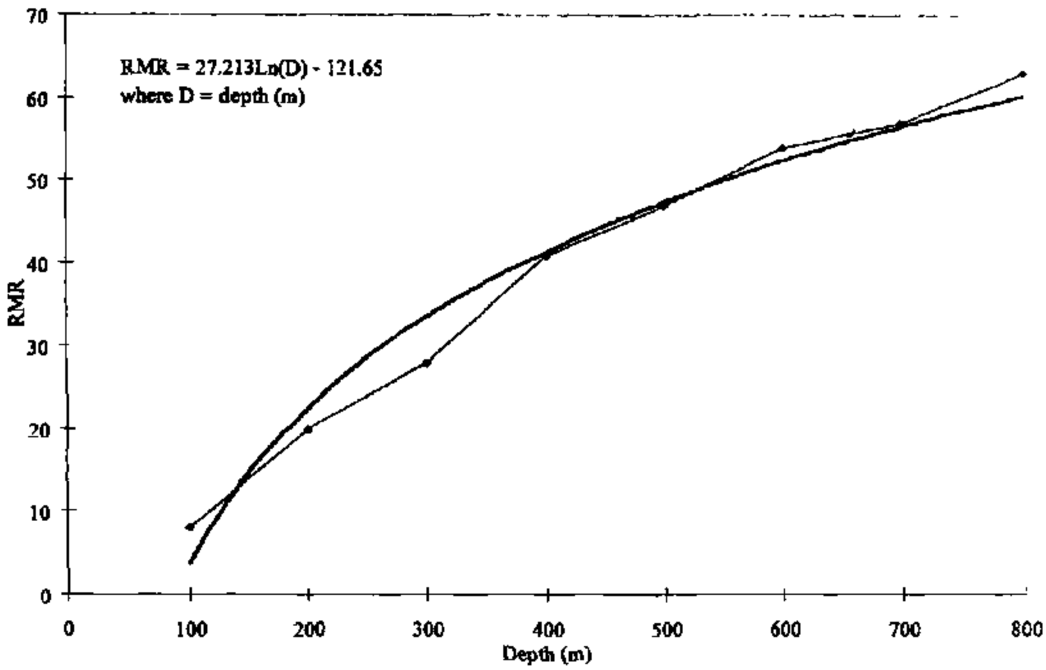


Fig 7: Model relationship between depth and RMR.

Consequently the rock mass classification rating (RMR) increased with depth Figure 7 illustrates this relationship and is represented by the following expression:

$$RMR = 27.213Ln(D) - 121.65 \quad (7)$$

where D = Depth of seam below surface (m)

Figure 8 shows the modelled surface subsidence when compared to the SEH prediction for the 400m depth case. The displacement distribution modelled was found to be valid throughout from seam level to the surface and additionally the redistribution of flank abutment stresses seemed reasonable.

7.2 Seam Extraction Thickness and Panel Width Variation.

The modelling methodology derived from simulating the 2m extraction thickness and 200m panel width proved insufficiently sensitive to variation in extraction thickness and panel width in terms of accurate prediction of surface subsidence. Manual control on the development of the caving or yielding zone was required to sensitise the model to these parameters. Manual iteration of the model had to be introduced with a limitation placed on the propagation of the yield and failure zone above the extracted panel to produce a universal modelling technique. The relationship between RMR and depth was used to determine stiffness parameters as İn the analyses previously discussed. A series of numerical models were established that examined the sensitivity of the methodology developed when simulating the surface subsidence predicted by the SEH method for var) mg coal seam extraction thicknesses and panel widths. From the modelling results İt was found that the extent of the yield and failure zone around the longwall panel significantly influenced the magnitude of maximum subsidence and the surface subsidence trough profile shape when cornpared to the SEH method (Alejano Monge et al 1995). For the purpose of this publication the sensitivity studies carried out for the

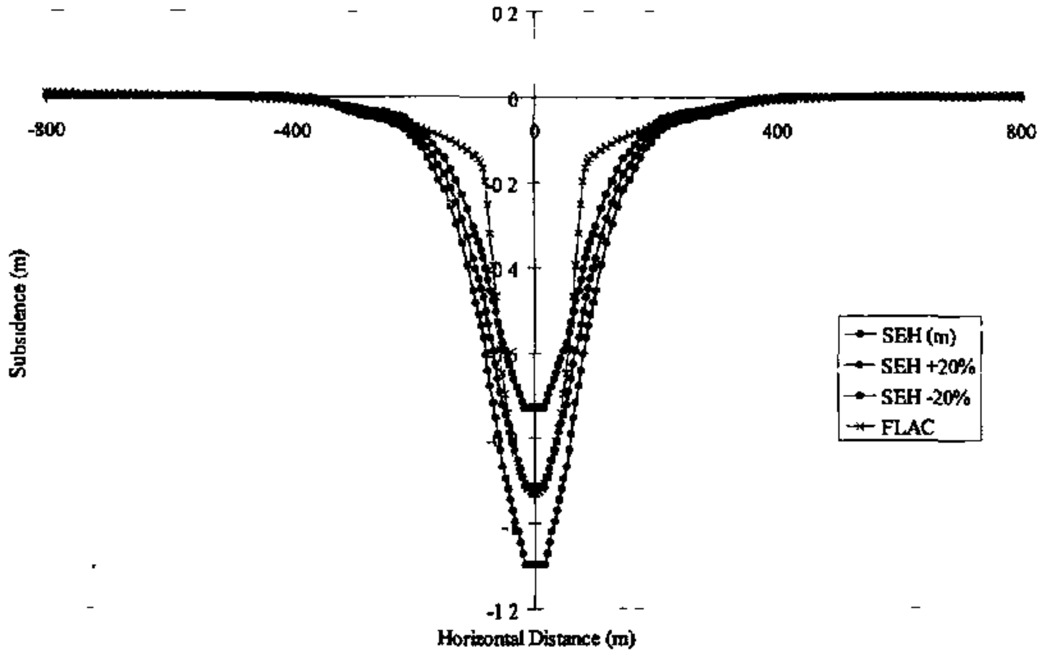


Fig 8: Modelled surface subsidence compared to SEH prediction for 200m longwall panel at 400m depth.

400m depth case was selected for further analysis and is presented below.

7.3 Seam Extraction Thickness Variation (400m depth Case)

Seam extraction thicknesses of lm, 1.5m, 2m, 2.5m and 3m were specified within the numerical model for the 400m depth case, and run. The fine tuned properties remained the same and the following expression was derived to provide an indication of the extent of yield and failure zone around a longwall panel for a specified extraction thickness, Figure 9:

$$\frac{Y}{X} = 37.435e^{0.413X} \quad (8)$$

where Y = Extent of yield and failure zone (m)
X = Seam Extraction Thickness (m)

From evaluating the results displayed in Figure 9 it was noted that when seam extraction thickness was varied within the 400m depth case, then the extent of the zone influenced by the longwall panel required to be significantly increased.

7.4 Panel Width Variation (400ra Depth Case)

The results of varying the panel width for the 400m depth case indicated that the yield and failure zone above a longwall panel was influenced by the variation of panel width while seam extraction thickness remained constant. Longwall panel widths of 150m, 200m 250m and 300m were specified. Figure 10 shows the relationship between the extent of the j ield and failure zone and panel width in the models:

$$\frac{Y}{X} = 89.596Ln(PW) - 394.59 \quad 19)$$

where PW = Panel Width (m)

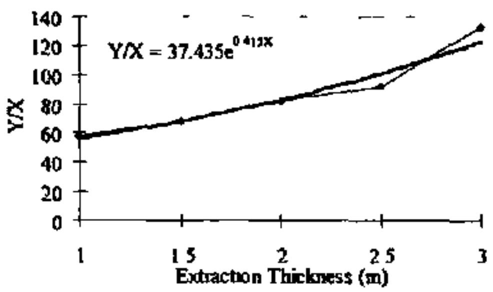


Fig 9: Extent of the failure zone varying extraction thickness.

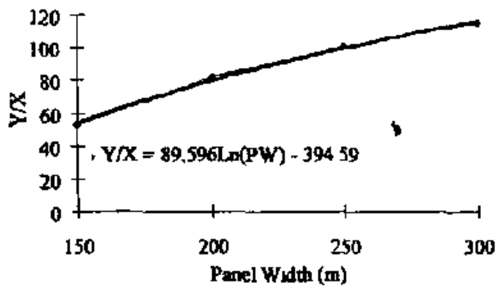


Fig 10: Relationship between extent of the failure zone for different longwall panel widths.

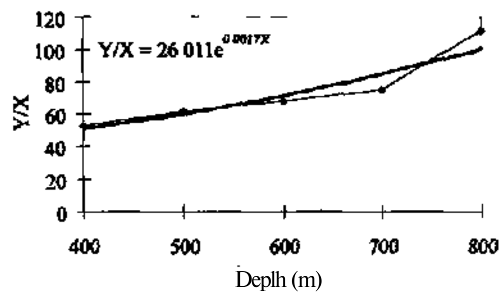


Fig 11 Relationship between depth and extent of the failure zone for 150m wide longwall pane)

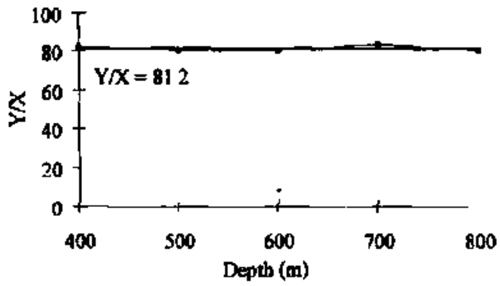


Fig 12: Relationship between depth and extent of the failure zone for 200m wide longwall panel

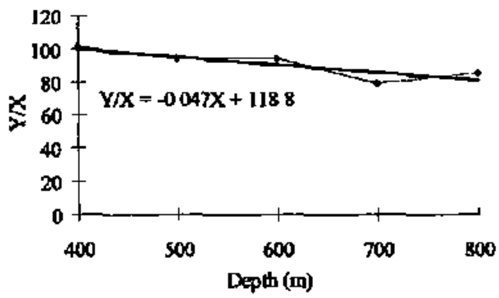


Fig 13: Relationship between depth and extent of the failure zone for 250m wide longwall panel

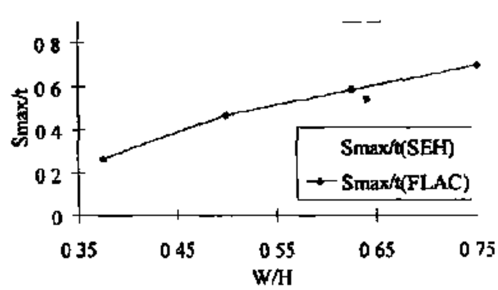


Fig 14· S_{max}/t vs W/H for depth= 400m

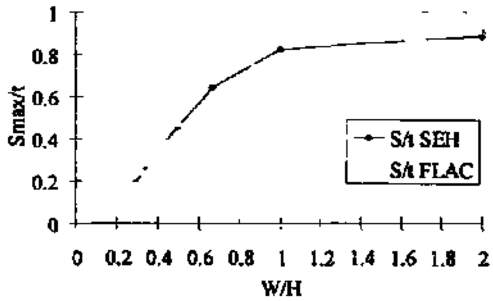


Fig 15: S_{max}/t vs W/H for depth= 100m - 800m.

Further sensitivity analyses were conducted where the full variation of panel widths of 150m, 200m and 250m were specified for the 400m to 800m depth range, seam extraction thickness remained constant at 2m as did the properties determined from RMR.

Figures 11, 12 and 13 illustrate the relationships between panel width and depth below surface for the 150m, 200m and 250m panel widths. For the 200m panel width a relatively constant yield and failure zone of 162.4m extent above the panel with little variation was indicated from the full series of analyses. When the panel width, was reduced to 150m the extent of the zone influenced by the panel extraction for the 400m case decreased to 106m. However the specified zone of influence above the panel increased with depth within the model. When the 250m panel width model results were evaluated this yield and failure zone increased to 200m for the 200m case, decreasing slightly with depth to 162m at 800m below surface

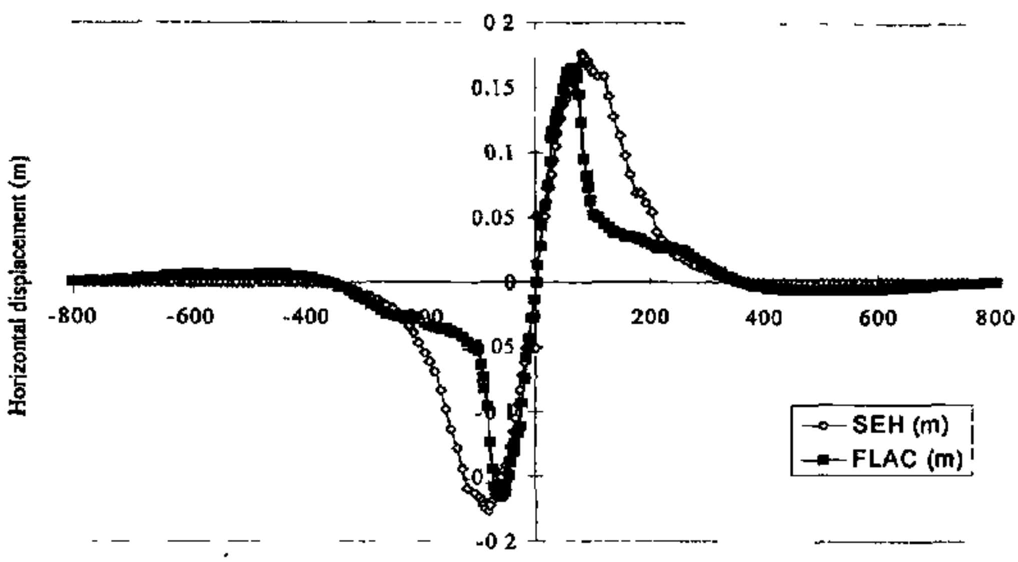
The results from the panel width -variation models for the 400m depth case with a 2m extraction thickness, were plotted with maximum subsidence/extraction thickness ratio (Smu/t) against panel width/depth ratio (W/H) and compared to the same configuration predicted by the SEH Method (Figure 14). The results of the models were found to be in close agreement with the predictive methods results. The results for the full series of modelled depths were evaluated in terms of (S J t) vs (W/H) for the 200m panel with 2m extraction thickness and compared with the SEH method prediction. The full range of numerical models was further validated when compared with the predicted results, (Figure 15).

7.5 Strain Softening Sensitivity Analyses

When strain-softening constitutive relations are used İn numerical modelling, results may. be sensitive to element size and shape (Trueman et al 1992). In the grid specified for the modelling series symmetrical elements were utilised and the width to height aspect ratio between adjacent elements were kept well within tolerances suggested by FLAC (Itasca 1995). A sensitivity analysis was conducted for the 400m depth case where a much more dense grid with smaller symmetrical elements was utilised. A model with a total of 36,000 elements as opposed to the usual 10,000 elements was specified and run. The maximum modelled subsidence was within 3% of the original run with a near perfect subsidence profile simulated. This condition occurred when the post failure property zone was specified to propagate to the _ame extent as in the model with the smaller grid.

7.6 Adjustment to Horizontal Displacements in the SEH Prediction Method

The empirically derived horizontal displacements curve usually does not start and finish on zero displacement. This is an error and must be distributed to give a balanced displacement curve. The most valid method of correction is to distribute the displacement closure in proportion to strain, since where strain is high, measurements are most likely to be in error. This gives the correct profile shape and has a small error in symmetry, which can then be eliminated by averaging values on ehher side of the centre point. (Whhtaker et al., 1985). The horizontal displacement at the surface of the 400m depth case determined from the SEH method and modelled in *FLAC* are presented in Figure 16. The results indicate that the model reasonably closely simulates the SEH predicted horizontal displacements.



Horizontal distance (m)

Fig 16: Horizontal displacement distribution along surface, SEH compared to FLAG

8 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

A valid but complex methodotogy for simulating surface subsidence for UK Coal Measures has been developed, applicable to a comprehensive range of depths between 100m to 800m. A relationship between RMR and depth for pre and post failure stifihess determination was derived raising a number of interesting questions and ideas for faster research. The use of Rock Mass Classification principles to more accurately characterise UK Coal Measure rocks would be useful for fine tuned in-situ strength and stiffness determination. The modelling technique developed is sensitive to extraction thickness variation and longwall panel width variation when the propagation of the zone of influence above the panel is finite. Research is currently ongoing into interactive yield and failure propagation control within the input file, as well as extending the subsidence modelling technique to international coalfields.

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