A Semi-Empirical Method for the Prediction of Mine Subsidence and Associated Parameters in Indian Coalmines

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ABSTRACT

The empirical methods of subsidence prediction are site specific and are not based upon the rational concepts of Rock mechanics. Purely mechanistic methods on the other hand could not find wide applications because of their limitations in representing the complex behaviour of a rockmass. Moreover these methods have a main handicap in general availability of accurate rock properties and geological data which are usually difficult and expensive to obtain. In order to overcome disadvantages of these two approaches a hybrid approach of carrying out parametric studies by numerical modelling and using its conceptual results in field database to develop a semi-empirical model has been adopted and discussed here.

The method of prediction of maximum possible subsidence, S_{max} has been reported elsewhere [Bahuguna et al, 1993]. The results obtained from numerical analysis have been used to identify and correlate the various parameters effecting the shape of the subsidence profile with the known parameters viz the nature of overburden rockmass and the mining geometry. A new Profile Function based on the present work has been recommended for use in the Indian coalfields. The profiles of slope, horizontal displacements and horizontal strains may be obtained from subsidence values along the given line. Results of a few of many cases tested by this method have been discussed and were found to be satisfactory when compared with field values.

1.0 INTRODUCTION

The empirical methods of subsidence prediction are quick, simple to use and yield fairly satisfactory results in the areas for which they are developed but they are not based on the theory of Rock Mechanics. The mechanistic methods on the other hand, though more fundamental than empirical methods have their own limitations in representing non-linear and complex behaviour of the overburden rockmass. The results obtained by mechanistic methods generally do not conform to the values observed in the field but if used qualitatively these prove to be remarkably well in studying the effect of each individual subsidence contributing factor.

In the present work, the parametric studies of the effect of each subsidence contributing factor has been carried out by numerical modelling and by using its conceptual results in a field database a semi-empirical method has been developed.

2.0 PARAMETRIC STUDIES

In empirical methods, a large number of systematically acquired field measurements covering all possible situations are required to develop a reliable prediction model. Generally the field data are available in limited number and for local situations only. To supplement the field data additional data was generated by numerical analysis. Numerical modelling by Boundary Element Method was carried out for parametric studies. Two computer programs MSEAMS [Crouch,1976] and MULSIM/BM [Beckett and Madrid, 1988] based on Displacement Discontinuity Method [Sinha,1979] a subvariation of Boundary Element Method have been used for these studies. MSEAMS is a two dimensional BEM program considering the overburden rockmass as homogeneous, linearly elastic and transversely anisotropic medium. MULSIM/BM is a three dimensional BEM which also assumes the overburden rockmass as homogeneous linearly elastic but isotropic medium. Theory of elasticity is valid for layered media provided slip along bedding planes is simulated by assuming very low shear modulus of rockmass. [Singh,1973]. Mechanistic characteristics of rockmass such as overburden of mine workings are so highly complex and anisotropic that it could so far not be possible to simulate the rock behaviour accurately. Therefore a correct quantitative evaluation of subsidence deformations has so far not been possible by any of the mechanistic methods [Bahuguna, 1991b]. The linear elastic models however produce too wide and shallow subsidence trough because of the tendency of linearly elastic strata to cantilever excessively [Mikula and Holt, 1988]. These models do not produce good results specially when the rock structure is more complicated because of their limitations to simulate vertical joints.

The use of non-linear elastic models by Finite Element Method (FEM) produce comparatively better results [McNabb 1987; Siriwardane, 1985] than linearly elastic models in subsidence prediction. FEM can account for non-linear and rheological material behaviour and for different rock properties in the same region but it has problems too. One problem is that the constitutive behaviour of broken overburden rockmass is not yet fully known. Another problem arises of contact stresses,due to which the sum of roof settlement and floor upheaval exceeds the seam thickness creating an unusual situation.Thirdly, it requires the rock properties to be known all over different strata in the overburden, which is difficult and expensive compared to the small advantage it offers specially when qualitative analysis of normalised subsidence as in the present studies. Salamon [1988] opined that, the linearly elastic models, however unable to produce acceptable surface subsidence, do simulate the ground movements qualitatively because of their flexibility and adaptability. Therefore, while it is recognised that a discontinuous rockmass does not behave in a linearly elastic manner, it was felt that the simple boundary element method (BEM). analysis based on these assumptions would be satisfactory to qualitatively identify the effect of various contributing factors on subsidence and other associated parameters in Indian coalmines where percentage of strong sandstone layers in the overburden is generally high (65-93%). These qualitative results could then be used to help in developing empirical equations.

Proper selection of material properties of rockmass is of great significance in numerical modelling of a subsidence problem. This may also be done by 'calibrating' the model with known field data. In the present studies the material properties were not available either from in situ or from laboratory tests. Therefore the following empirical correlation [Bahuguna et al. 1993] between the Young's modulus in horizontal direction E_h and known percentage of hard rock layers present in overburden was used for obtaining the values of E_h :

$$\underset{\text{(in MPa)}}{E_h} = 500 + 195\,(\text{\% of sandstone layers in the overburden}) \qquad (1)$$

For the anisotropic material model MSEAMS the value of E_v (in the vertical direction or in the direction perpendicular to bedding planes) was taken to be one fifth of E_h. It has been suggested [Singh,1973] that a jointed rockmass may be characterized as an anisotropic elastic material of very low shear modulus to simulate slip along bedding planes. The ratio G/E_v is therefore used to classify the degree of discontinuities in the overburden rockmass whereas from equation (1) above the strength of the overburden rockmass is indicated by higher values of Young's modulus.

By back analysis the shear modulus G was chosen for the anisotropic model so as to simulate the known values of subsidence. The values of shear modulus G thus obtained were used to classify the overburden rockmass by correlating these values with the degree of disturbance present in them.

Table 1 gives a new classification of rockmass [Bahuguna,1993] based on its condition marked by the presence of natural planes of weakness and degree of fragmentation caused by repeated workings. The classification at its present form is proposed only for subsidence prediction problems and may not be considered for general use unless tested for other problems.

2.1 Rock Factor, R_f

The presence of more hard rock layers in the overburden results in less subsidence at the surface [Tandanand & Powell, 1984]. At the same time the discontinuities or planes of weakness such as joints, fractures,faults,parting and separation make the caprocks weaker and result in increased subsidence values.

A rock factor R_f has been visualised [Bahuguna, 1993] to give the combined effect of the composition and strength of the overburden rockmass. The composition is expressed in terms of percentage of hardrock layers (sandstone, limestone etc.) present in it and the strength, in terms of presence of natural discontinuities and degrees of fragmentation in rockmass due to repeated workings.

R_f is a factor which indicates the combined effect of composition and strength of overburden rockmass on subsidence in numerical terms keeping all other subsidence influencing factors unchanged. Its value ranges from zero for no subsidence to 1 for maximum subsidence. The values of R are obtainable from curves given in Fig.1 at different percentage of hardrock layers and for each of the five classification of overburden rockmass given in Table 1.

With judicious engineering judgment and field experience it will be possible to choose the proper curve, in the absence of G/E values for obtaining values of R_f from Fig.1.

Table 1 - Classification of Overburden rockmass

Rocmmass Classification	G/E_v	Description
1. Competent	0.07-0.38	Massive rockmass with few planes weakness
2. Undisturbed	0.03-0.07	No previous mining but few natural discontinuities
3. Partially disturbed rockmass	0.016-0.03	Parting between the mined seams more than 5 times the seam thickness or cases with no previous mining but many natural discontinuities
4. Disturbed rockmass	0.005-0.016	Parting between the mined seams not more than 5 times the seam thickness and many discontinuities
5. Highly disturbed rockmass	< 0.005	Highly fragmented rockmass with repetetive workings or having very thick seams mined in descending slicing

Workings having caved or worked seams around them where overburden rockmass has become fragmented and weak because of natural discontinuities and mining operations may be termed as highly disturbed, disturbed and partially disturbed rockmass according to the degree of weakness as given in Table 1. Such rockmass exhibit varying degree of anisotropy according to the degree of weakness. The rockmass may be termed as undisturbed where no previous mining activity exists in the vicinity of the mine workings and natural discontinuities are also comparatively less. The term competent may be used for massive rockmass having very few discontinuous planes of weakness thus producing negligible subsidence on the ground surface. Such rocks are nearly isotropic.

3.0 SEMI EMPIRICAL METHOD

The semi-empirical model thus adopted follows the following sequential steps :-

- Prediction of Maximum Possible Subsidence (S_{max}),
- Prediction of Maximum Subsidence (S_0 for a given mine geometry),
- Prediction of Subsidence profile,
- Prediction of associated parameters viz slope, horizontal displacements and horizontal strains.

4.0 PREDICTION OF S_{max}

The semi-empirical method developed for the prediction of S_{max} has been discussed in details somewhere else [Bahuguna et al, 1993]. The method is an improvement over an empirical method suggested earlier by the author (Bahuguna et al, 1991). The present semi-empirical method is based on the following formula for the prediction of S_{max} [Bahuguna 1993]

$$S_{max} = m \cdot g_f \cdot e \cdot R_f \cdot d_f \cdot d' \cdot t \quad (2)$$

Where m = thickness of the coal seam,
g_f = goaf treatment factor,
e = extraction factor,
R_f = Rock factor for the effect of composition and strength of overburden rock mass,
d_f = factor for the effect of depth of workings,
d' = factor for the effect of angle of dip α, of seam,
t = time factor (to be taken as 1 for finished subsidence).

In the present method, the values of various subsidence influencing factors may be assigned as given below for different situations on the basis of parametric studies described earlier :(Bahuguna et al, 1993):

1. Goaf Treatment Factor(g_f) : The value of this factor may be taken as 0.95 for caving and 0.07 to 0.1 for cases of hydraulic sand stowing according to the degree of stowing [Saxena, 1991]

2. Extraction Factor(e) : The factor for partial extraction may be taken equal to $(ER)^k$, where ER is the extraction ratio given in fraction and k is a constant ranging from 1 to 2, (i.e. 1 for soft to 2 for hard coal seams for simple application in Eq. 2.)

3. Depth factor(d) : Subsidence has been found to be increasing with the increase in the depth of the seam. For Indian coalfields the value of this factor may be taken as :

   0.87 for depths upto 250 m
   0.96 for depths from 251 to 400 m
   1.00 for depths more than 400 m.

4. Factor for dip of the Seam(d'):- S_{max} decreases with the increase in the angle of dip α,of the seam. For seams dipping upto 20° the effect of dip may be taken equal to $\cos\alpha$ where α is in degrees.

5. Combined effect of composition and condition of rockmass (R_f): The values of $\mathbf{R_f}$ as described in the previous section may be obtained from Fig.1, with the help of information listed in Table 1.

5.0 PREDICTION OF MAXIMUM SUBSIDENCE, S_0

Maximum posible subsidence S_{max} occurs at or near the centre of panel with critical dimensions. If the width of the panel is smaller than critical dimension, the maximum subsidence is smaller than S_{max}.

$$S_o = S_{max} \cdot W' \quad (3)$$

Where W', the effect of width/depth ratio (w/d) is given as :

$$W' = 1 - [e^{-n(w/d)}] \quad (4)$$

Where w and d are the width and depth of extraction respectively and n is an empirical constant whose value range from 2.5 to 3.5 (on average 3.0).

Further, if the length of the panel is also of subcritical dimension the magnitude of S_o is further reduced

$$S_o = S_{max} \cdot W' \cdot L' \quad (5)$$

Where L', the effect of subcritical length of the panel. It has similar effect as of W'. So the effect of the subcritical length,

$$L' = 1 - [e^{-n(1/d)}] \quad (6)$$

Where l is the length of the panel.

Therefore $S_o = S_{max} [1 - e^{-n(w/d)}] [1 - e^{-n(l/d)}]$ (7)

6.0 PREDICTION OF SUBSIDENCE PROFILE

Important parameters on which the shape and extent of subsidence trough depend are

- (i) S_{max}
- (ii) Angle of draw ,ζ,
- (iii) Magnitude of subsidence over ribside and,
- (iv) Distance of point of inflection from ribside.

Program MSEAMS was used for parametric studies in the determination of extent and shape of the subsidence profile along a given line in the subsidence trough. A 2-meters thick coal seam was modelled using one by one three valuess of G/E_v ratios of 0.005, 0.01 and 0.05 for host rock representing three different cases of overburden based on its strength.

Profiles for each model were obtained at different w/d ratios ranging from 0.2 to 2.6. In all 36 profiles, 12 for each model were obtained from computer runs for parametric studies. The field data was then plotted as per the pattern obtained from parametric studies.

6.1 Angle of draw (ζ)

Angle of draw was calculated for all 36 profiles by assuming the trough edge to be at a point undergoing vertical movement up to 6 mm and up to 20 mm. The plots between angle of draw (ζ) and w/d ratios for all the three models and for both cut-off cases (Fig.2) show the change in the size of angle of draw with the variation of w/d ratio. The higher cut-off limit of 20 mm showed more realistic results. This is because the linear elastic model produced a wider subsidence trough and the points undergoing subsidence up to 6 mm were obtained far away from ribside.

These plots indicate the dependence of size of angle of draw on the strength of the rockmass. The more fragmented the rockmass is (as represented by lower G/E_v ratio) the larger is the angle of draw. Yao et al (1991) also found that strong beds in the overburden tend to decrease the value of ζ. These plots also indicate the increase in the size of angle of draw with the increase in the w/d ratio upto certain value of w/d beyond which its value (angle of draw) stabilized.

These findings do not support the practice adopted in most of the empirical methods of considering a constant angle of draw [NCB (SEH) 1975] for a particular coalfield. Therefore, for predicting subsidence profiles the value of ζ which is dependent on these factors may first be calculated in each case to delineate the extent of the subsidence movements.

Numerical analysis also offers the explanation for different values of ζ in longitudinal and transverse directions i.e. anisotropic behaviour of rockmass in different directions even in the horizontal plane itself (Hood et al, 1983). Further, at the commencing end, the degree of fragmentation may be more and to a larger extent because of cumulative effect of continuous mining operations over a period of time whereas the rockmass ahead of travelling face (forefield) may be comparatively less disturbed. Therefore the size of ζ may be more on the commencing (static) end than the size of travelling angle of draw on moving (dynamic) end side. This difference in the size of angle of draw accounts for the assymetric subsidence profiles observed even in the nearly horizontal seams.

To establish a correlation from actual field database, 36 profile lines from nearly horizontal panels were investigated. The static angle of draw (ζ_1) and travelling angle of draw (ζ_2) were then plotted separately against respective w/d ratios as shown in Fig. 3 and Fig. 4 respectively which gives their upper envelop values in each case. These plots showed that the available data could be grouped as per the value of R_f as well. The value of ζ stabilized at the critical w/d ratio in each group.

6.2 Subsidence over ribside (S_{rib})

The ratio S_{rib}/S_o is one of the significant parameters that control the shape of the subsidence profile. The values of S_{rib} were obtained from the previously mentioned 36 profiles generated by numerical modelling. The plots between ratio S_{rib}/S and w/d (Fig. 5) suggest that for more fractured strata represented by lower G/E_v ratio, the magnitude of subsidence over ribside in terms of maximum subsidence S_o is less in comparison to that for the compact rockmass. This implies that for more disturbed rockmass the subsidence profile is deeper in the middle portion i.e. a funnel shaped whereas for less disturbed overburden the profile is shallow i.e. a saucer shaped. It may also be seen from Fig. 5 that for smaller w/d ratio S_{rib}/S is more than for large w/d ratio. The S_{rib}/S_o value again stabilizes at and beyond certain w/d ratio.

7.0 DISTANCE OF POINT OF INFLECTION FROM RIBSIDE

The point of inflection is a point on the subsidence curve where its curvature changes from convex to concave and vice-versa. At this point the curvature of the ground and the horizontal strains are zero. The distance x of this point from the ribside is also an important parameter which guides the shape of the subsidence profile. The result of parametric studies from numerical modelling are shown in a plot in Fig.6. The distance x of the point of inflection from ribside is in terms of depth d. Fig.6 shows that for smaller w/d ratios this point lies outside the ribside showing that at a given depth for smaller width of extraction the subsidence trough has shallower and flatter bottom. As the width increases the point of inflection moves to inside the gob area. i.e. the profile now becomes deeper inside the gob area.

8.0 PROFILE FUNCTION

To obtain a mathematical expression for subsidence along a profile line i.e. a profile function, field data from 16 profiles were used. A representative best fit formula as given below was obtained by successive trials.

The subsidence S_i at a point i and at a distance X_i from a point undergoing maximum subsidence, S_o may be given by the following Profile Function

$$S_i = S_o \left[e^{-M.\{x_i/(r+x_i/2)\}2}\right] \quad (7)$$

For critical and supercritical widths,

$$S_i = S_{max} \left[e^{-M.\{x_i/(r+x_i/2)\}2}\right] \quad (8)$$

Where M is a profile constant being discussed in the next paragraph,and r is the critical diameter,$[r = d(\tan\zeta_1 + \tan\zeta_2)]$ as shown in Fig.7. For super critical widths the subsidence trough becomes flatter in the central portion up to two points situated at the distances of $w/2 - d \tan\zeta_1$, and $w/2 - d \tan\zeta_2$, from the centre of the panel on the respective sides. For super critical widths these are the points from where X_i is measured outwards (for use in Eq.8.)

The profile constant M governs the magnitude of subsidence over ribside and the position of the point of inflection. The effect of variation of M has been shown in Fig.8. Profile constant M is dependent upon the overburden rockmass or factor R , representing it. The given correlation has been derived by matching the empirical curves obtained from Eq.7 or Eq.8 with corresponding subsidence profiles obtained from field measurements. The value of M may be obtained from Fig.9 for different values of R_r.

9.0 PREDICTION OF OTHER ASSOCIATED PARAMETERS

The parameters associated with subsidence which may have damaging impacts on various surface properties and structures are the slope and curvature of the subsidence profile curve, horizontal displacements of ground points and the horizontal strains these points experience due to subsidence. The determination of slope, horizontal displacement and horizontal strain are discussed below. Curvature can be expressed as the first derivative of the slope of the profile.

10.0 DETERMINATION OF SLOPE OR TILT (g)

Slope or tilt gives the differential settlement between the two points on the ground. The slope g_i at i^{th} point is given by

$$g = \frac{S - S_{1-1}}{dx} \qquad (9)$$

Where S_i and S_{i-1} are the vertical displacements i.e subsidence at i^{th} and $(i-1)^{th}$ points and dx is the distance between these two points.

11.0 DETERMINATION OF HORIZONTAL DISPLACEMENTS (u) AND STRAINS (e_+ or e_-)

The profile curve of horizontal displacements has been found similar in nature to the profile curve of slopes. Therefore a linear proportionality may be established between the two curves which suggest that horizontal displacement at the i^{th} point from the panel centre may be given by

$$U_i = B \, . \, g_i \qquad (10)$$

Where B is the proportionality constant and g_i is the slope of the profile at the i^{th} point. Proportionality constant B has been found to be dependent on the nature of overburden rockmass i.e. the rock factor R_f and also on w/d ratio of the extracted panel.(Fig.10). Once the horizontal displacements are known the horizontal strains may be found out from the following formula

$$e_{\pm} = \frac{\Delta u}{dx} \tag{11}$$

Where Δu is the difference in the horizontal displacements between two consecutive points i.e. i^{th} and $(i-1)^{th}$ points which were originally situated at a distance dx apart, i.e.

$$\Delta u = u_i - u_{i-1} \tag{12}$$

Where u_i etc are positve on the left half of the profile and negative on the right half such that the strains obtained from Eq.11 are positive or tensile (e_+) in the outer portion of the subsidence trough and negative or compressive (e_-) towards the panel centre.

Strain profiles calculated from Eq.11 with the help of displacement values obtained from Eq.10 were matched by successive trials against the known values of strains from field data of 16 mine workings. The values of proportionality constant B were determined for these workings by back analysis. The values of B were plotted against the values of w/d ratios and four curves were obtained (Fig.10) for four different ranges of R_f. Thus the value of B is obtainable from these curves for use in Eq. 10.

12.0 RESULTS

The method described above was applied for the prediction of S_{max} or S_o, subsidence profile and profiles of slope and horizontal strains in known cases from different mine workings for which data from field measurements were available. The data, from various Indian Coalfields was used for the validation of results. The results of prediction of S_{max} and S_o have been found to be very satisfactory and have been given elsewhere [Bahuguna et al,1993].

Normalised subsidence, slope and horizontal strains were obtained from the developed model based on author's Profile Function method and program MSEAMS. These profiles were compared with those obtained from field measurements as well as from other profile functions. In all 10 profiles from 8 mine workings were considered for testing the results. Profiles from only one longwall (Dhemomain Colliery) and 2 Bord & piller mine workings (Ratibati and East Katras Collieries) are given in this paper. The irregular panels were simulated to be rectangular in shape by averaging their lengths and widths. Relevant field data for each case are given in Table 2. The three cases representing the overburden rock mass of R_f values i.e.- low (0.115), medium (0.630) and high (0.875),have been considered.

Table 2 Details of the panels

Parameters	Dhemomain line W2	Ratibati line B	East Katras line a
1.Extraction thickness	2.10 m	3.8 m	7.5 m
2.Dip of the seam	1 in 8	1 in 12	1 in 6
3.Average depth(d)	162 m	42.5 m	65. m
4.Average width(w)	134 m	122 m	100 m
5.w/d ratio (w/d)	0.83	2.87	1.1
6.Method of extraction	Longwall	Bord & Pillar	Bord & Pillar
7.Goaf Support	Caving	Caving	Caving
8.Percentage of extraction	100%	75%	70%
9.Rock factor(R_f)	0.115	0.630	0.875

The layouts of the panels with survey lines along which the field measurements were done are given in Figs 11, 12,and 13.

The predicted and observed subsidence along the given lines are shown in Figs.14, 15 and 16. The predicted subsidence matched well with the measured in the field in all the three cases. The effect of leftout stooks and crushed pillars in the central portion may be seen in case of bord and pillar workings of East Katras and Ratibati mines. The comparison of predicted and measured slope profiles is given in Figures 17,18 and 19. The predicted profiles matched very well in Figs.17 and 18. In Fig.19 the measured difference of level between the surface points was more because of the cracks developed on the ground.

The comparison of predicted strains and the values of strains as deduced from measured ground displacements are given in Fig. 20, 21 and 22. It may be seen that the predicted values were more or less matching well with the field values. Since the magnitudes of strains involved were very small the discrepancies obtained may not affect much as the predicted values are generally higher. Therefore the prediction of strains may also be considered as satisfactory.

13.0 CONCLUSION

The effect of nature of overburden rockmass i.e. its composition and condition has been simulated by a Rock factor R_r. The more the superincumbent strata are weak and fragmented i.e. the larger is the value of R_r the more the value of S_{max} will be in such situation. Besides S_{max} the extent and shape of the subsidence profile and the profiles of slope, horizontal displacements and subsequently the profiles of horizontal strains are also found to be dependent upon Rock factor R_r and w/d ratio.

The presented semi-empirical method is supported by the theory of Rock Mechanics and at the same time is developed from a field data base. The method consists of simple but comprehensive correlations, is easy to understand and simple to use in the field and does not require expensive data and complex analysis. The method may be easily adapted for other countries.

14.0 REFERENCES

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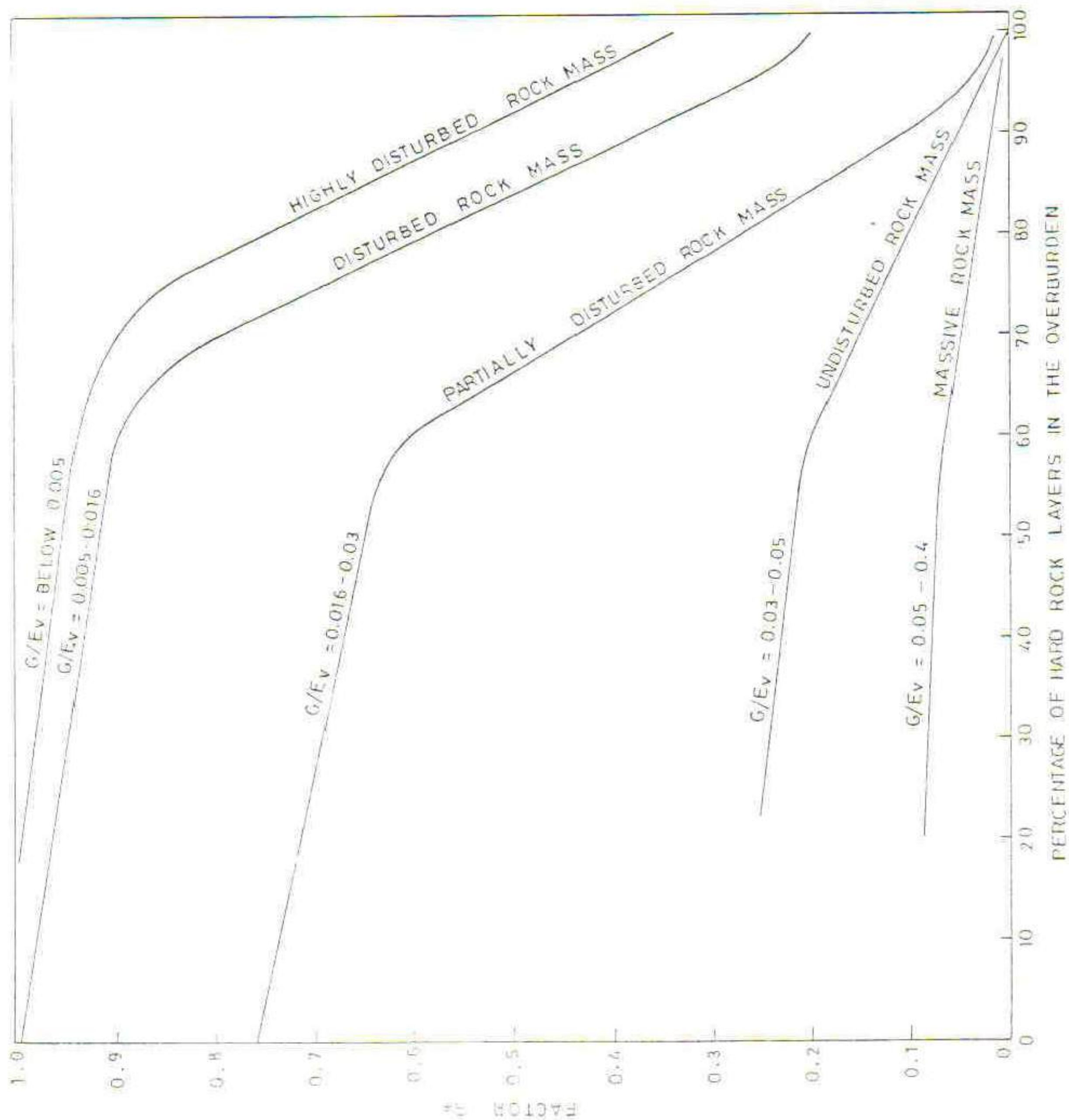

Fig. 1 Relationship between R_f and hard rock layers in the overburden

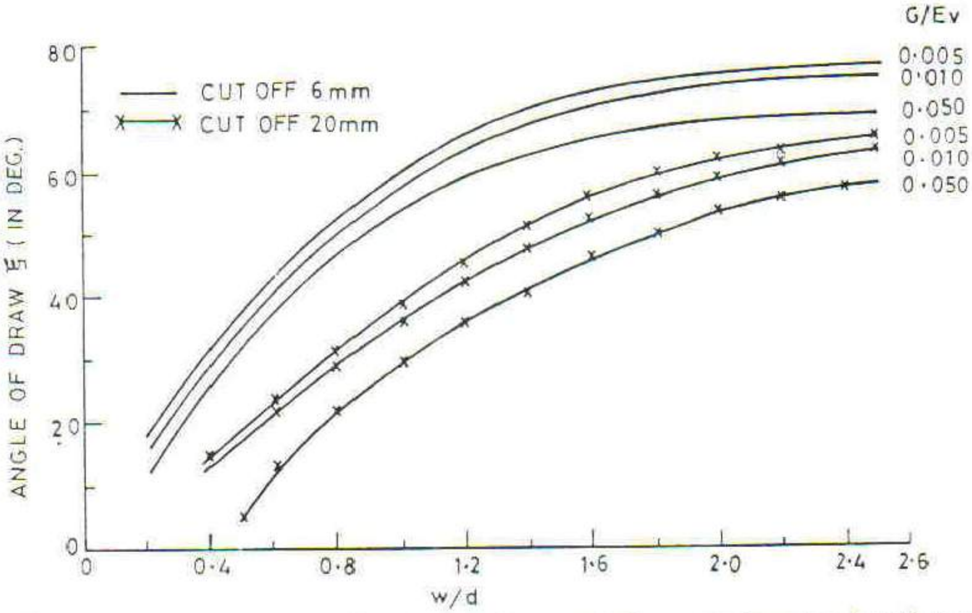

Fig. 2 — Plots showing dependence of ξ on overburden & w/d ratio

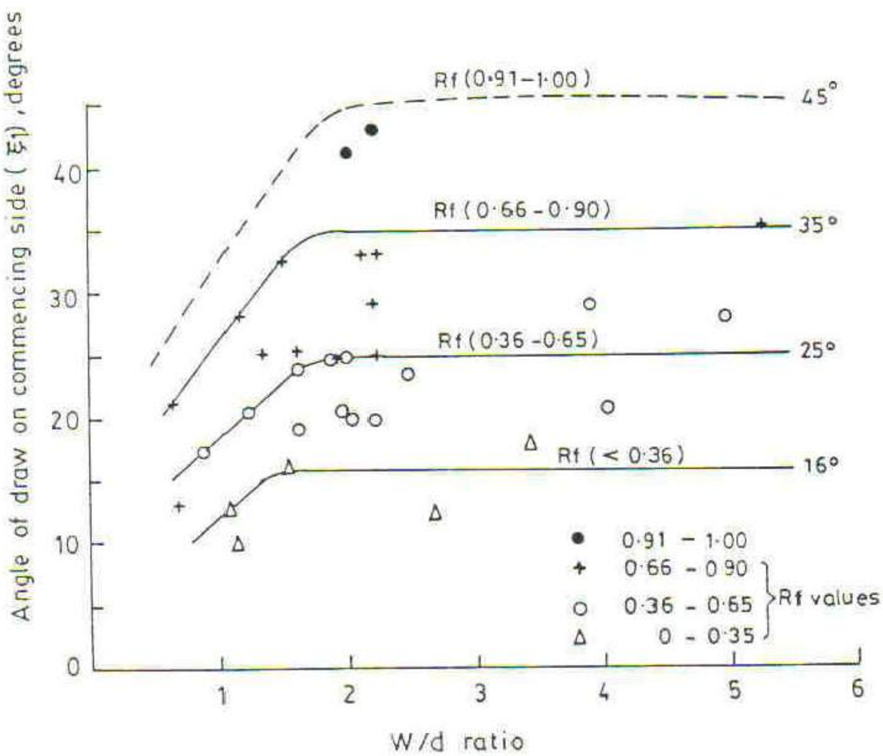

Fig. 3 – Angle of draw on commencing side (ξ) for different W/d ratios and Rf values

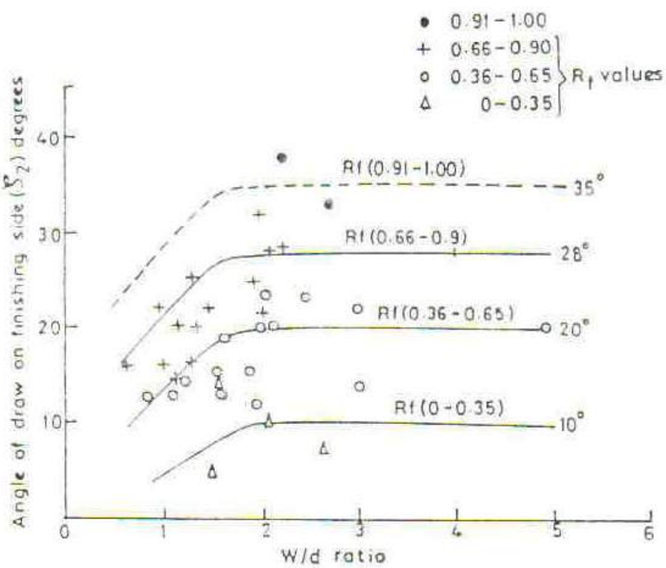

Fig. 4 Angle of draw ζ_2 on finishing (dynamic) end

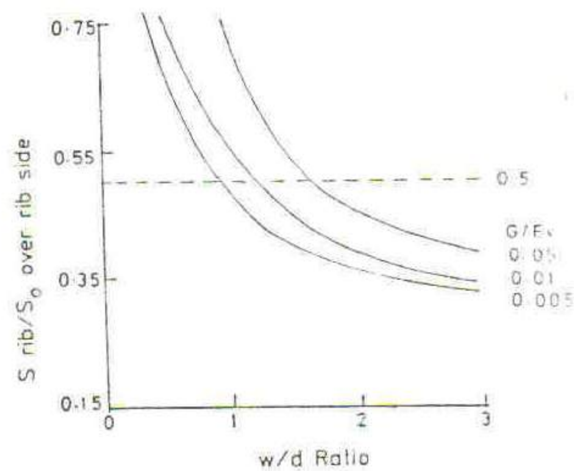

Fig. 5 -Subsidence over Ribside

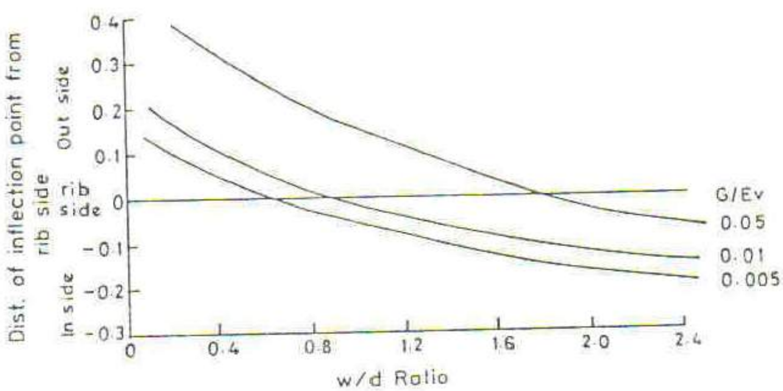

Fig. 6 -Dependence of Position of Point of Inflection on Overburden w/d Ratio

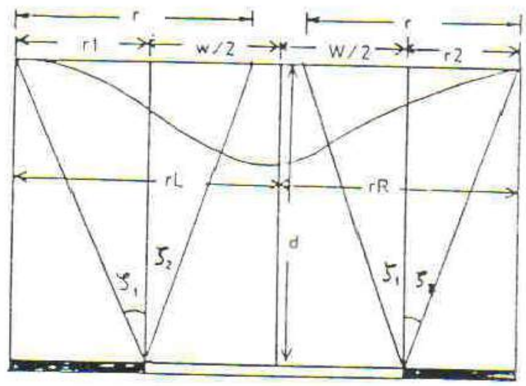

Fig. 7 -Extent of Subsidence Trough

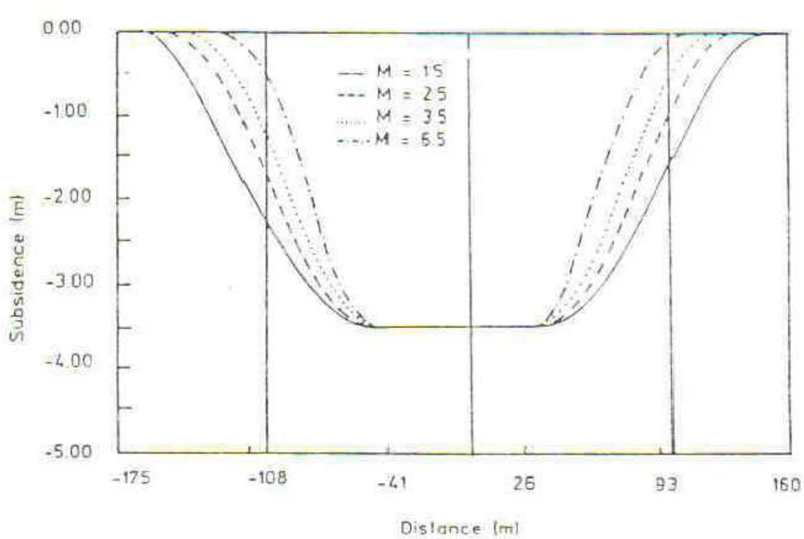

Fig. 8 -Subsidence Profiles for Different Values of M

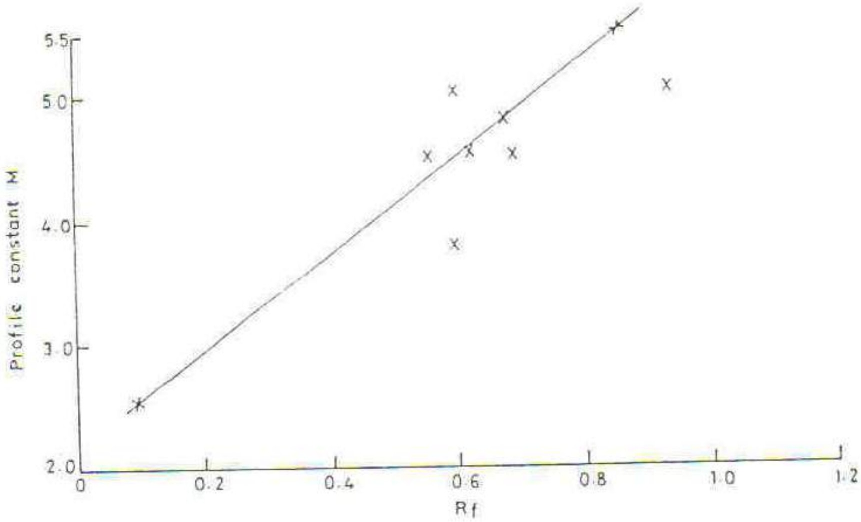

Fig.9 Relationship between R_f and M

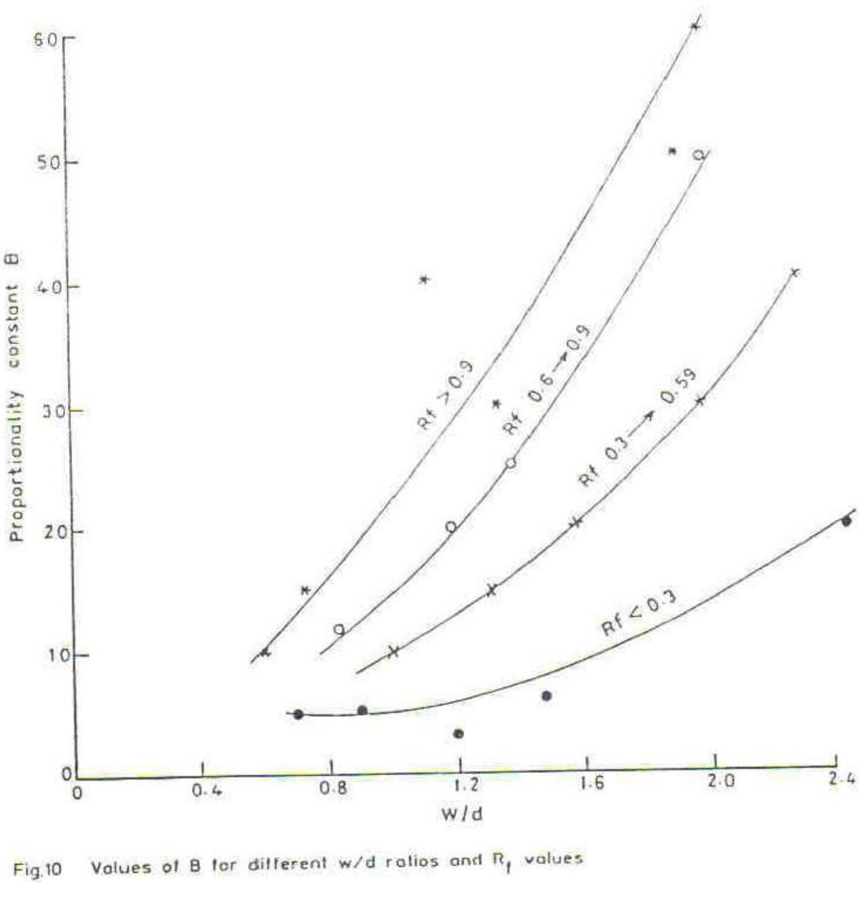

Fig.10 Values of B for different w/d ratios and R_f values

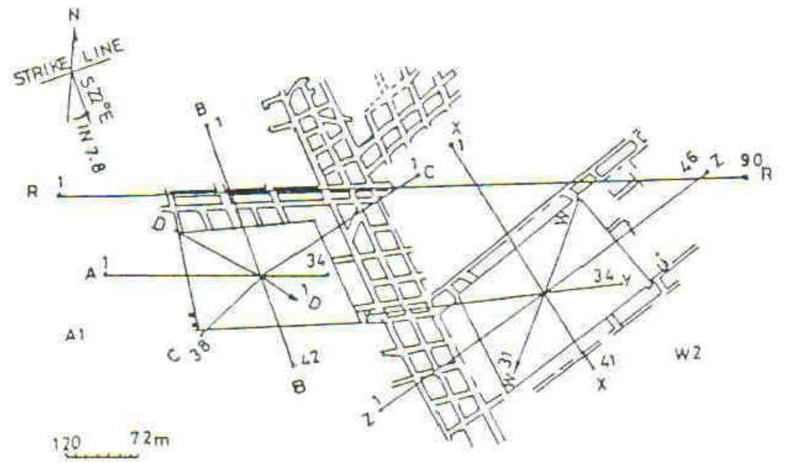

Fig. 11 Layout of Dhemomain colliery (Longwall panel W2)

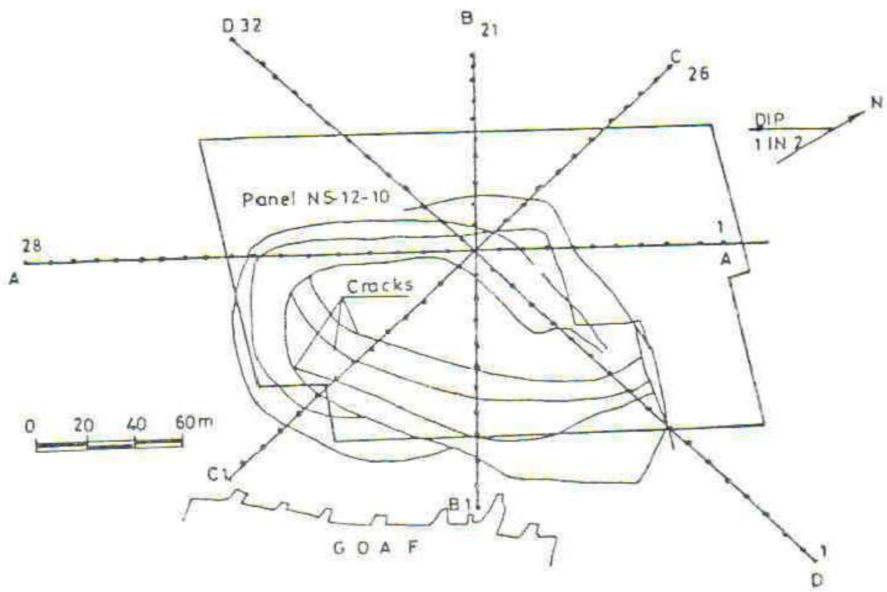

Fig.12 Layout of Ratibati colliery (Panel NS-12-10)

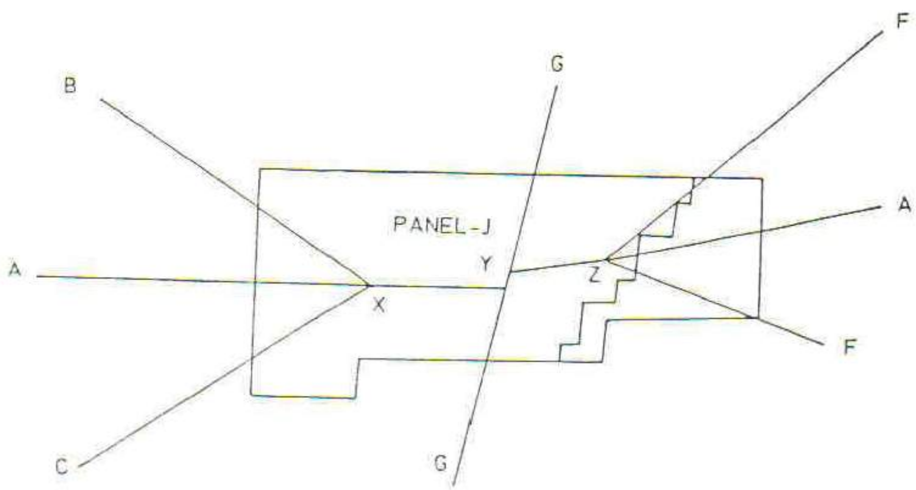

Fig.13 -Layout of East Katras Colliery (Panel 10J)

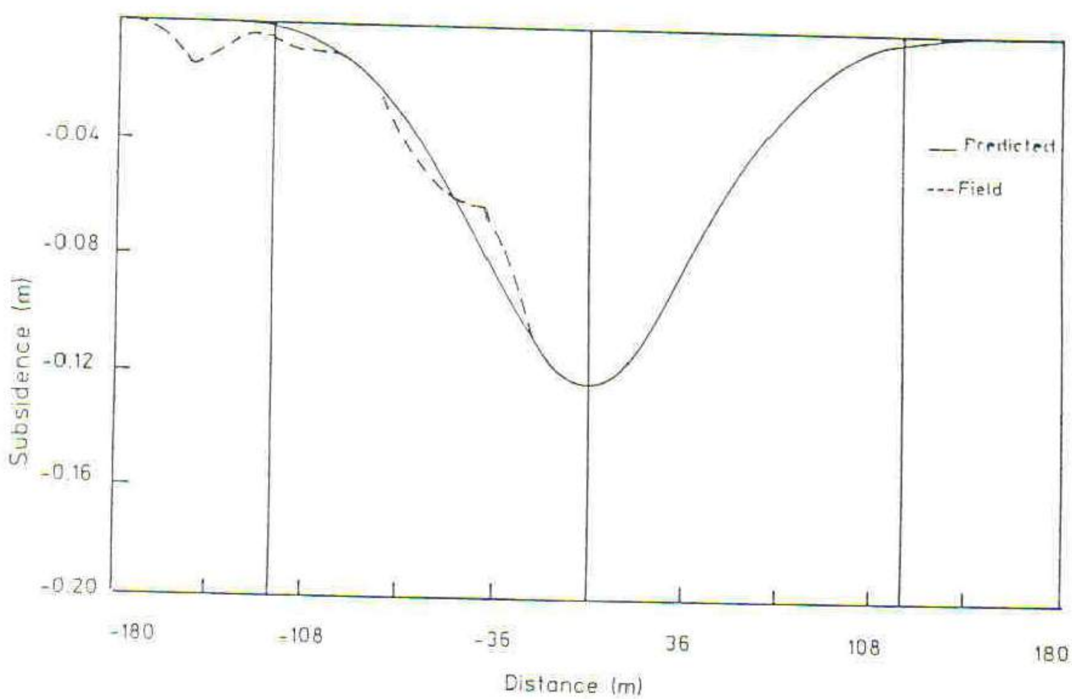

Fig 14 -Subsidence Profile-Dhemomain Colliery (Panel W2, Line W)

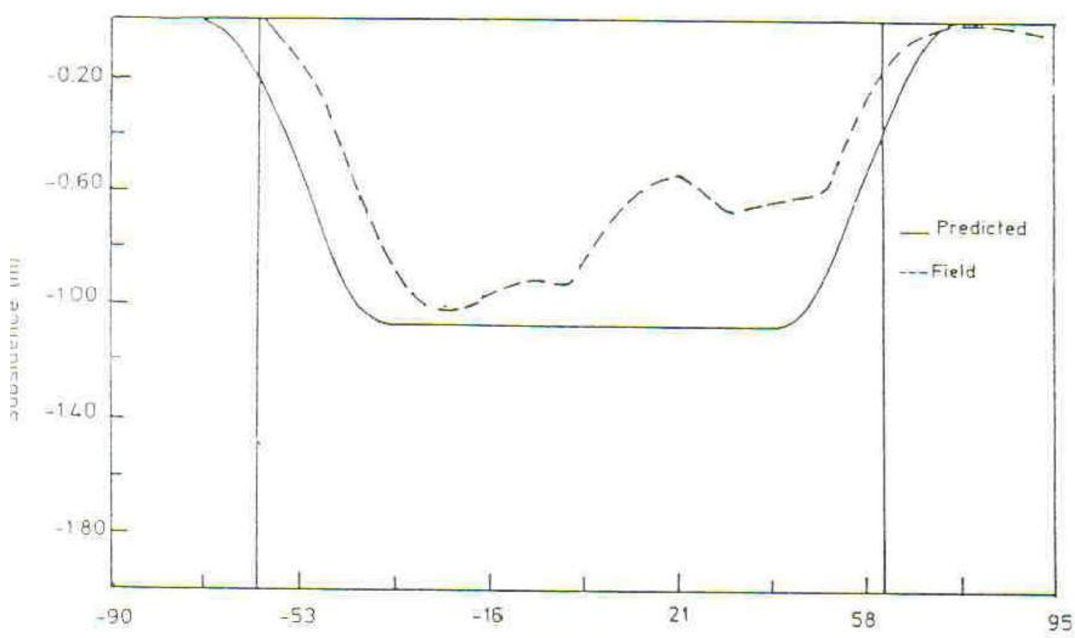

Fig. 15 -Subsidence Profile-Ratibati Colliery (Panel NS-12-10, Line C)

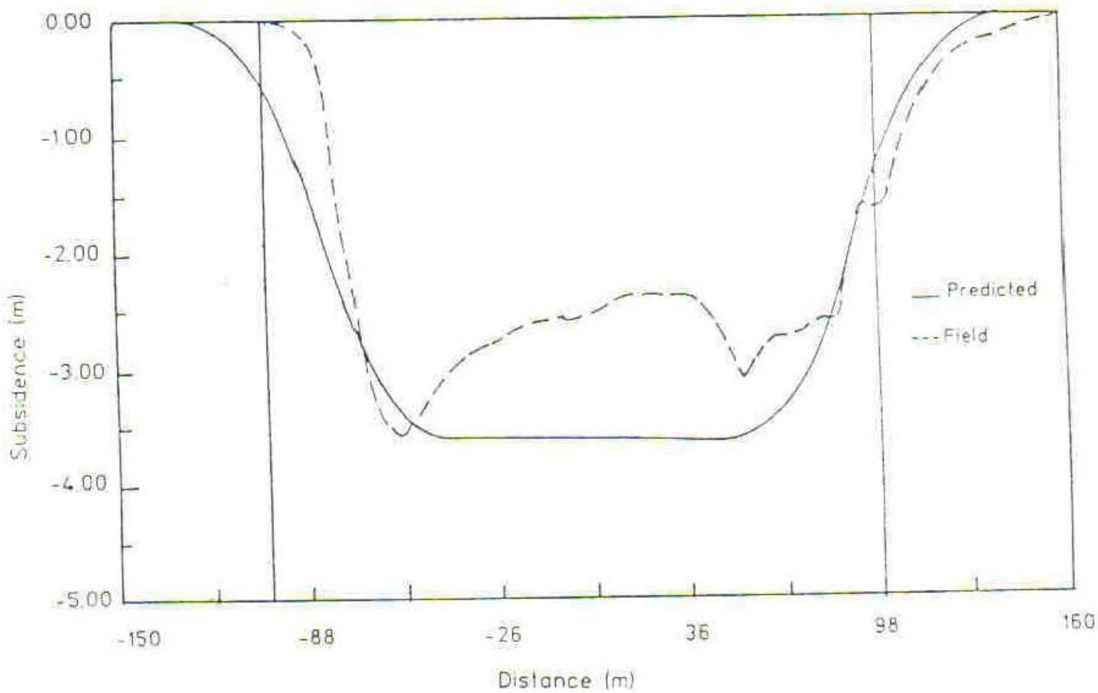

Fig. 16 -SubsidenceProfile-East Katras Colliery (Panel 10J, Line A)

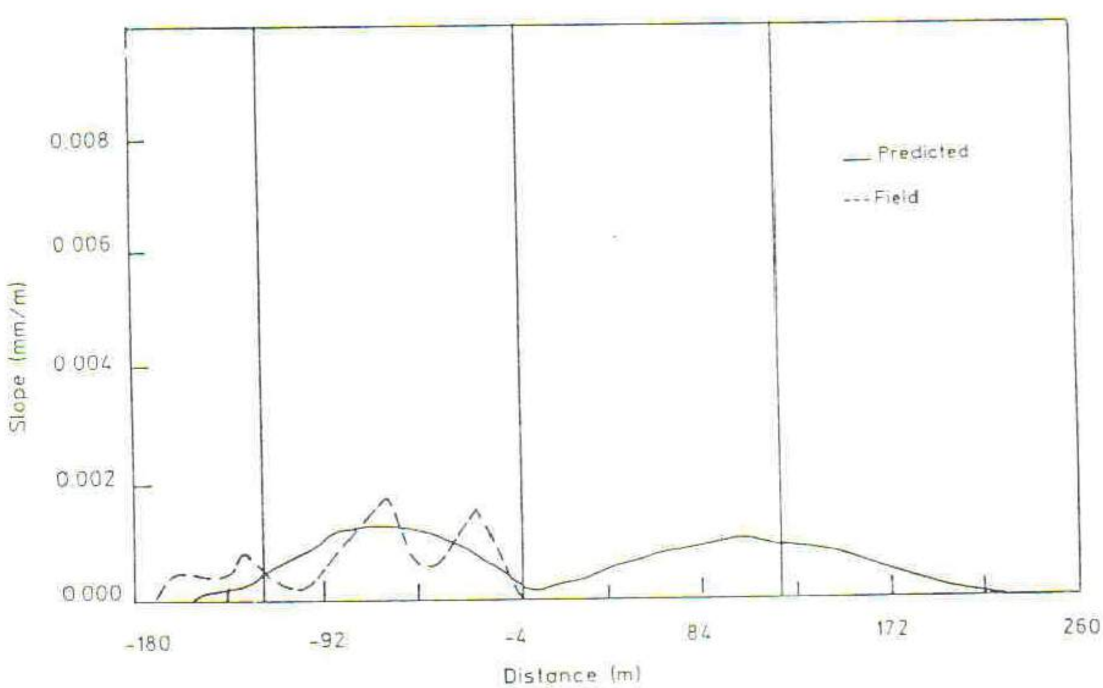

Fig. 17 -Slope Profile-Dhemomain Colliery (Panel W2, Line W)

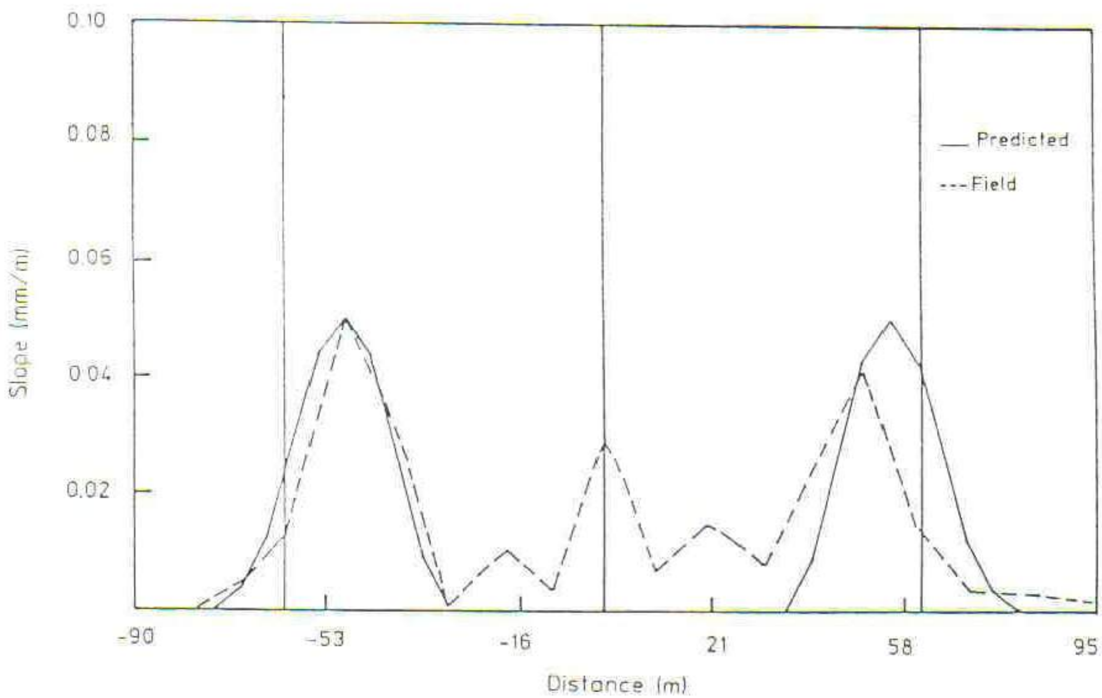

Fig. 18 -Slope Profile-Ratibati Colliery (Panel NS-12-10, Line C)

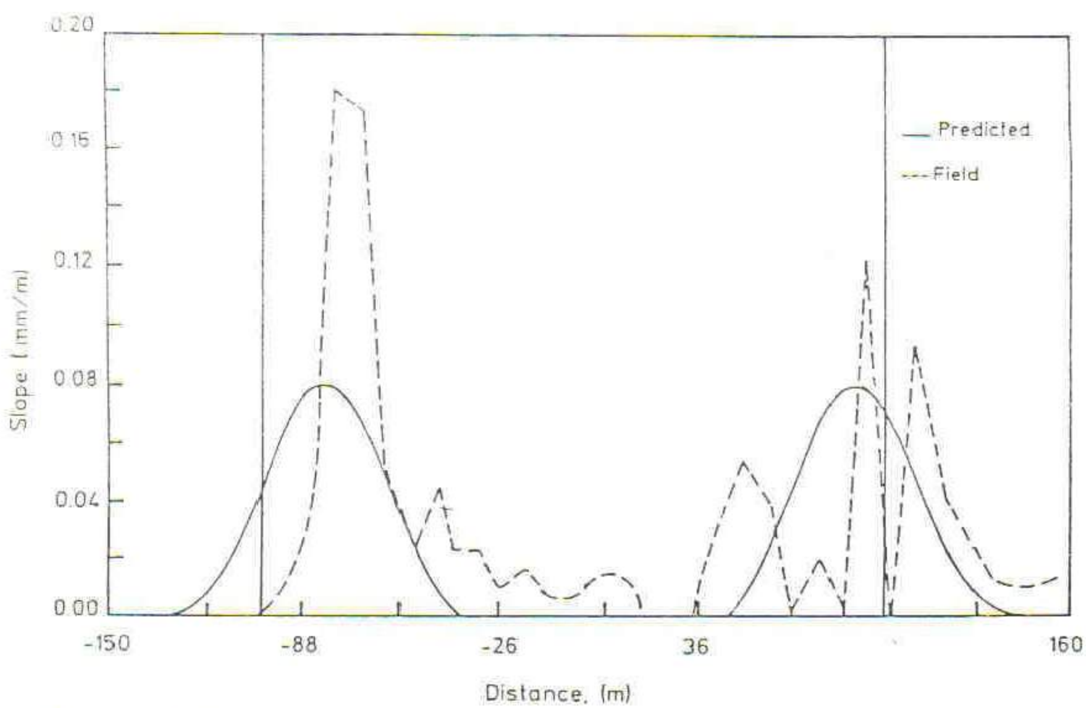

Fig. 19 -Slope Profile-East Katras Colliery (Panel 10J, Line A)

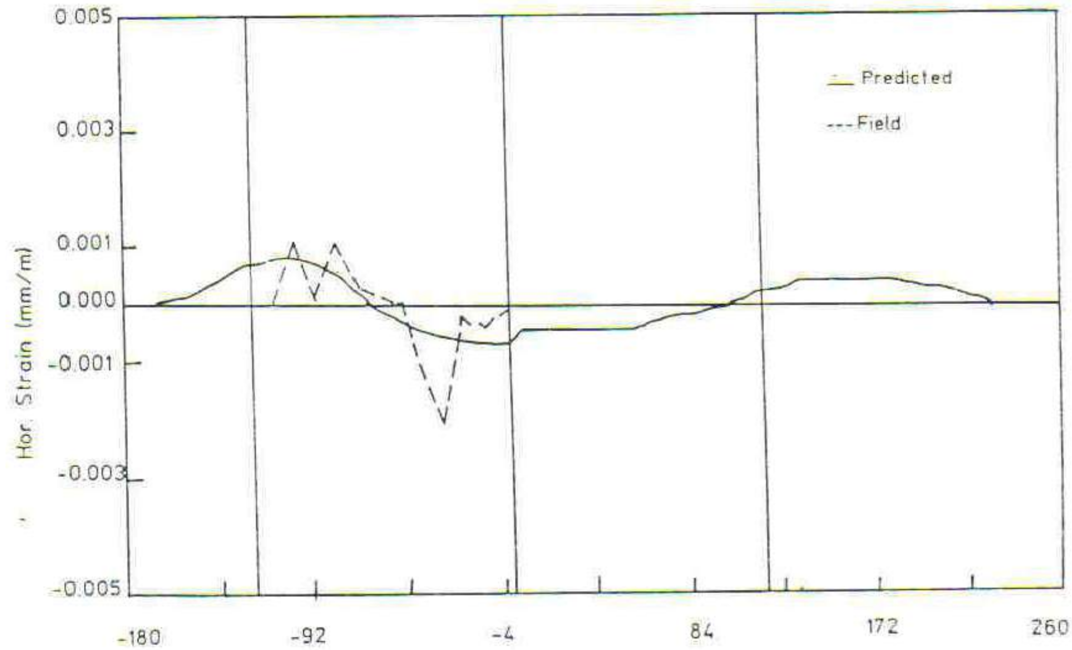

Fig. 20 -Strain Profile-Dhemomain Colliery (Panel W2, Line W)

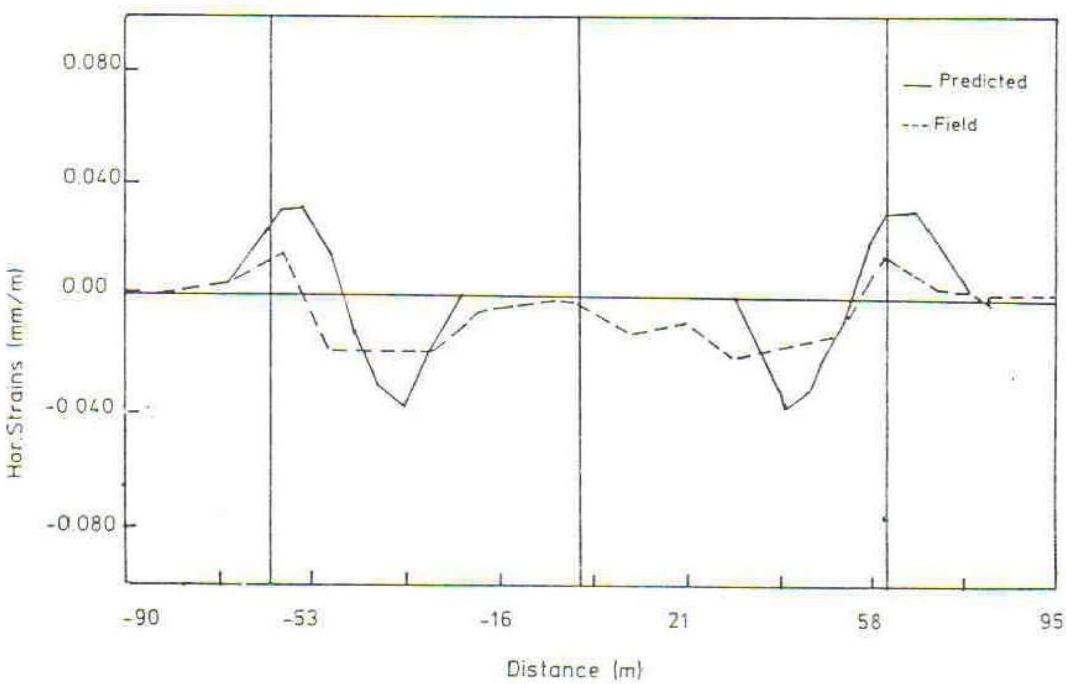

Fig. 21 -Strain Profile-Ratibati Colliery (Panel NS-12-10, Line C)

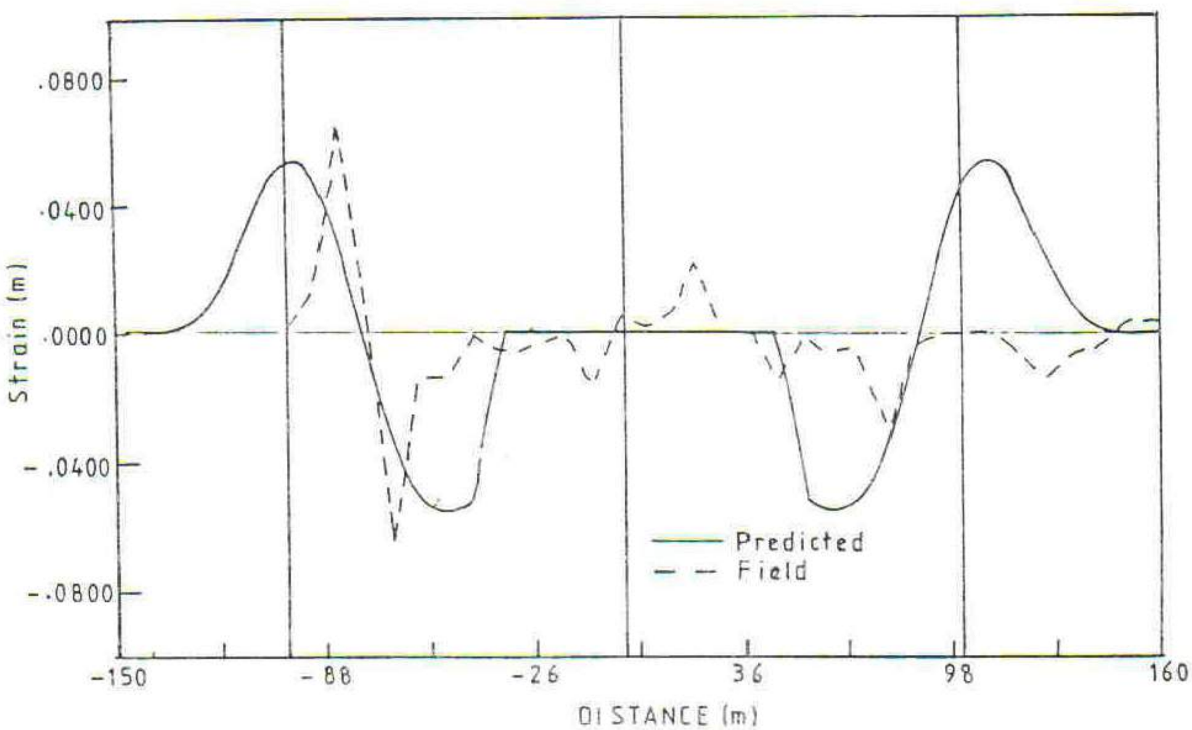

Fig. 22 - Strain Profile - East Katras Colliery (Panel 10J-Line A)