NUMERICAL MODELING-BASED STUDY IN BORD AND PILLAR WORKING – A PREREQUISITE FOR SUPPORT DESIGN IN MINES

Bijay Mihir Kumar*, Jhareswar Maiti, Prabhat Kumar Mandal*****

भारत के भूतल कोयला खदानों में खदानों की सुरक्षा हेतु सपोर्ट का डिजाइन एक महत्वपूर्ण कार्य होता है। डेवलपमेन्ट तथा डिपलरिंग दोनों ही स्थितियों में बोर्ड एवं पिलर विधि से भूमिगत कोयले के निष्कर्षण हेतु नियमित सपोर्ट डिजाइन आवश्यक होता है। पिलरों के चारों तरफ उपरी छतों तथा किनारों पर स्ट्रेस का फैलाव तथा इसकी प्रगाढ़ता सपोर्ट की डिजाइन में एक महत्वपूर्ण भूमिका निभाता है। खदानों में सपोर्ट डिजाइन की समझ एवं निर्माण हेतु न्यूमरिकल मॉडलिंग एक शक्तिशाली एवं प्रमाणित हथियार के रूप में अब प्रकट हुआ है। इस आलेख में केस स्टडी वाले खदान के एक पैनेल में सपोर्ट डिजाइन के लिए न्यूमरिकल तकनीक के उपयोग हेतु विश्लेषण किया गया है। खदान के केस स्टडी पैनेल के भूगर्भीय तकनीकी स्थितियाँ न्यूमरिकल मॉडलिंग द्वारा अनुरूपित हुई। इसके लिए द्विआयामी फायनाइट डिफरेंस कोड फ्लैक का उपयोग किया गया। केस स्टडी खदान के निवर्तमान भू-खननीय स्थितियों के लिए फ्लैक 2डी अनुरूपण, कार्य स्थलों पर परिचालन के विभिन्न स्टेजों के लिए सुरक्षा के गुणक के आकलन हेतु किया गया। ये स्थितियाँ थी — डेवलपमेन्ट, एक पिलर, दो पिलरों एवं तीन पिलरों के साथ निष्कर्षण। केस स्टडी वाले खदान के विकसित गैलरियों के निवर्तमान सपोर्ट प्रणाली के लि न्यूमरिकल मॉडलिंग वं रॉक मास रेटिंग आधारित सुरक्षा गुणन की गणना सपोर्ट प्रणाली के लिए की गई। एक पिलर, दो पिलरों एवं तीन पिलरों के निष्कर्षण के बाद रिब पिलर एवं स्लाइस गैलरियों के निकटतम छत के सबसे निचले हिस्से (0.5 मी.) के सुरक्षा गुणक की गणना की गई।

इस केस स्टडी से यह पता चलता है कि कार्य स्थलों के सपोर्ट डिजाइन से संबंधित पूर्व सूचना के लिए न्यूमरिकल मॉडलिंग एक उपयोगी तकनीक है, जिसके लिए डिजाइन सपोर्ट प्रणाली से संबंधित निदानकारी उपाय पहले से ही किया जा सकता है।

INTRODUCTION

Bord and pillar method of mining is widely prevalent method of underground mining, which contributes over 90 percent of the present underground coal production. The number of accidents and injuries are more in belowground mines. In 1986 the share of fatal accidents and fatality due to fall of roof were 42.5 and 47.2 percent respectively (DGMS report, 1990). In 2002, the same were 47.9 and 57.37 percent respectively (DGMS report, 2002). The fall of side has been identified the next dangerous killer in underground mines. Bord and pillar mines started with formation of bords when pillars are left as natural support during development stage. At development stage problems regarding strata movement are negligible. This operation involves locking up of huge amount of coal in the form of pillars for natural support. Only up to 3m thickness of a coal seam, for every ton of coal produced during development, on an average 3 tons of coal is locked up underground in pillars (Mandal et al., 1998). The amount increases with increase of thickness of seams. The pillars so formed during development are extracted during depillaring. Actual threat comes during depillaring operation due to withdrawal of natural support i.e. extraction of pillars. The extraction of pillar destabilizes nether roof, burden and ultimately surface endangering the workers and workings. For controlling the depillaring operation efficiently with higher productivity and safety, prior information regarding strata movement/loading is no doubt advantageous than proceed blindly. Modeling of strata deformation, stress field and load over support gives a fair idea of active movement, resultant fall and chances of overriding.

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STATEMENT OF THE PROBLEM

Depillaring operation starts with the extraction of pillars which, creates the problem of strata control. If the operations have not been designed scientifically, there are dangers of major strata movement, which may result in overriding of pillar and premature collapse endangering safety and productivity of the mine. In the past and also in recent years, in the Jharia coal field and elsewhere in India during extraction of pillars premature collapse have occurred leading to occurrence of severe bumps. Considerable quantities of coal has thus been lost. Efficient prediction of roof load and subsequent support design guidelines makes the situation much safer. So, the objective of this study is to assess the ground stability during development and depillaring operation of a bord and pillar working and provides a suitable design guide lines for making support design in advance.

A BRIEF DETAIL OF THE NUMERICAL MODELING-BASED STUDY

Before applying any numerical modeling technique, all the geo-mining conditions pertinent to the specific problem need to be clearly defined. These parameters mainly include geometry of the area to be studied, rock properties (elastic modulus, strengths, RMR) for each stratum and insitu stress field (Sheorey, 2001). Further necessary boundary conditions need to be applied. If planes of symmetry exist, the model can be made concise with the help of geometric boundary conditions along these planes without causing error in the estimation. In case of a seam developed by bord and pillar method for which the stability of the roadway needs to be assessed, one need not model the entire area, but need to model only a quarter pillar with half width of the gallery as shown in Figure 1.

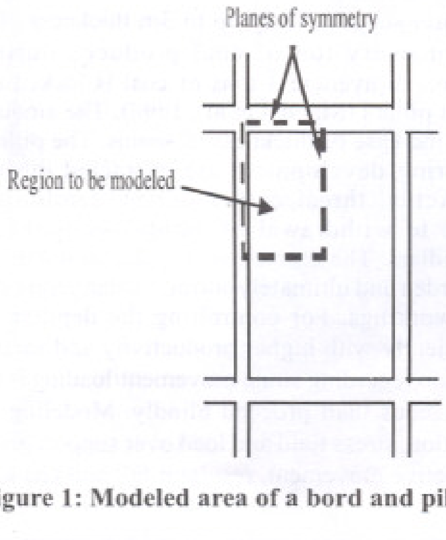

Figure 1: Modeled area of a bord and pillar workings

The different steps involved in numerical modeling are shown in Figure 2. The different steps are described below

Constitutive model setup.

↓

Generation of grid deformed to desired shape

↓

Define constitutive behavior and assigning material properties

↓

Specify boundary and initial condition

↓

Given suitable step to constitutive model to achieve equilibrium state.

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Examining the model result, if it is unsatisfactory perform any alternation, and again give suitable step for model setup to achieve a desired equilibrium state

Figure 2 : Different steps involved in numerical modeling

Constitutive Model for Numerical Modeling

Various constitutive models based on different laws are available in different software packages. In this study, FLAC-2D software package was used for the determination of different mining induced stresses and safety factor analysis. In FLAC-2D, six constitutive models are incorporated for solving different problems with different approaches. The models are as follows:

1. Elastic-isotropic model
2. Mohr-coulomb plasticity model
3. Null model
4. Elastic, transversely isotropic model
5. Ubiquitous joint
6. Strain-softening model

The elastic-isotropic model type was used in this study. In elastic- isotropic model the required properties are (i) Bulk modulus (K), (ii) Shear modulus (S_h) and (iii) Density (P). The bulk modulus and shear modulus are calculated from Equation (1) and Equation (2).

where,

$$K = E / 3(1-2 v) \quad (1)$$

$$S_h = E / 2(1+2 v) \quad (2)$$

Where, E = Modulus of elasticity and

v = Poisson's ratio.

CASE STUDY

The case study was conducted in a mine situated in southeastern part of India. A total of three potentially workable coal seams A, B, and C were identified in the area. The working of C seam of this colliery comprises bord and pillar development with 3.6 to 4.8 m wide galleries and 20m x 20m square pillars. The thickness of the seam was 1.8 m and was developed to full thickness of the seam. The immediate roof was intercalated shale and sandstone, coal and medium grained sandstone. The depth of the workings varied from 54 to 100 m. Development of C seam was on the verge of completion and depillaring of a few panels had been started by the conventional splitting and slicing method. In this method, each pillar was divided into two equal halves by driving central split galleries. Each half of pillar was then extracted by driving slice towards the goaf while retreating from the slice.

Geo-Technical Details

For the purpose of the study, geo-technical information of the case study mine were collected. An available borehole logging located at 5 dip and $61^1/_2$ level with coal measure formations up to 28 m from roof of the C coal seam was chosen. The detailed mechanical property of the borehole section is shown in Figure 3.

From the borehole logging, it shows that roof of the C seam consists of medium grained sandstone, coal, carbonaceous shale and fine-grained sand stone layers. Floor of the C seam also consists of medium grained sandstone. Testing of mechanical properties of the core sample showed that compressive as well as tensile strength is the maximum for the fine-grained sand stone. The average compressive strength of the rock strata varies from 15.4 – 45 MPa. Similarly, the average tensile strength of the rock strata varies from 2 – 6.3 MPa. The estimated RQD (rock quality designation) is the maximum for medium grained sandstone (91) and minimum for carbonaceous shale (27). It was also found that in the stratum above 20 m from the seam, the core recovery was very low.

Numerical modeling

The geotechnical condition of the case study panel as discussed above was simulated by numerical modeling. For this purpose, the two-dimensional Finite Difference Code, FLAC (ITASCA, 1992) was used. For simulation purpose, an elastic-isotropic model was considered. The rock mass properties used for modeling are given in Table 1 and Table 2. Table 1 shows the rock mass properties of the roof of the coal seam whereas Table 2 shows that properties used for the coal and floor.

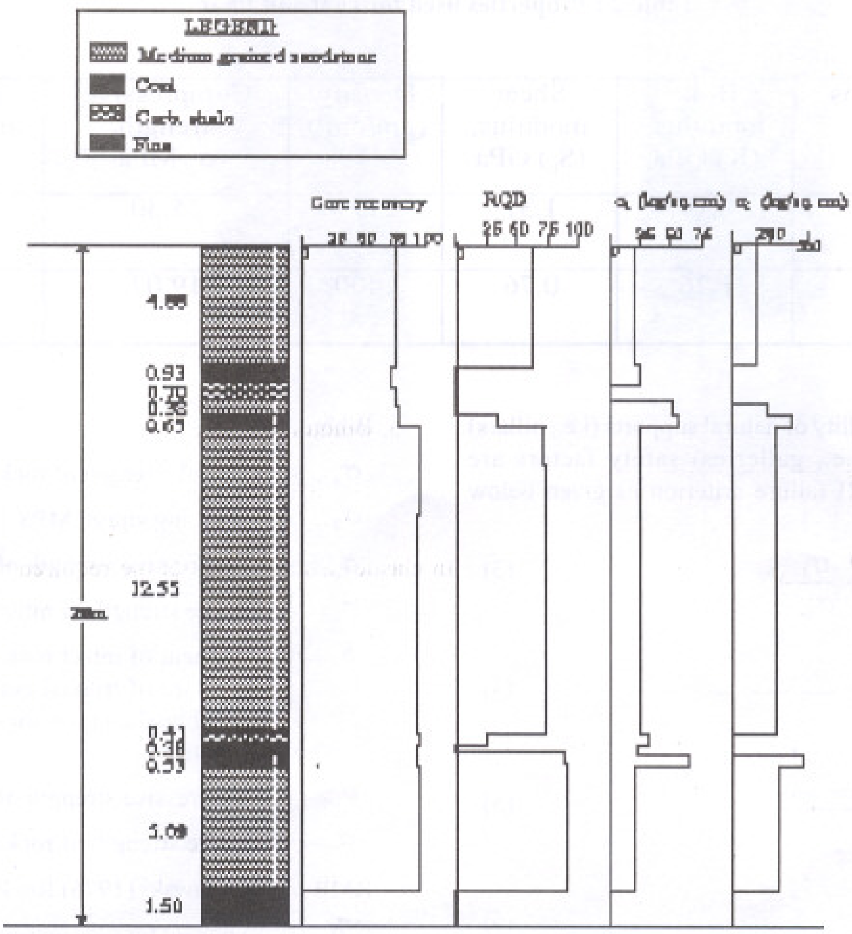

Figure 3 : Mechanical property of the C coal seam of the case study mine

Table 1 : Properties of rock mass of the roof of the coal seam used in numerical modeling

Formations	Young's modulus, GPa	Bulk modulus, (K) GPa	Shear modulus, (S_h) GPa	Density; (gm/cm^3)	Compressive strength, MPa	Tensile strength, σ_{tm} MPa
Medium grained sandstone	4.00	2.68	1.61	2200	27.52	2.06
Fine grained sandstone	2.48	1.66	1.00	2380	45.14	6.25
Coal	1.86	1.26	0.76	1400	19.07	2.15
Carbonaceous shale	1.89	1.26	0.76	1400	19.07	2.90
Medium grained sandstone	2.95	1.97	1.18	2200	27.50	2.47
Fine grained sandstone	4.73	3.17	1.9	2370	38.41	5.48
Medium grained sandstone	3.48	2.33	1.4	2240	23.42	5.02
Coal	1.86	1.26	0.76	1400	19.07	2.50
Medium grained sandstone	3.21	2.15	1.29	2140	15.46	2.07

Table 2 : Properties used for coal and floor

Formations	Bulk modulus, (K) GPa	Shear modulus, (S_h) GPa	Density (gm/cm^3)	Compressive strength, σ_c MPa	Tensile strength, σ_{tm} MPa
Sandstone	2.19	1.31	2197	25.30	2.39
Coal	1.26	0.76	1400	19.07	2.13

To assess the stability of natural supports (i.e., pillars) and exposed span (i.e., galleries) safety factors are calculated using CMRI failure criterion as given below (Sheorey, 1997).

$$\sigma_1 = \sigma_{cm}(1+\frac{\sigma_3}{\sigma_{tm}})^{b_m} \quad (3)$$

$$\sigma_{cm} = \sigma_c e^{(\frac{RMR-100}{20})} \quad (4)$$

$$\sigma_{tm} = \sigma_t e^{\frac{(RMR-100)}{27}} \quad (5)$$

$$b_m = b^{\frac{RMR}{100}} \quad (6)$$

Where,

σ_1 = Triaxial strength of rock mass, MPa

σ_3 = Confining stress, MPa

σ_c = Compressive strength of intact rock, MPa

σ_t = Tensile strength of intact rock, MPa

b = Exponent of intact rock which controls the curvature of triaxial curve (value taken as 0.5 for coal and 0.6 for other coal measure formation)

σ_{cm} = Compressive strength of rock mass, MPa

σ_{tm} = Tensile strength of rock mass, MPa

RMR = Bieniawski (1976) Rock Mass Rating

b_m = Exponent for rock mass corresponding to the intact rock constant defined above

The factor of safety is defined as (Sheorey, 1997):

$$SF = \frac{\sigma_1 - \sigma_{3i}}{\sigma_{1i} - \sigma_{3i}} \text{ except, when } -\sigma_{3i} > \sigma_t \quad (7)$$

$$SF = \frac{\sigma_t}{-\sigma_{3i}} \quad (8)$$

where,

σ_{1i} = Induced major principle stress, MPa

σ_{3i} = Induced minor principle stress, MPa

For the existing geo-mining conditions of the mine, FLAC-2D simulations were done to assess the safety factor of the workings for different stages of operations. They are the development, depillaring with one pillar, two pillars and three pillars extraction.

Model results

Simulation of virgin state

In this model, a domain of 225.2 x 152 m^2 including 50 m floor formation, 2 m coal seam and 100 m roof rock mass formation was simulated. Here, five pillars of 20 x 20m^2 (corner to corner) and six galleries of 4.2 m each were considered for the simulation of the panel. The model boundary was kept 50 m away from the excavation on both sides. The boundary also included 50 m floor and 100 m roof strata. The model result shows that the major virgin principal stress in the coal seam to horizontal is 5 MPa. Similarly, the minor virgin principal stress is 2 MPa acting vertically.

Simulation of development

In this step, the galleries were excavated and the model was run for the assessment of the safety factors of the developed workings. Safety factor contour for developed workings is shown in Figure 4.

Figure 4 shows that the safety factor of the developed pillar varies from 2.56 to 4.65. The safety factor of the lower most portion (0.5 m) of the immediate roof in the gallery ranges from 0.45 to 0.97 which is unstable and required immediate support. The height of immediate roof up to 1.0 safety factor is 1.5 m, which is supposed to be parted down and thus required to be supported. For the development working safety factor of 1.5 may be considered safe (CMRI Report, 1987). The height of immediate roof up to 1.5 safety factor is found to be 2.5 m.

Simulation of depillaring

As stated earlier the simulation modeling of the depillaring operations was conducted up to extraction of three pillars. In the first step, one pillar was extracted to see the effect of stress redistribution and stability status in and around the working face. Similarly, in the second and third steps two and three pillars were extracted and accordingly the effects of stress redistribution and ground stability were assessed. The safety factor contours of depillaring after one pillar, two pillars and three pillars extraction were generated during the model run. Safety factor contours of the depillaring operations after one pillar extraction, two pillars extraction and three pillars extraction are shown in Figure 5 through 7 respectively. Figure 6(a) and Figure 7(a) shows that safety factor contours in and ahead of the face during depillaring with two pillars and three pillars extraction respectively.

Analysis of model results after one pillar extraction

The safety factor values of the pillar after one pillar extraction are shown in Figure 5. The value of safety factor of the 2 m thick immediate rib varies from 1.16 to 2.15. Since the safety factor of the rib is more than 1, it should be reduced for minimizing stress concentration inside the goaf. The safety factor of the lower most portion (0.5 m) of immediate roof in the slice gallery ranges from 0.9 to 1.2. The minimum safety factor of the pillar nearest to the slice is 2.78. There is a marginal decrease of safety factor values in the immediate roof of the advanced galleries from developed to depillared working after one pillar extraction.

Analysis of model results after two pillars extraction

Figure 6 shows that the value of safety factor of the immediate rib varies from 0.91 to 1.61. Since minimum safety factor is less than 1, it is expected to fail and no stress concentration inside the goaf will occur. The safety factor of the lower most portion (0.5 m) of immediate roof in the slice gallery ranges from 0.86 to 1.18. These safety factor values are slightly less than the safety factor values in the same immediate roof after one pillars extraction. Here, support density to be increased in comparison to earlier stage of depillaring. The minimum safety factor of the pillar nearest to the slice is 2.39. Figure 6(a) shows that there is marginal decrease of safety factor values in immediate roof and also to the immediate pillar of the advanced workings up to one pillar from developed to depillared working after two pillar extraction.

Analysis of model results after three pillars extraction

Figure 7 shows the value of safety factor of the immediate rib varies from 0.69 to 1.27. The safety factor of the lower most portion (0.5 m) of immediate roof in the slice gallery ranges from 0.83 to 1.18. The minimum safety factor of the pillar nearest to the slice is 1.85. Figure 7(a) reveals that there is decrease of safety factor values in immediate roof and also to the immediate pillar of the advanced workings up to one pillar from developed to depillar working after three pillar extraction.

Support design based on numerical modeling

Numerical modeling based study revealed that the safety factor of the lower most portion (0.5m) of immediate roof in the gallery ranges from 0.45 to 0.97 which is unstable and required immediate support. The height of immediate roof up to 1.0 safety factor is 1.5m, which is supposed to be parted down and thus required to be supported. Therefore, the thickness of immediate roof to be supported is minimum 1.5m. The rock load of the immediate roof may be calculated as follows:

Rock load (P_n) = thickness of immediate roof to be supported (t) x density (d) (9)

Taking thickness of immediate roof to be supported is 1.5m (as per numerical study) and density 2.2 t/m^3 for the same immediate roof (sandstone), rock load comes 3.3 t/m^2.

The existing developed galleries of the case study mine were supported by three rows of full column grouted roof bolts each of 1.5m length at the interval of 1.2m. Taking the anchorage strength (load bearing capacity) for each roof bolt of 1.5m length is 8t, the support resistance can be calculated by using Equation (10).

$$\text{Support resistance} = \frac{\textit{support capacity in one row}}{\textit{Area to be supported in one row}} \quad (10)$$

Support resistance for existing 4.2m wide galleries comes 4.76 t/m^2. The safety factor of the existing support system is calculated by the following relation:

$$\text{Support safety factor} = \frac{\textit{Support resistance}}{\textit{Rock load}} \quad (11)$$

Using Equation (11), support safety factor for the existing support system in developed galleries is found to be 1.44.

Support design based on rock mass rating (RMR)

The safety factor of the support system was computed based on Rock Mass Rating (RMR). The total RMR of the roof was taken 50.5. The rock load that experienced in the roof was calculated by using CMRI formula (CMRI, 1987):

Rock load (Pr) = B x d (1.7 - 0.037 RMR + 0.0002 RMR^2) (12)

where, B = Width of the gallery, 4.2 m

d = Dry unit weight of roof rock (Medium grained sandstone), 2.2 t/m3

RMR = 50.5

By putting these values in Equation (12), the rock pressure in the gallery of 4.2m width comes to 3.16 t/m2. Support resistance for the existing support system for 4.2m wide developed galleries as mentioned above comes 4.76 t/m2. Thus, safety factor for the support system comes 1.5.

CONCLUSION

The safety factor of the support design of the developed and depillaring operations of the case study mine was calculated through numerical modeling. The height of the immediate roof of the developed galleries of the case study mine obtained from the numerical modeling is 1.5m. The rock load comes from the immediate roof is 3.3 t/m2. Where as the value of the rock load obtained from Rock mass Rating (RMR) is 3.16 t/m2. The value of the support safety factor of the existing support system in developed galleries of the case study mine obtained from the numerical modeling and rock mass rating are 1.44 and 1.5 respectively. Though, the existing support system in developed working found to be almost adequate by rock mass rating, however, for better safety, the value of safety factor of the support system (which is 1.44 obtained from numerical modeling) may be increased to more than 1.5 by increasing the support density. The minimum value of safety factors of 2 m thick rib were found to be 1.16, 0.91 and 0.69 after one, two and three pillars extraction. Similarly, minimum safety factor of the lower most portion (0.5 m) of immediate roof in the slice gallery are 0.90, 0.86 and 0.83 respectively. It is found that the safety factor of the rib is more than 1 thus after one pillar extraction; it should be reduced for minimizing stress concentration inside the goaf. Therefore, it is better to pre-diagnose by numerical modeling technique of any designed method for pre-information regarding the support design of the working

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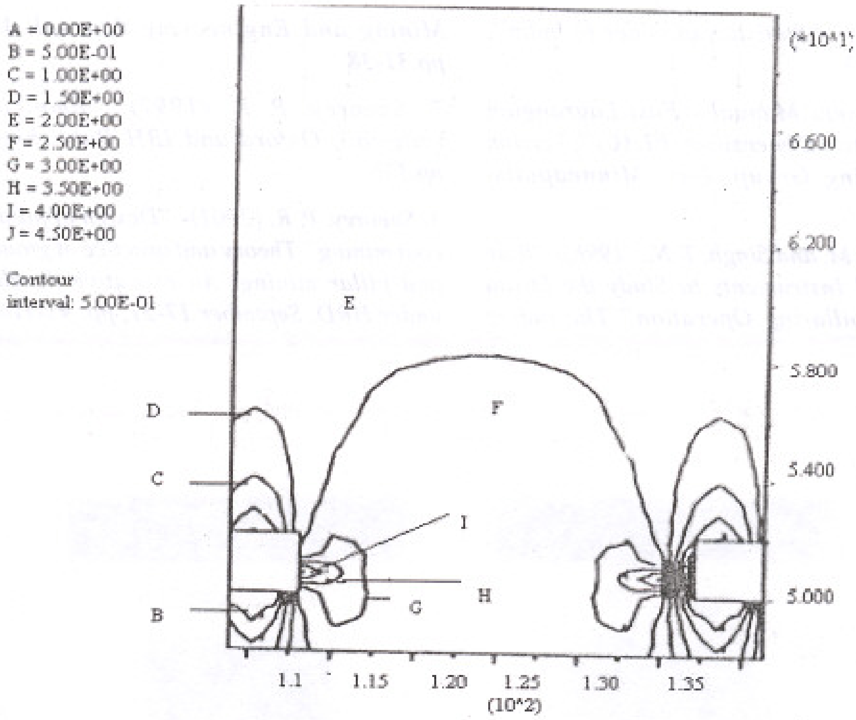

Figure 4 : Safety factor contours for developed wokings

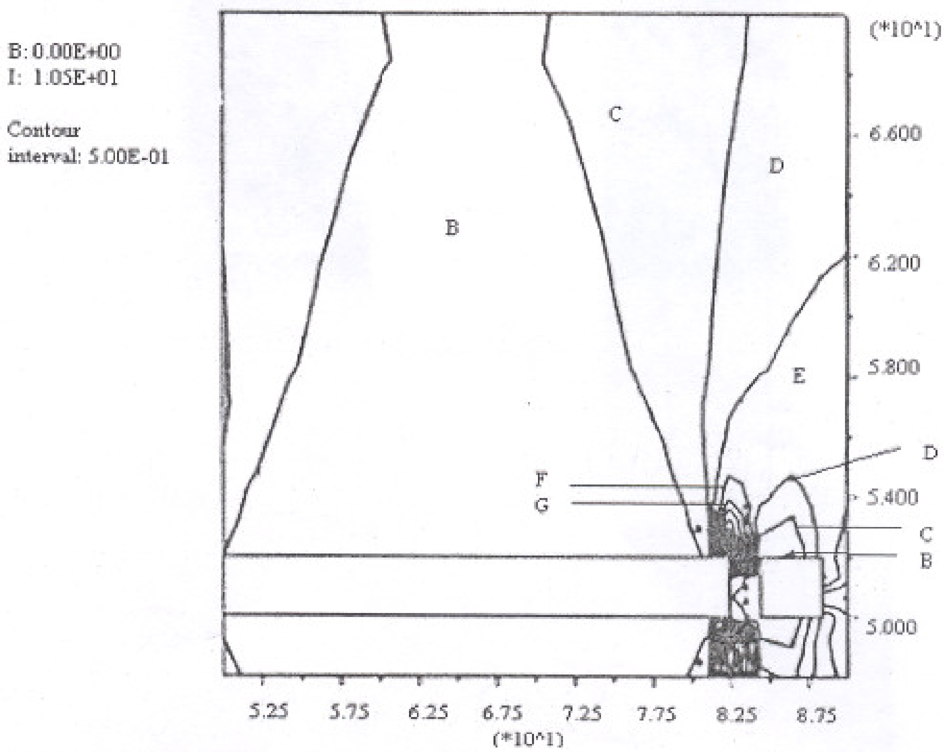

Figure 5 : Safety factor contours for depillared workings (after one pillar extraction)

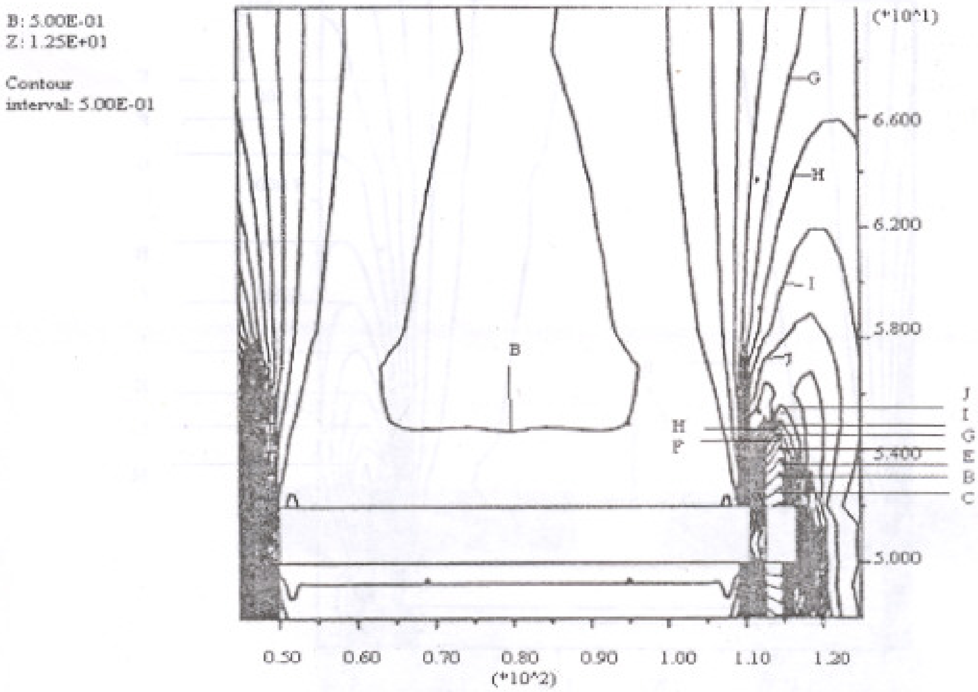

Figure 6 : Safety factor contours for depillared workings (after two pillars extraction)

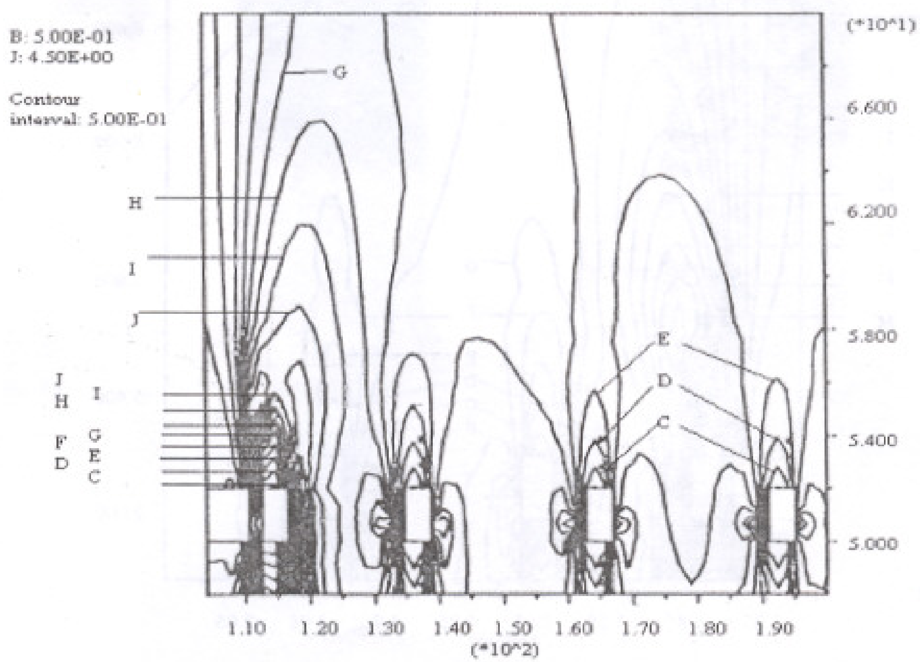

Figure 6(a) : Safety factor contours in and ahead of the face during dipillaring with two pillars extraction

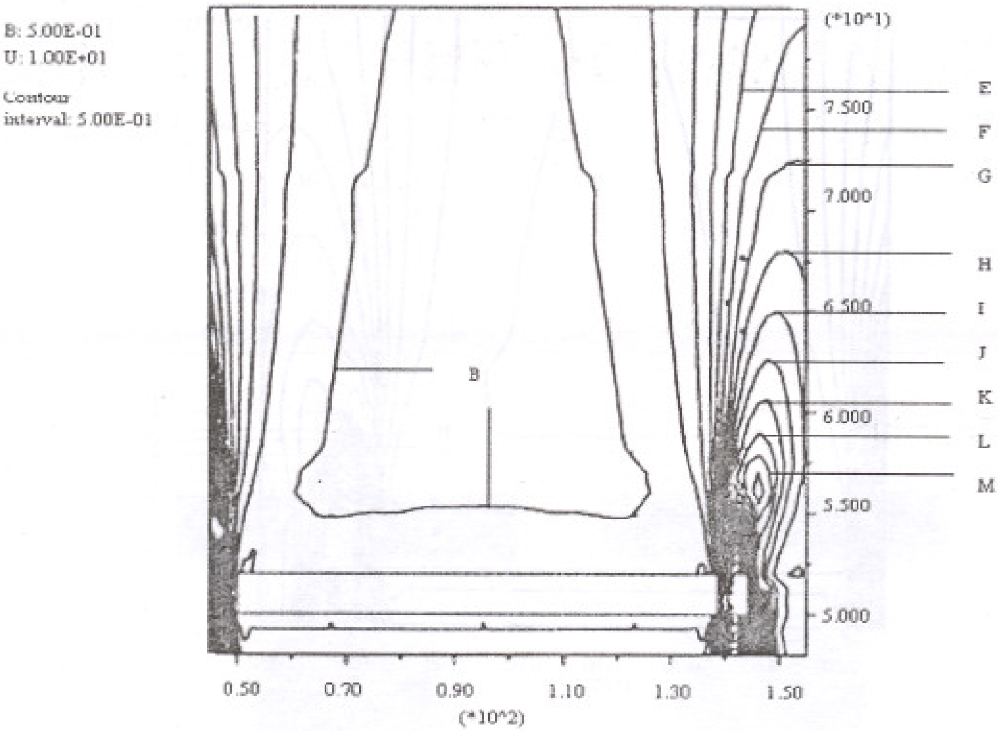

Figure 7 : Safety factor contours for depillared workings (after three pillars extraction)

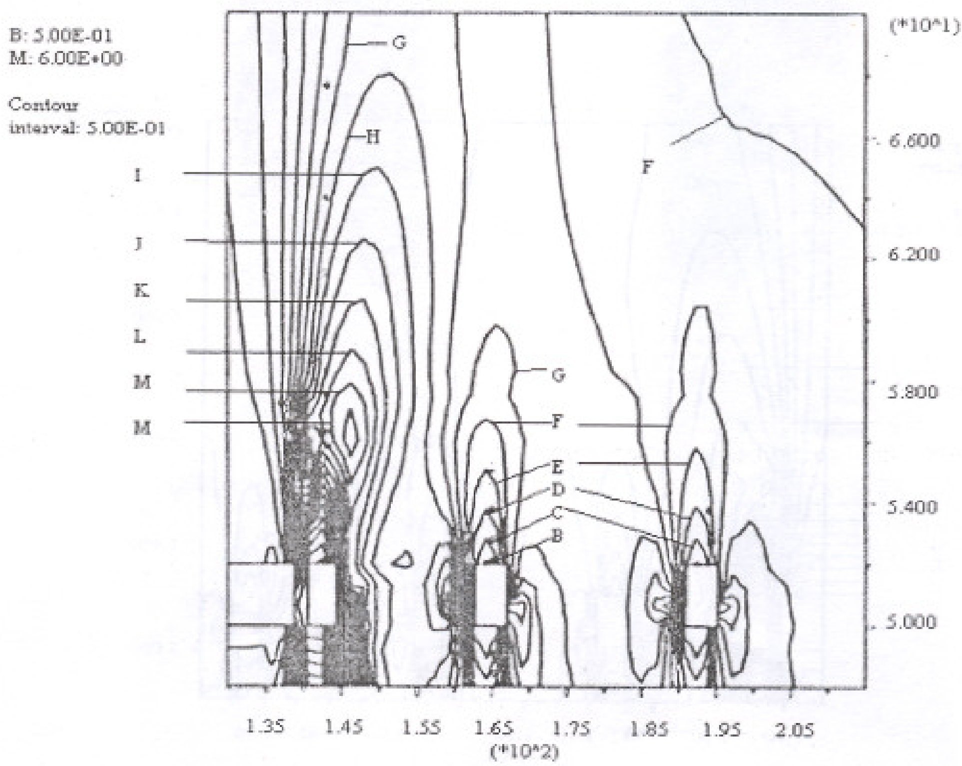

Figure 7 (a) : Safety factor contours in and ahead of the face during dipillaring with three pillars extraction