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Role of Geological Discontinuities on Devising Suitable Support System in Indian Coal Mines

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ABSTRACT

Severe roof stability problems are encountered in many of the Indian coal mine roadways. Typically, these mines are intersected with faults and other geological structures. These faults are well - demarcated straight faults and have shifted the beds (coal/sandstone/shale) without causing any adverse ground control problem to the adjacent beds. The most baffling part of these coal mines is that the same stretch of level galleries/dip rises having similar rock type, strike of the bed and joint pattern do not have a similar roof problem. Two such mines were investigated to know i) causes of failure in the roof ii) reason for ambiguous behavior of the failure zone and iii) means to check the failure. The investigations included actual measurement of principal stresses inside the mines by hydrofracture method to evaluate the extent of stress perturbation due to geological discontinuities and numerical modelling of the study area to understand the causes of failure and to explore the means to check the failure. The investigations revealed that i) the cause of failure is due to the high concentration of maximum shear stress at the roof when maximumhorizontal principal stress (σ_H) direction is 90^o to orientation of level gallery/dip raises ii) the stress perturbation due to the influence of geological structures gives the clue that why in the same stretch of level galleries/dip rises having similar rock type, strike of the bed and joint pattern do not have a similar roof problem. From the investigations it is recommended that i) **Where development is yet to be undertaken:** Developing the level galleries/ dip rises in the recommended directions vis a vis stress may help in improving the roof condition ii) **Where the existing level galleries and dip rises cannot be modified vis a vis stress direction.**A systematic and scientific way of support system is required for the mines.

Keywords:Hydrofracturing; in-situ stress; level galleries/dip rises, stress perturbation

1. INTRODUCTION

In coal mines the knowledge of the magnitude and orientation of the horizontal stress field can have a major impact on decision regarding mining method, size and orientation of roadways and support practices (Dolinear et al., 1982). It is now a well-known fact that one of the principal horizontal stresses is always greater than vertical stress at least upto a depth of 500 m. In some of the Australian coal mines (Gale and Fabjanczyk, 1991) the favorable orientations of roadways vis a vis maximum horizontal stress has been established. Measurements at North Selby colliery of British coal measure (Bigby et al., 1992) indicated that the horizontal stress component acting across a tunnel is a major controlling factor on roof stability. Though the increases in major horizontal stress near the longwall corners were quite high, these were close to in line with the gate roads and the components across the gate roads were relatively low. This confirms the advantages of orienting longwalls close to the direction of maximum horizontal stress.

The directional influence of high horizontal stress is also observed in a number of bord and pillar mining layouts in India (Anireddy and Ghosh, 1994). Mine roadways oriented across the direction of major horizontal stress may experience severe roof falls and strata control problems due to buckling of rock layers. High horizontal stress and adverse orientation of level roadways with respect to the direction of maximum horizontal stress can affect severely roadways condition (Aggason and Curran, 1979). The present paper is based on investigations at two Indian mines viz., Tandsi and Thesgora mines of Western Coalfield Limited (WCL) as both the mines are traversed by major faults and having severe roof problems. The most baffling part of these two coal mines is that the same stretch of level galleries/dip rises having similar rock type, strike of the bed and joint pattern do not have similar roof problem

2. BRIEF DESCRIPTIONS OF TANDSI MINE

The detailed exploration in Tandsi block has proved the existence of 3 coal seams designated from top to bottom as seam – III, II and I. Seam III is persistent in nature as well as attained workable thickness in the entire mine area. The present mining is concentrated at 3.5 m thick No. III seam. The strike in major part of the area is generally EW with localized swings. The immediate roof of 3.5 m No. III seam is made of fine to medium grained grey white, moderately hard sandstone with occasional bands of shale and carbonaceous shale streaks at places. Above 3.5 m height, there is a thin (less than 1 m) coal seam, known as Rider seam. The floor consists of sandstone frequently inter-bedded with shale and carbonaceous shale. There is no overlying or underlying workable seams in the mine. The strata gradient is in 1 in 15, and the pillar size (center to center) is 35X35m galleries with a height of 3.0m is driven along the sandstone floor. Three major faults stand as boundary faults of sector B. The sector being on the upthrown side in all the cases. The development galleries have also met with some additional minor faults. Two persistent sets of joints, spacing 30 to 50 cm for both the sets, have been found to exist in the coal seam.

2.1 Geology of Tandsi Block

Tandsi Block exhibits a rugged topography. The general altitude is around 520m to 550m. The sedimentary sequence encountered in Tandsi block belongs to the lower Gondwana. The strike in major part of the area is generally EW with localized swings. In western and central parts of the block, the strike is N70°-80°W in the eastern part it swings to N40°-50°E. The dip of the strata in western and central part is north easterly and the gradient is varying from 1 in 9 to 1 in 12. In the eastern part, however, the dip is north westerly with a gradient of 1 in 7. Out of 22 faults, 4 faults have magnitude of throw of over 100 m and are oriented at E-W direction. Rest of the faults has magnitude of throw varying from 10 m to 50m and are mostly oblique in nature. The roof and floor strata mainly consist of coarse to medium grained sandstone.

3. BRIEF DESCRIPTIONS OF THESGORA MINE

Seam VA of Thesgora (Sector B) block is being developed on bord and pillar system since 1994. Bigby et al. (1992) indicated that the horizontal stress component acting across a tunnel is a major controlling factor on roof stability due to buckling of shale layers.

In both mines viz., Tandsi and Thesgora mines roof falls were observed both in dip drives and level galleries. The unfavourable orientations of these roadways with respect to high in-situ horizontal stress directions are suspected to be the cause of the roof fall. This is also observed that these roof falls do not occur throughout the mines at the same level though there is no change in the orientations of these roadways. The reason for such observation may be due to favourable orientation of the roadways with respect to the maximum horizontal stress direction. This reorientation of the horizontal stress has happened due to the influence of discontinuities like fault. In sector B of the Thesgora block, the maximum depth of seam V A is around 180 m. The seam thickness varies from 4 to 7 m and has a gradient of 1 in 10 towards North-East. The 4.0 m wide galleries are being driven along the sandstone floor of the seam with a working height of 2.8 to 3.0m. The roof problem of Thesgora mine has been found to be associated with the dip-rise development only. The level galleries were free in general from any such trouble. The probable causes of such roof failures can be the following factors.

a) Un-favorable orientation of joint planes vis a visdiprises. But orientation of the discontinuities was found to be largely favorable for dip rises.
b) The effectiveness of the roof bolting and stitching system. Both the dip and level galleries were found to be supported properly with bolt and stitching. Anchorage tests of these bolts and stitches indicated load bearing capacity above 10 T
c) Delay in the installation of bolts. No such delay was reported in such cases. Moreover, coal due to its low density and high value of elasticity generally constitute a good roof and can stand some delay in support.
d) Unfavorable orientation of the dip rises vis a vis principal horizontal stress orientation. Though there is no change in the geometry of the mining and the physical properties of the rock and coal, the pattern of roof fall is not continuous and restricted in to certain areas

3.1 Geology ofThesgora block

At Thesgora mine no.1, the 3.5 m thick No. 3 coal seam (gently dipping by 1 in 12 due NE) is workable coal seam. The immediate roof of seam is predominantly constituted of sandstone with occasional bands of shale & carbonaceous shale whereas the floor of the seam is mainly of sandstone frequently interbanded with shale and carbonaceous shale. The seam has been developed on bord & pillar system along the top section, with a working height of 2.7 m, gallery width 3.6 m and pillar size 35X35m. The hydrofrac testing was conducted at the floor of this seam in the carbonaceous shale/fine grained sandstone

4. HYDRAULIC FRACTURE EQUIPMENT SET UP AND TESTING PROCEDURE

The Mindata, Australia manufactured hydrofrac assembly with steel reinforced packer elements were used for fracture initiation and extension. The test interval length was about 0.15 m. The length of each packer element was about 0.17m. In the case of hydrofrac experiments in the 48 mm diameter boreholes at Tandsi and Thesgora mines, the tool was operated via the tubing (maximum operating pressure 85 MPa) and high-pressure hose which were used for packer inflation, injection of water into the test interval and to move the tool within the borehole. The maximum injection rate of the electric pump was 4 l/min using a mixture of water and oil for pressurization. Packer and interval pressure as well as the flow rate were measured up hole. All values were recorded in both digital (3 channels) and analog strip chart recorder (Fig. 1).

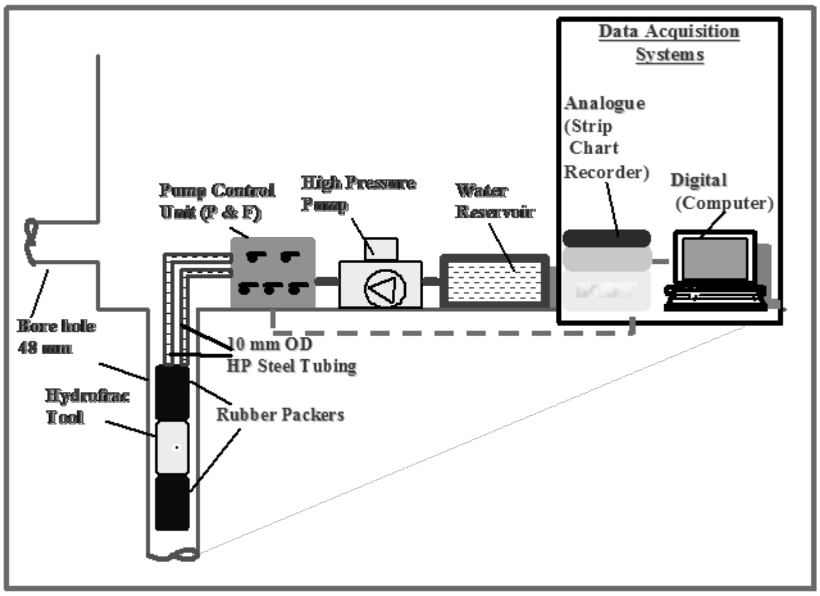

Figure 1 - Experimental setup for hydrofrac system

After the hydrofrac assembly was positioned at a predetermined test section (selected on the basis of core inspection and permeability tests), the injection pressure was increased until a hydraulic fracture was initiated or a preexisting fracture was opened. Subsequently, two to three fracture reopening cycles were conducted. Between the injection cycles the system was vented. The back flow from the fracture into the interval section was observed by short valve closures during the venting phase. Finally, the packers were deflated and tool was moved to the next test section.

After all the hydraulic fracturing tests were conducted in all the boreholes, an impression packer tool with a soft rubber skin together with a magnetic single shot orientation device was run into the holes to obtain information on the orientation of the induced or opened fracture traces at the borehole wall.

During the course of hydraulic fracturing stress measurement at these two mines, the following data acquisition systems were used: Analog on a paper strip chart recorder (Yokogawa, Japan), 2 channels, paper speed: 20 mm/min), and in real time mode on hard disk of a Pentium computer, under the control of the program PICO Log, 16 bits (PICO Technology Limited).

At Tandsi mines the hydrofracture testing was conducted inside borehole drilled vertically down at 13 dip at 8th crosscut district (Fig. 2) inside sandstone. The overburden at the test site was 230 m.

In most of the cases, new fractures were created and in few of the cases only pre-existing fractures were reopened and normal stresses across the fractures were measured. Table 1 gives borehole wise test results in detail and Fig. 3 shows a typical pressure-time plot for the hydrofracture testing.

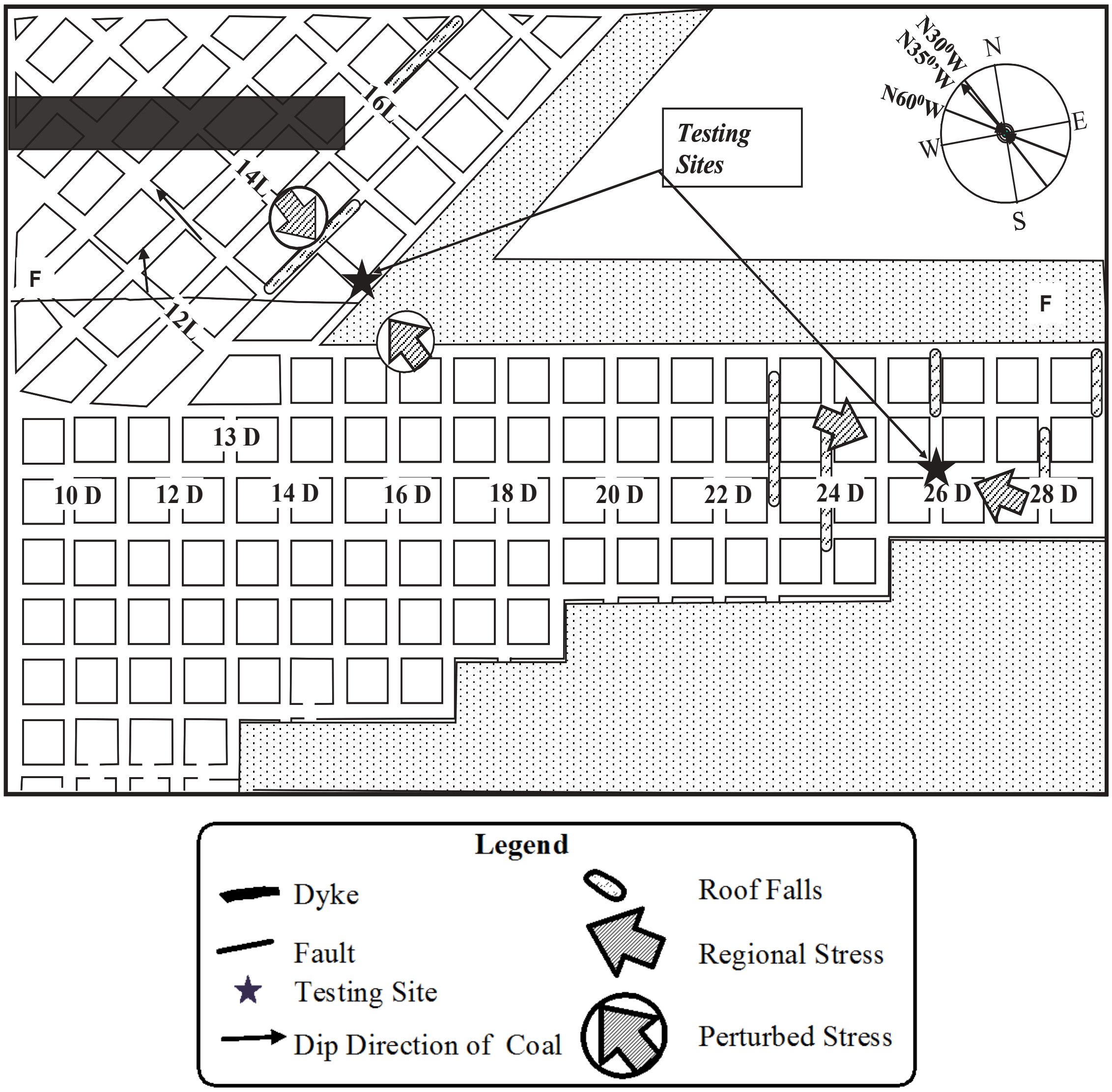

Figure 2 - Plan of Tandsi mine

Table 1 - Pressure and fracture orientation data derived from hydrofrac testing inside vertical borehole at Tandsi coal mines

Depth (m)	Psi (Shut-in pressure) (MPa)	Fracture orientation data		
		θ	β	α
13.00	05.92	172°	262°	79°
16.00	09.20	040°	130°	50°
19.00	06.40	163°	073°	69°
22.00	06.00	140°	230°	90°

Notations: θ = Strike direction (north over east), β = Direction of inclination, and α = Inclination of the fracture plane (with respect to horizontal).

4.4 Stress Evaluation Procedure and Results

The in-situ stress measurements at these two coal mines were conducted with the following test situations:

i) Pronounced topography
ii) Proximity of large excavations
iii) Presence of anisotropic rock

Due to the above aspects a medium to large scatter in fracture orientation data were noticed which negated the use of classical simple hydrofrac hypothesis suggested by Hubert and Wills (1957). Therefore, data analysis required a more sophisticated method, namely the interpretation of measured normal stress acting across arbitrary oriented fracture planes. In this method the shut-in pressure P_{si} is used to measure the normal stress component under the assumption that the vertical is a principal stress axis and the vertical stress σ_v is equal to the weight of the overburden (Enever and Wooltorton,1983; Enever et al., 1990). The analysis program GENSIM was used to calculate the magnitude and the direction of principal stresses on the basis of the following equation:

$$\sigma_h = \left(P_{si} - n^2.\sigma_v\right)/\left(m^2 + l^2.\sigma_H/\sigma_h\right) \qquad (1)$$

Where, *l, m, n* are the cosines of the direction of the induced fracture plane related to the principal stress axis.

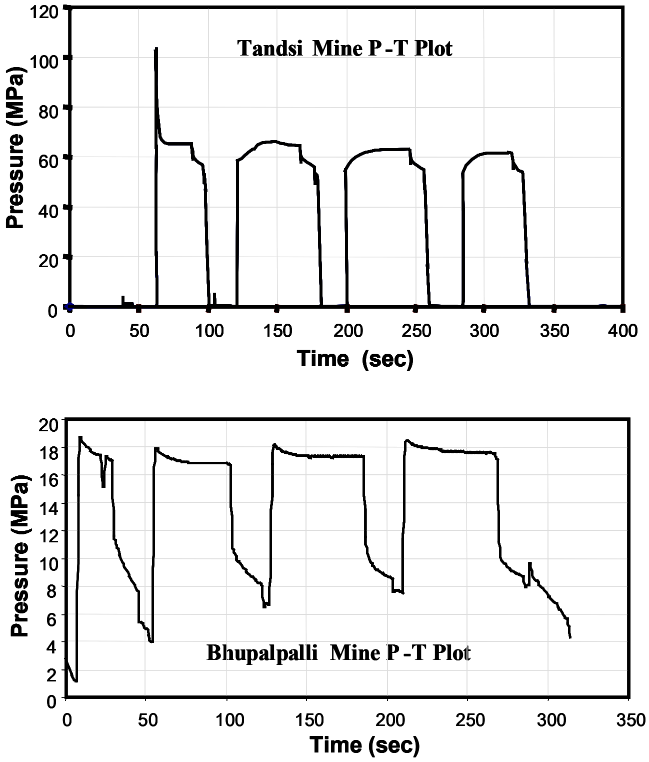

Figure 3 - Showing pressure-time plot of Tandsi mine and Thesgora mine

5. DETERMINATION OF PERTURBED STRESS

The in-situ stress magnitude and orientation are found to be controlled by the major geological structures like folds, faults and intrusive. These structures bring about local heterogeneity in rocks, thus leading to refraction and / or rotation of stress trajectories (Sengupta et al.,1997) In both mines viz., Tandsi and Thesgora mines roof falls were observed both in dip drives and level galleries. The un-favorable orientations of these roadways with respect to high in-situ horizontal stress directions are suspected to be the cause of the roof fall. This is also observed that these roof falls do not occur throughout the mines at the same level though there is no change in the orientations of these roadways. The reason for such observation may be due to favorable orientation of the roadways with respect to the maximum horizontal stress direction due to reorientation of the horizontal stress due to the influence of discontinuities like fault. In-situ stress was measured at these two mines using hydrofrac technique to determine a) regional stress and b) perturbed stress.

At Tandsi mines the hydrofracture testing were conducted inside boreholes drilled vertically down at two sites. 1st site at 26 dip at 8th crosscut district inside sandstone away from structural discontinuity. The stress regime evaluated depicts unperturbed in-situ stress. The overburden at the measurement site was 230 m. The 2nd site at 13 dip is inside sandstone at the vicinity of a fault. The stress regime evaluated depicts perturbed in-situ stress. The overburden at the measurement site was 255 m.

At Thesgora mines the hydrofracture testing were conducted inside boreholes drilled vertically down at two sites.

i) 1st site at 20th level 3 dip away from structural discontinuity. The stress regime evaluated depicts unperturbed in-situ stress. The overburden at the measurement site was 212 m.
ii) 2nd site at 19th level 3 dip at the vicinity of a fault. The stress regime evaluated depicts perturbed in-situ stress. The overburden at the measurement site was 187 m.

These two types of stresses were required to establish the role of faults in stress perturbation. The hydrofracture results are given in Figs. 4 and Tables 2 and 3

Table 2 - Stress regime indicated by the testing at two sites at Tandsi mines

Stresses	1st site at 26 dip at 8th crosscut (Overburden 230 m) (Regional Stress)	2nd site at 13 dip (Overburden 255 m) (Perturbed Stress)
Maximum Horizontal Principal stress (σ_H), MPa	9.00 ± 0.618	11.20 ± 0.906
Minimum Horizontal Principal Stress (σ_h), MPa	4.50 ± 0.309 (MPa)	5.60 ± 0.453
Vertical Stress (σ_v), MPa [density of rock=2.2 gm/cc]	5.06	5.61
Ratio $K = \sigma_H/\sigma_v$	1.77	1.99
Maximum Horizontal Principal Stress Direction (σ_H)	N 120° (N 60°W)	N 150° (N 30°W)

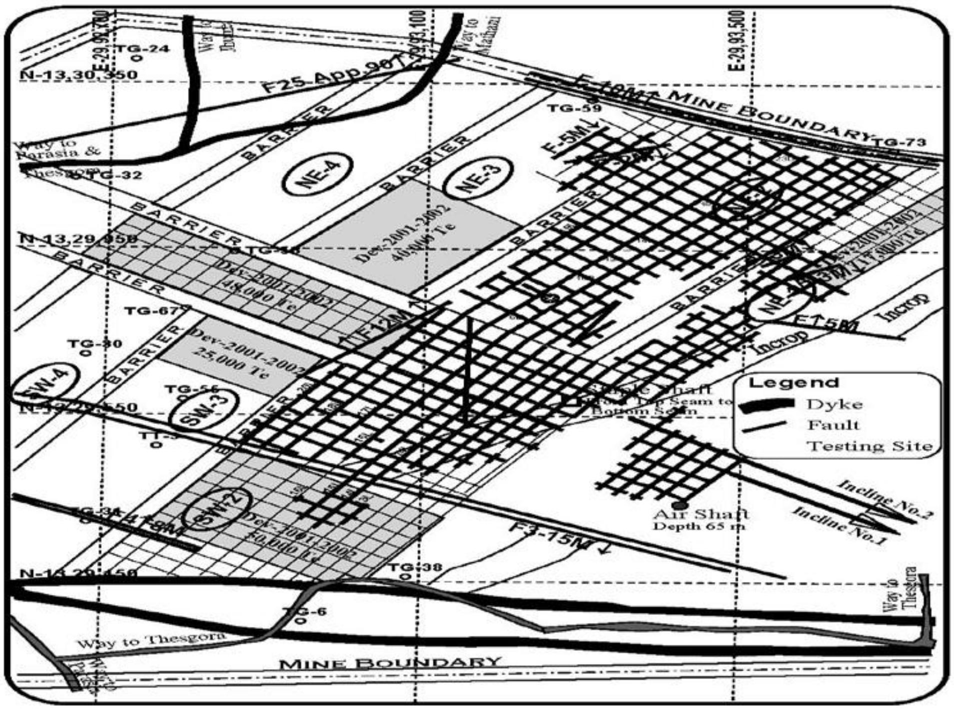

Figure 4 - Part plan of Thesgora mines showing locations of testing sites for in-situ stress measurements by hydrofrac method and directions of regional and perturbed stresses

Table 3 - Stress regime indicated by the testing at two sites at Thesgoramines

Stresses	1st site at 20th level 3 D (Overburden 212 m) (Regional Stress)	2nd site at 19th Level 3 D (Overburden 187 m) (Perturbed Stress)
Maximum Horizontal Principal stress (σ_H), MPa	6.04± 0.0679 MPa	6.00 ± 0.0162 MPa
Minimum Horizontal Principal Stress (σ_h), MPa	4.03 ± 0.453 MPa	2.82 ± 0.0108 MPa
Vertical Stress (σ_v), MPa [density of rock=2.2 gm/cc]	4.66 MPa	4.11 MPa
Ratio K = σ_H/σ_v	1.29	1.46
Maximum Horizontal Principal direction (σ_H)	N 100° (N 80°W)	N 170° (N 10°W)

6. INVESTIGATION OF STRESS REDISTRIBUTION DUE TO MINING GEOMETRY

Investigation conducted in Australian coal mines (Gale and Fabjanczyk, 1991) has established a relation between roof failure in the roadways and the angle between the roadway axis and the maximum horizontal stress direction. In a typical Bord and Pillar mining method the dip drives and level galleries are driven perpendicular to each other. Now in a particular set of direction of maximum horizontal stress either one of these or both may be oriented unfavourably with the orientation of the maximum horizontal stress. ***In this study a detailed investigation is carried out by numerical modeling to establish the most favourable direction of the dip drives/level galleries vis a vis direction of maximum principal horizontal stress from the stability point of*** *view.* For the study of redistribution of stresses due to change in mining geometry three cases were considered.

i) Orientation of maximum horizontal principal stress (σ_H) is parallel to orientation of level gallery/dip rises
ii) Orientation of maximum horizontal principal stress (σ_H) is perpendicular to orientation of level gallery/dip rises
iii) Orientation of maximum horizontal principal stress (σ_H) is 45° to orientation of level gallery/dip rises

The objective of the study is to estimate effect of the above three conditions on the stability of roof so that proper measure can be taken to reduce the roof stability problem by change in geometry of the workings and also to estimate the support requirement. A detailed investigation is carried out by numerical modelling to establish the most favorable direction of the dip drives/level galleries vis a vis direction of maximum principal horizontal stress from the stability point of view & design suitable support system.

Numerical simulation is a powerful technique for studies on rock mechanics and engineering, but its accuracy and reliability lie on the used simulation approach, constitutive model, material properties etc. The finite element method is a numerical solution, divided into non-overlapping regions connected to each other through points called nodes. The behavior of each element satisfying equilibrium conditions, compatibility, material constitutive behavior and boundary conditions is described, and the elements are assembled.

As a result of numerical analysis, redistribution of major principal stress, maximum stress at the roof is observed when Maximum Horizontal Stress is perpendicular to orientation of level gallery/dip raises. The minimum principal stress at the roof is observed when Maximum Horizontal Stress is parallel to orientation of level gallery/dip raises (Table 4).

The results of numerical analyses for roof convergence, maximum deformation at the roof is observed when Maximum Horizontal Stress is perpendicular to orientation of level gallery/dip raises. The minimum deformation at the roof is observed when Maximum Horizontal Stress is parallel to orientation of level gallery/dip raises (Table 4).

The results of numerical analyses on redistribution of shear stresses, maximum shear stress at the roof is observed when Maximum Horizontal Principal Stress is perpendicular to orientation of level gallery/dip raises. The minimum shear stress at the roof is observed when Max. Horizontal Principal Stress is parallel to orientation of level gallery/dip raises (Table 4).

Table 4 - Different results observed in the immediate roof from all the cases

Condition	Major Principal stress (σ_H) magnitude	Deformation (mm)	Shear stress	Shear displacement (mm)
i) σ_H parallel to level gallery	5.43 MPa	5.96	0.91 MPa	3.60
ii) σ_H is 45° to level gallery	6.98 MPa	8.34	1.27	8.24
iii) σ_H perpendicular to level gallery	9.60 MPa	14.57	1.94 MPa	15.81

The results of numerical analyzing on shear displacements, maximum shear deformations at the roof are observed when Maximum Horizontal Stress is perpendicular to orientation of level gallery/dip raises. The minimum shear stress shear deformations and total deformation at the roof is observed when Maximum Horizontal Stress is parallel to orientation of level gallery/dip raises (Table 4).

Thus, it indicates that the level gallery/dip-raise should be oriented at parallel to sub-parallel direction with respect to maximum principal stress direction to reduce roof problems.

7. RECOMMENDATION FOR SUPPORT

On the basis of the numerical modelling the supports recommended are as follows:

a. Where development is yet to be undertaken

Determination of maximum horizontal principal stress and then developing the level galleries/ dip rises in the recommended directions vis a vis stress (Around 45 ^{o} to the maximum horizontal stress as keeping level galleries or dip rises parallel will make the other vulnerable) may help in improving the roof condition.

b. Where the existing level galleries and dip rises cannot be modified vis a vis stress direction

A systematic and scientific way of support system is recommended for the mines as given in Tables 5 and 6 and Figs. 5 and 6.

Table 5 - Support recommendation for Tandsi mine

Existing Support Details	Recommended Support Details
• Roof bolts 2.4 m length	• Roof bolts 2.4m length; bolt Young's modulus 100 GPa.
• Spacing 0.75m across gallery and 0.6m along gallery	• Spacing 0.6m across and along galleries
• Resin grouted	• Resin grouted, grout bond stiffness 1.0e9 N/m/m and grout cohesion 1.0e6 N/m
• W-strap fixed with dome plate + dome ball + nut	• W-strap fixed with dome plate + dome ball + nut

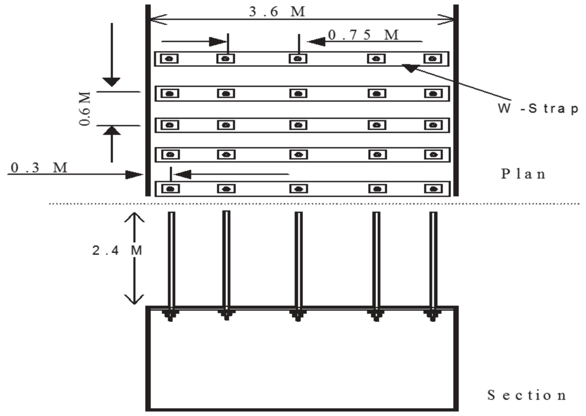

Figure 5 - Existing and recommended support system at Tandsi mines

Table 6 - Existing and recommended support system at Thesgora Mines

Existing Support Details	Recommended Support Details
• J-Hooks of 1.2 m length	• Roof bolts 2.4m length, bolt Young's modulus 100 GPa
• Spacing 1m	• Spacing 0.6m
• Hooks grouted with cement capsules to full length	• Resin grouted, grout bond stiffness 1.0e9 N/m/m, grout cohesion 1.0e6 N/m.

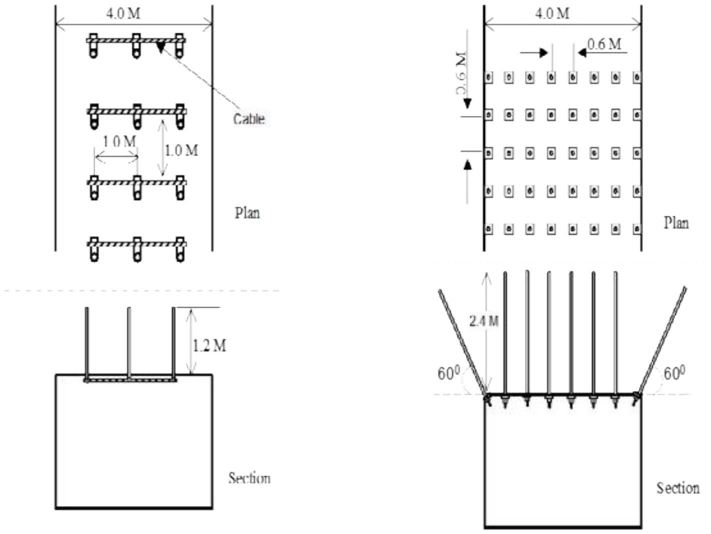

Figure 6 - Existing and recommended support system at Thesgora mines

8. CONCLUSIONS

The measurement of in-situ stress followed by parametric study by numerical method suggests significant influence of geological discontinuities (viz., faults, shear zone etc.) on stress concentration in coalmines. This stress perturbation in turn gives the answers that why stretch of level galleries/dip rises having similar rock type, strike of the bed and joint pattern does not have a similar roof problem. The analysis can be summarised as follows:

i) The presence of geological structures such as fault, shear zone etc. affect the stress concentration/ orientation significantly.
ii) Due to changes in stress concentration caused by above phenomena, the level galleries/ dip rises lie favorably/un-favorably vis a vis level orientation of maximum horizontal principal stress.
iii) Severe problem of stability at roof is clearly observed when level galleries/ dip rises are oriented perpendicular to the direction of maximum horizontal principal stress. This occurs due to high concentration of shear stresses at the roof and sagging of roof layers.
iv) Least concentration of shear stresses at the roof occurs when the orientation of level gallery/dip rise is parallel to maximum horizontal principal stress.
v) It is also observed from the point of stability that when the dip rise/ level gallery is perpendicular to each other, the optimum direction is found to be 45° to the orientation of maximum horizontal principal stress.
vi) In case the point (v) above is not achievable, a rational approach for design of support system should be adopted to avoid stability problem.

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