Application of empirical and numerical modelling for stability analysis of developmental workings in an underground coal mine

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ABSTRACT: Seam XVB of Bhelatand Amalgamated Colliery, Tata Steel Limited, India is being developed in the southern part of the leasehold area where the stability of the overlying roof strata is disturbed due to the presence of geological discontinuities. In this study empirical methods and numerical modelling have been used to ascertain the stability of the workings. CMRI-ISM RMR (Central Mining Research Institute – Indian School of Mines Rock Mass Rating System) classification system is the most popular and practiced empirical method for roof support design in Indian coal mines. Firstly, structural mapping of the panel was carried out in seam XVB. Further, an attempt has been made to estimate the factor of safety of the existing pillars, the rock load on the galleries & junctions of seam roof using both the methods. Finally, using the existing support design, the support safety factor (SSF) was determined, and recommendations were made to improve the existing SSF.

Keywords: CMRI-ISM RMR, Empirical methods, Numerical modelling, SSF.

1 INTRODUCTION

The safety and productivity of underground mines is largely dependent on the correct characterisation and classification of the roof rocks. Presence of thinly laminated rock in the immediate roof is one of the major reasons for roof failures (Paul et. al., 2012). Another cause attributed to roof failures is the blasting in the development faces (Suresh and Murthy, 2005). Adequate support design plays an important role in attaining the proper stability for underground workings (Singh et. al., 2005). Thus, the rock mass classification system is considered as one of the most important tools to evaluate the behaviour of the rock mass and design the subsequent support system. Application of proper rock mass classification system and extensive numerical modelling using software like FLAC 3D provide a useful insight into the stability of the workings (Paul et. al., 2020). In this paper CMRI-ISM RMR (Central Mining Research Institute – Indian School of Mines Rock Mass Rating System) classification system has been used to determine the RMR (Rock Mass Rating) as it suits the Indian geo-mining conditions. Finally, numerical modelling of the underground panel was carried out using FLAC 3D and the loads on the galleries and junctions were compared with the empirical values.

2 BACKGROUND

Bhelatand Amalgamated Colliery is one of the underground operative mines of Tata Steel Limited located in Jharkhand state in the eastern part of India (Figure 1). A total of 19 coal seams / seam sections (seam XVII to I) have been identified by exploratory drilling. Presently, underground workings are being done up to seam XI from seam XVII in some areas of the leasehold. In the concerned area of study (SOF-South of Fault) seams XVII and XVI which are overlying seam XVB has been worked out and are partly caved whereas the seams below XVB are all virgin. Seam XVB (2.49 m thick) is being extensively developed by Bord and Pillar method of mining by driving galleries of average 4.8 m in width and of 2.49 m in height. The average dimension of the pillar is 50m x 50m (centre to centre). The minimum and maximum depth of cover of the panel from the surface are 405.87m and 445.59m respectively. The immediate roof of the XVB seam consists of shale, sandstone, and shale sandstone intercalation. The partings from the floor of XVB seam development workings to the roof of the underlying XIV seam is 75 m. The parting from the roof of seam XVB to the floor of overlying seam i.e., seam XVT is 2.50 m – 3.00 m. The panel of seam XVB in the study area is divided into two domains based on the outcome of geological mapping. The area along the M level lies in close proximity to the regional fault F7-F7' has as a poor rock mass while the other levels (N/O/P) down south of the M level have relatively stronger rock mass. The levels are often abbreviated as 'L' in the text and figures.

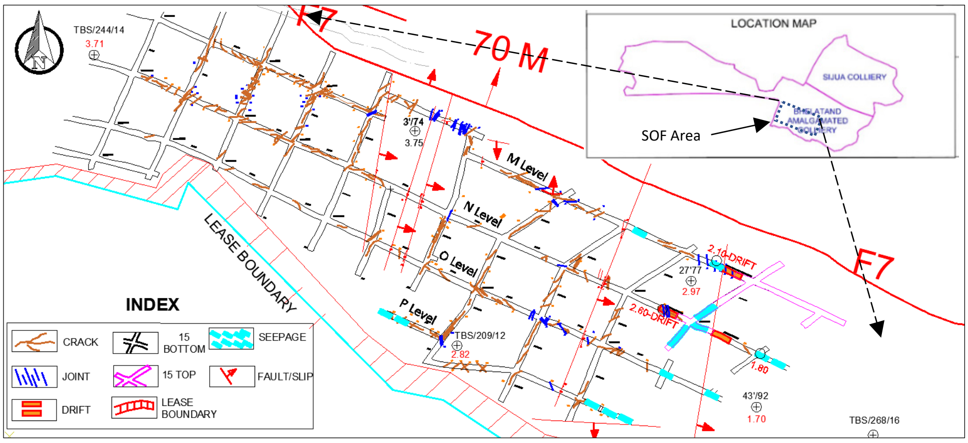

Figure 1. Geotechnical map (plan view) of the study area.

3 OBJECTIVE

The objectives of this study are as follows:

- To ascertain the stability of galleries and junctions empirically and numerically
- To compare the loads in both the above methods and calculate the support safety factor

4 DETERMINATION OF CMRI-ISM RMR

Geotechnical mapping was carried out along the M Level, N Level, O Level and P Level of the developed area in the panel of seam XVB. The discontinuity characteristics like joints, cleat, slip planes, slickensides, fall area etc. were mapped for persistence, aperture, spacing, orientation, infillings and is represented in geotechnical map (Figure 1) above. Two sets of cleats in coal were mapped in the panel. Cleat -1 (N50°/60°→N140°) is almost parallel to the dip/rise galleries while cleat – 2 (N110°/55°- 60° → N20°) is sub-parallel to the level galleries. Thus, both these sets form potential threat of spalling along the dip-rise galleries and the level galleries as was observed during the mapping exercise. Higher frequency of cracks, joints, slip planes, slickensides, faults & ball coal was also observed all along the M level due to its proximity to the regional fault F7 (70 m throw towards north). One set of joint trending N40° is present all throughout the panel while another random set trends N90°. A number of small faults/slips trending N40°/75°-80° →N130° with throw ranging from 0.25 m to 1.0 m are scattered throughout the panel with a number of seepage areas.

RMR of roof rocks of seam XVB has been determined using CMRI Geomechanical Classification System (CMRI Report, 1987; Venkateswarlu et.al., 1989). RMR for M level and N/O/P levels are calculated separately as mentioned earlier. Ratings of different parameters are given in Table 1 below.

Table 1. RMR calculation for different lithologies.

	Shale (0.40 m)		Sandstone (0.46 m)		Shale-Sandstone intercalation (1.28 m)	
Parameter	Description	Rating	Description	Rating	Description	Rating
Layer thickness	7.8 cm	14	14 cm	18	4.25 cm	8
Structural features	Indices 18	0	Indices 18	0	Indices 18	0
Weatherability	98.26%	16	97.65%	15	98.03%	16
Compressive strength	410.80 kg/cm^2	8	450.07 kg/cm^2	9	390.70 kg/cm^2	8
Groundwater	Dripping, moist	9	Dripping, moist	9	Dripping, moist	9
RMR	47		51		41	

Thus, the combined RMR is: [(47*0.4) + (51*0.46) + (41*1.28)] / (0.4+0.46+1.28) = 44.27

The RMR is further adjusted by 10% for solid blasting, 10% for gallery width, 20% for depth of working and 30% for high lateral stress. Thus, the adjusted RMR for M level is 20.08 which is classified as poor (Class IV A).

The thickness of different lithologies in the roof in levels N, O and P levels are 0.20 m, 1.25 m and 1.15 m. Thus, the combined RMR for N/O/P level is: [(45*0.2) + (52*1.25) + (44*1.15)] / (0.2+1.25+1.15) = 47.92. The RMR is further adjusted by 10% for solid blasting, 10% for gallery width, 20% for depth of working and 20% for medium lateral stress. Thus, the adjusted RMR for N/O/P level is 24.85 which is classified as poor (Class IV A).

5 ESTIMATION OF ROCK LOAD

Rock load was estimated for galleries (Venkateswarlu et.al., 1989) and junctions (Ghosh and Ghosh, 1992) using following equations:

Rock load in gallery (t/m^2) = B.D. [1.7 – 0.037.RMR + 0.0002. RMR^2]
Rock load at junction (t/m^2) = $5.B^{0.3}$.D. $[1 – RMR/100]^2$
where, B = Roadway width (m), and D = Dry density (t/m^3).
In the study area, Density of roof rocks, D = 2.54 t/m^3, and Width of gallery, B = 4.8 m
Rock load at galleries & junctions of M level: 12.03 t/m^3 & 13.90 t/m^3 respectively.
Rock load at galleries & junctions of N/O/P level: 11.03 t/m^3 & 11.49 t/m^3 respectively.

6 NUMERICAL MODELLING

Numerical modelling was carried out using software FLAC 3D. Several input parameters for the modelling study are discussed subsequently.

The in-situ stresses are influential factors to assess the stability of an underground structure. Based on a thermo-elastic shell model of the earth, Sheorey (1994) predicted the average in-seam horizontal stress as a function of depth, young's modulus, coefficient of thermal expansion, geothermal gradient and poisson's ratio. The Mohr-Coulomb material model is adopted in FLAC 3D analysis.

Scaling/conversion of the physico-mechanical properties of the laboratory test of the intact rock to the rock mass (Table 2) is essential for the successful simulation of underground working. Sheorey's failure criterion (Sheorey, 1997) is used to obtain the rock mass properties from the intact rock properties.

The value of the rock mass cohesion obtained from the Sheorey's criterion is increased by 10% and the internal friction angle of the rock mass is reduced by 5° to use them as the equivalent Mohr-Coulomb parameters (Das et al., 2019). The failure of the bedding planes among the strata is simulated by the ubiquitous joint model. The cohesion and the friction angle values of the interfaces are considered as 0.18 MPa and 24° respectively in the modelling (Das et al., 2017). The physical properties of rock and coal used in numerical modelling are given in Table 2.

Table 2. Rock properties used in numerical modelling.

Rock type	Youngs modulus GPa	Tensile strength MPa	Density g/cc	Poisson's Ratio	Cohesion MPa	Friction (°)	Dilation (°)
Coal (M L)	2.53	0.20	1.30	0.30	0.22	25	0
Coal (N/O/P level)	2.53	0.17	2.58	0.30	0.18	24	0
Parting XVT & XVB (ML)	6.37	1.05	1.30	0.28	1.16	25	0
Parting XVT & XVB (N/O/P L)	6.37	0.90	2.58	0.28	0.97	24	0
OB (ML)	6.75	1.08	2.57	0.23	1.16	24	0
OB (N/O/P L)	6.75	0.93	2.57	0.23	0.97	23	0

The simulation was carried out to assess the stability of the coal pillars as well as the surrounding rock mass in the proposed development panel in seam XVB. The average vertical stress on the coal pillar of size 50m X 50m (centre to centre) obtained from numerical modelling is estimated as 13.89 MPa (Figure 2). The strength of the pillar using the pillar strength formula widely used in Indian geo-mining condition (Sheorey, 1992) is estimated as 49.21 MPa. The Factor of Safety calculated (Sheorey, 1987) by dividing the empirical strength of the pillar with average vertical load on it obtained numerically is found to be 3.54.

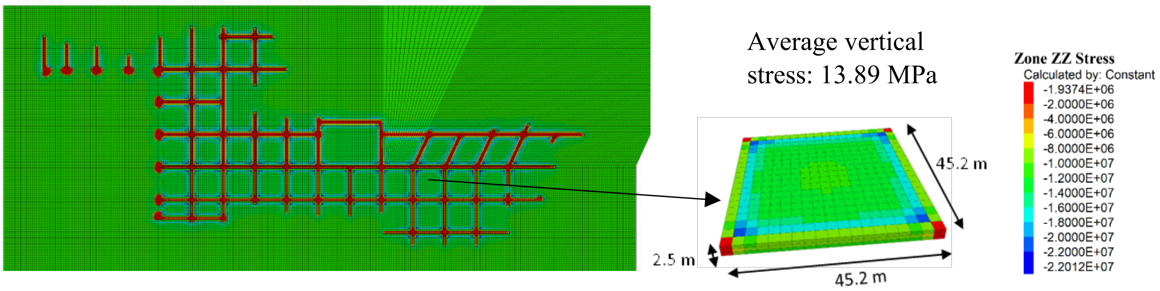

Figure 2. Vertical stress field in the panel and pillars.

From the Figure 4a, the yield zone reaches up to 7.00 m at the junction and 6.25 m at the galleries in M level. At places near the centre of the galleries the yield zone may decrease up to 6.00 m as well, but the region has very limited distribution and the worst-case scenario has been considered for further calculation. The rock load is calculated by multiplying the yield zone with the average density. Figure 4b shows yield zone of 6.50 m at the junction and 5.40 m at the galleries of the N, O and P levels of the workings. The rock loads as calculated from the numerical model is shown in Table 3.

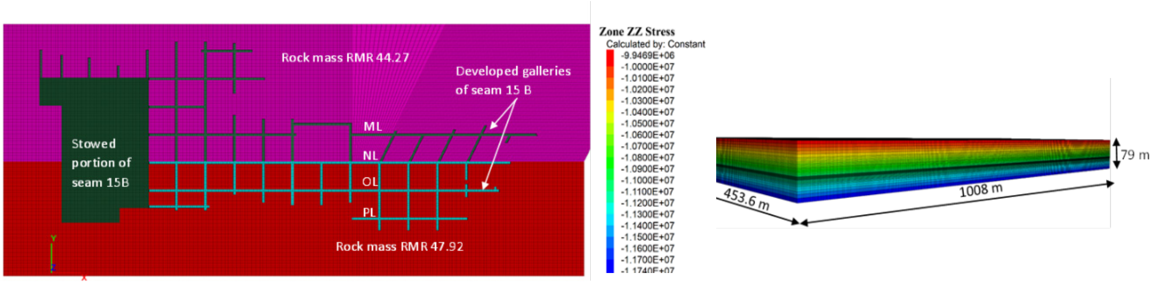

Figure 3. Planar and sectional view of the panel.

Table 3. Rock load in galleries and junction.

Level	Location	Rock load height, h_{SF} (m)	Weighted Average density of roof, D (t/m^3)	Rock Load (t/m^2), D*h_{SF}	Rock load (t/m^2) as determined through CMRI-RMR
M Level	Gallery	3.25 m rock; 3.0 m coal	1.30 for coal; 2.50 for rock	12.65	12.03
	Junction	4.0 m rock; 3.0 m coal		13.00	13.90
N/O/P Level	Gallery	3.0 m rock; 2.4 m coal		11.03	10.62
	Junction	3.5 m rock; 3.0 m coal		11.49	12.65

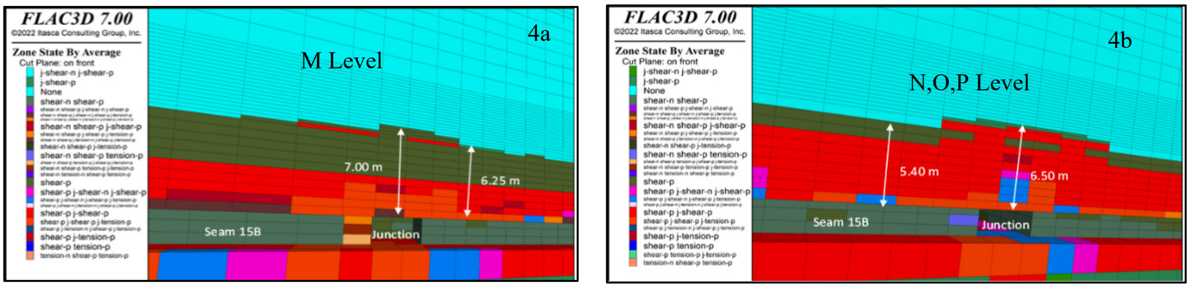

Figure 4a & 4b. The yield zones above galleries and junctions (Sectional view).

7 SUPPORT DESIGN AND SUPPORT SAFETY FACTOR

The support system was designed considering the rock loads calculated nunmerically and empirically. The galleries are supported using four (04) full column resin grouted roof bolts of 1.95 m long having 1.8 m grouted length in one row and twenty (20) 6.0 m long fully grouted cable bolts all along the gallery. The anchorage strength of the roof bolt of length 1.8 m (grouted length) and diameter at least 20 mm, made of TMT/MS ribbed bar and grouted with full column resin capsules is considered as 13t and the anchorage strength of cable bolts are 25t. Similarly, the junctions are supported using twenty (20) full column resin grouted roof bolts of 1.95 m long having 1.8 m grouted length and ten (10) 6.0 m long fully grouted cable bolts. The support resistance in the galleries is calculated using the formula:
(No. of roof bolt in a row X Anchorage strength - t)/ (Width of the gallery -m X Row spacing – m)
Similarly, the support resistance in the junction is calculated using the formula:
(No. of roof bolts X Anchorage strength - t)/ (Width of the gallery -m X Width of gallery – m)
Therefore, the support resistance at the galleries is 19.17 t/m^2 and at the junctions is 22.14 t/m^2.

8 DISCUSSION

The support safety factor is calculated by dividing the rock load with the calculated supported resistance. The comparison made between the SSFs calculated empirically and numerically is given below in Table 4. It is clear from the table that using support design as mentioned earlier, the minimum SSF at junctions and galleries are above 1.5 which is considered to be safe for operation.

Table 4. Comparison of SSF between empirical and numerical modelling.

	Rock load (t/m^2) Numerical		Rock load (t/m^2) Empirical		SSF Numerical		SSF Empirical	
	Gallery	Junction	Gallery	Junction	Gallery	Junction	Gallery	Junction
M Lvl.	12.03	13.90	12.65	13.00	1.59	1.59	1.52	1.70
N/O/P Lvl.	10.62	12.65	11.03	11.49	1.81	1.75	1.74	1.93

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