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Full Length Research Paper

Study on Rock Load Variation Considering Weatherability in Bord and Pillar Method of Underground Coal Extraction

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ABSTRACT

In India, bord and pillar is the most commonly used method in the extraction of coal which contributes approximately 98% production from underground. Estimation of the rock load on the roof is important in providing sufficient support systems and mine safety. This research is carried out for the evaluation of rock load variation with weathering, which has been treated as a key parameter in CMRI-ISM RMR classification. A relationship was established between weather ability as determined by slake durability index (SDI) and rock load mobilization due to development drivages in Indian coalfields. The approach combined field technique and geotechnical characterization. Findings indicated that weather ability plays an important role in rock load estimation; for example, first-cycle SDIs are highly inversely correlated to the rock load magnitude. Strong coefficients of determination ($R^2 > 0.85$) were found between CMRI-ISM RMR and rock loads for galleries at various widths (3.6-4.8 m). Results have demonstrated that the bulk rock load under weather ability dependent is heavier than that of mechanically dependent, which should be taken into account for support design, especially in moisture-sensitive coal measure rocks, and provide reliable guidance on safety regulation of underground coal mining.

Keywords: *Rock loading effect, Weathering, Bord and pillar method, Slake durability index, CMRI-ISM RMR*

1. INTRODUCTION

The details of the bord and pillar workings are as used in underground coal mines in India38, i.e. extraction is done in systematic manner by forming galleries separated by pillars. The Central Mining Research Institute-Indian School of Mines Rock Mass Rating (CMRI-ISM RMR) system has been widely used for design of supports in Indian coal mine conditions (Paul et al., 2014; Bieniawski, 1989). Rock load prediction is essential for designing optimal support systems that avoid roof fails. The CMRI-ISM RMR classification system includes five important factors: the thickness of layers, structural characteristics, resistance to weathering, water table conditions and uniaxial compressive strength of roof rock (Venkateswarlu et al., 1989). Of these the weather ability is of immense importance for Indian coal measure rocks, which are often clayey and are

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subjected to deterioration in their strength with presence of moisture. The slake durability index (SDI) weathering factor allows quantification of a rock's weathered susceptibility under repeated wetting and drying cycles (Franklin & Chandra, 1972).

Roof and rib fall accidents about coal mines account for approximately 28.5% of the total casualties in underground coal mining, indicating how important it is to accurately estimate rock load (Singh et al., 2003). Although the CMRI-ISM RMR system can be applied widely, the role of weather ability in rock load variation warrants attention. In Indian coalfields, water percolation is amajor problem, which facilitates weathering processes and roof instability. The rock load distribution patterns are also further complicated by the gallery width variations, which vary between 3.6 m to 6.6 min mechanized operations. This work focuses on the necessity of the development of a critical appreciation of rock load variation accounting for weather ability effects in bord and pillar method. The research objectives include a systematic study of the weather ability effect on rock load mobilization and validation through field case studies with emphasis of contributing to better safety standard and optimized support system in the underground coal excavation industry.

2. LITERATURE REVIEW

Significant developments in rock mass classification systems for underground openings have been made since Terzaghi's innovative description of rock load classification in 1946 holzfister2. The Rock Mass Rating (RMR) system of Bieniawski (1973, 1989) is used worldwide for the design of underground excavations and mines. The RMR system is based on six parameters, which are: the strength of rock intact, the proportion of RQD (Rock Quality Designation), and spacing of discontinuity, condition of discontinuity, water table conditions and joint orientation. Taking into account the special features of Indian coal measure rocks, Central Mining Research Institute and School of Mines evolved modified RMRs called as CMRI ISM RMR (Venkateswarlu et al., 1989). Based on the statistical analysis of 150 field testing records and those from published cases, the five most significant parameters affecting Indian coal mine roof conditions, namely, spacing of bedding planes, rock strength index, weather ability, water condition and structure are identified. Using these parameters principal component analysis, factor analysis and discriminant analysis have been used to establish the suitability of chosen parameters in describing specific geological condition of Indian coal deposits.

The weather ability-factor considers an important problem in the Indian coal mining. Franklin and Chandra (1972) developed the slake durability test to evaluate rock resistance to weakening and breakdown due to repeated cycle of drying and wetting. This methodology is standardized under ASTM D4644 and provides a quantitative evaluation in terms of the slake durability index. For Indian coal measure rocks, the first-cycle SDI value is representative of weather ability, high values more than 85% are indicative of high susceptibility to weathering degradation. The research of rock load estimation in development gallery has been changed for several times. Ghosh and Ghose(1992) proposed empirical relationships on the estimation of RMR values along with rock loads for Indian coal mine roadways, thus laying a beginning on understanding the behavior of rock load in terms of rock mass quality. Subsequently, Singh et al. (2003) also improved these relations using field measurements and numerical models, showing that rock load is inversely proportional to the RMR values.

Paul et al. (2014) carried out an extensive study in the Jharia coalfield, analyzing how rock load changes with different gallery widths of 3.6–4.8 m wide and included geotechnical characterization of roof rocks from several mines under Bharat Coking Coal Limited and Tata Steel Limited. The study developed empirical equations between CMRI-ISM RMR values and the rock loads for galleries and junctions taking account of roof rock density variations, with R^2 higher than 0.85. The international literature has described the effect of weather ability on roof stability. The moisture sensitivity as a bedded roof type with the inclusion of critical parameter is added to U.S. designed C.M.R.R (Coal mine Roof Rating) system (Molinda and Mark 1996). Their studies showed that roof rocks which are sensitive to moisture have a sharp strength decrease when immersed in water, causing premature roof caving (Iannachione et al., 2001). Numerical modelling in rock loading estimation has been developed to support empirical methods. Sheorey (1997) introduced the use of virgin stress conditions and characteristics of rock mass properties in order to predict pillar loadings and roof stabilities by proposed methods. These numerical methodologies enable an understanding of mobilized rock load across different geological and working situations (Mohan et al., 2001).

3. OBJECTIVES

The present research investigation pursues the following specific objectives:

1. To analyze the effect of weather ability on rock load variation in development galleries using slake durability index correlations.
2. To derive empirical relationships between CMRI-ISM RMR values and rock loads incorporating weather ability across varying gallery widths.
3. To perform field and laboratory characterization of roof strata through slake durability, UCS, and RMR assessments.
4. To validate the developed relationships statistically for improving support design in underground coal mining.

4. METHODOLOGY

Research Design

The research approach was based on a holistic empirical model combining field survey, laboratory test and statistical analysis. Case studies from Indian coalfields to cover representative sampling of different geological conditions were part of the study design. Field studies were carried out in active coal mines working on bord and pillar method & the emphasis was made on development galleries having different roof rock characteristics.

Sample Selection and Study Area

Field studies were carried out in the Jharia and Raniganj coalfields which are one of the largest coal producing areas in India. The Jharia Coal Field (JCF), the largest coalfield of India, is situated in Dhanbad district, Jharkhand state and stretches over an area of about 38 x 18 km east–west to north–south with an area close to 450 km² (Paul et al., 2014). Mine areas were chosen according to the criteria of existing extraction, diversity of geological backgrounds and the presence of tunnels for development with different widths. Underground sites were sampled from mines of Bharat Coking Coal Limited and Tata Steel Limited. Gallery widths are 3.6 m to 4.8 m in traditional power mining and cover depth of range 80m-380m.

Geotechnical Characterization Tools and Techniques

Geotechnical characterization was made at the field and laboratory scale. The in-situ studies included detailed geological mapping of roof outcrops, discontinuity spacing and orientation measurement, structural feature characterization, and groundwater seepage characteristics. Between these two boreholes, the Rock pieces were extracted in an ordered manner from immediate roof orthogonal routinely for laboratory tests. Laboratory testing covered UCS tests as per Bureau of Indian Standards, slake durability tests with standard equipment following ASTM D 4644 procedure, and rock density measurement. The slake durability test consisted of placing a sample of lumps representative (450-550 g) in a steel rotating drum which, after two cycles of wetting and drying, and once dry the first cycle slake durability index was calculated as% by weight retained to the initial state. The CMRI-ISM RMR classification (Venkateswarlu et al., 1989) was adopted for rock mass rating. These five parameters were layer thickness, structural categories (determined by weather ability with quantity of first-cycle SDI), groundwater condition (observed from drilling 1.5- or 1.8-m holes and recording percolation rates in mL/min) and compressive strengths. The rate of subways and the number were classified according to the Classification Tables, with suitable corrections for depth; lateral stress, induced stresses (excavation manner), gallery spacing.

Data Collection and Analysis Techniques

Systematic documentation of geotechnical parameters was carried out in data collection at each field location. Field data sheets included the dimensions of galleries, thickness of coal seams, cover depth, observed rock type, and discontinuity classification, manifestation of groundwater, and structural features. The laboratory test results consisted of unconfined compressive strength values, Slake durability index and weight loss, and various density determinations. Rock Load: Rock load was estimated using empirical equations established for Indian coal mine conditions (Paul et al., 2014). RMR values adjusted with the weather ability influence using the ISM-CMRI field correlation were utilized to determine rock loads for galleries and junctions using the established RMR versus rock load equations for these in alignment with field conditions. Statistical Analysis: Statistical analysis was carried out using standard regression techniques to determine correlation coefficients and validate the relationship between weather ability-adjusted RMR values and control-mobilized rock loads. The analysis was based on data categorization according to the width of the gallery and the range of values. Statistically adequate fits were identified by R-Squared (R^2) and t-test for which assessed the significance at the 95% confidence level.

5. RESULTS

Geotechnical Characterization Results

The data set was obtained through extensive field investigations and subsequent laboratory testing across Indian coalfields, including borehole drilling and sampling with a 1 m spacing. The immediate roof rocks sample were shown to be compositionally and physically different. The layer thickness varied from 0.15 m to 1.80 m. Uniaxial compressive strength of immediate roof rocks was from 18 MPa to 95 MPa, which was used as a measure of immediate roof strength and signal of the heterogeneity of coal measure strata. Weather ability assessment slake durability testing also showed extensive variability. First-cycle SDI values lie between 85% and 99%, with shale dominated roof rocks expanded lower SDI due to higher clay content, making them more prone to slaking degradation. Groundwater seepage measurements indicated percolation rates from 0 mL/min to 45 mL/min with higher seepage corresponding to lower SDI. The CMRI-ISM RMR values calculated for the selected locations lay between 35 and 68, categorizing the roof terrain from poor to fair quality. Furthermore, weather ability was found to be the parameter with a statistically significant contribution to variability, in conditions of Indian coalmine geology.

Rock Load Estimation Analysis with Data Tables

Based on adjusted CMRI-ISM RMR values and established empirical relationships, rock load estimation for development galleries was performed. According to Paul et al., the evaluation was performed stratified by gallery width and roof rock density. Table 1 presents rock load estimation for the figure of 3.6 m gallery category width for different RMR values and weather ability conditions.

Table 1: Rock Load Variation for 3.6 m Gallery Width (Based on Paul et al., 2014)

Mine Location	RMR Value	Density (t/m^3)	Rock Load (t/m^2)	Weather ability Grade
Site A	42	2.35	4.92	Moderate
Site B	38	2.28	5.58	High
Site C	51	2.40	3.45	Low
Site D	45	2.32	4.28	Moderate
Site E	48	2.37	3.86	Low

The RMR values are inversely correlated with the mobilized rock loads as indicated from Table 1 above. The lower the RMR values meaning the highly weather ability susceptibility, the higher the rock load. Site B with 38 RMR had a mobilized rock load of 5.58 t/m2 while Site C with 51 RMR had a mobilized rock load of 3.45 t/m2. This indicates the weather ability impact on rock load behavior indicating highly weather able roof rocks that require substantial support provision..

Table 2: Rock Load Correlation for 4.2 m Gallery Width (Based on Field Data)

Mine Location	RMR Value	Density (t/m^3)	Rock Load (t/m^2)	Gallery Depth (m)
Site F	44	2.15	5.35	185
Site G	52	2.48	3.72	225
Site H	41	1.95	5.82	165
Site I	49	2.25	4.18	195
Site J	46	2.32	4.65	205

The data presented in Table 2 for the 4.2 m gallery width reveal the similar patterns of weather ability on the magnitude of the rock load it brings. In general, this span reveals high rock loads compared to 3.6 m galleries, especially if they have the same RMR values and the same weather ability factor. In this case, site H is characterized by RMR 41, which projects the high value of rock load, equaling 5.82 t/m². In the meantime, site G, with RMR 52, projects the reduced rock load, 3.72 t/m². The difference can also be explained by density fluctuations, which vary from 1.95 t/m³ to 2.48 t/m³, with higher densities of the roof rocks mobilizing larger rock masses.

Table 3: Rock Load Assessment for 4.8 m Gallery Width

Mine Location	RMR Value	Density (t/m³)	Rock Load (t/m²)	Structural Features
Site K	47	2.42	5.22	Moderate
Site L	54	2.50	3.85	Favorable
Site M	43	2.18	5.95	Unfavorable
Site N	50	2.38	4.38	Moderate
Site O	45	2.30	5.45	Moderate

The greater rock load ranged from3.85 to 5.95 t/m²(Table 3) For the upper limit WKm parameters of conventional gallery size=4.8 m, which was heavily different as Table 3 (Wells and Cording, 1997). In particular, site M (with a lower RMR index and negative engineering properties) had the higher rock load of 5.95 t/m² due to improved weather ability mechanisms subsumed under site M and this issue was reflected by this case that cited the dangerous geo technics in figure 20 has some progress tendency toward high synergy. Rock loading for L, with the highest quality of rock mass RMR 54 was lower as well and reached3.85 t/m².

Table 4: Junction Rock Load Analysis

Junction Location	RMR Value	Density (t/m³)	Rock Load (t/m²)	Junction Type
Junction P	40	2.28	7.12	T-junction
Junction Q	48	2.40	5.45	Cross-junction
Junction R	44	2.22	6.28	T-junction
Junction S	51	2.45	4.92	Cross-junction
Junction T	46	2.35	5.85	T-junction

Load calculations (attachment rock) for junction rock as presented in Table 4 show high loads compared to straight galleries owing to increased reach and stress intensification. Junction types undergo multi-way redistribution, leading to greater mobilization of rock load. Influence of weather ability could still be observed, where it was found that joints with smaller RMR values had significantly high rock loads (Singh et al 2003). Junction P with (RMR 40) rock load (7.12 t/m²) required greater support measures than Junction S that has RMR of 51 and corresponding rock load of 4.92 t/m².

Table 5: Statistical Correlation between RMR and Rock Load Parameters

Gallery Width (m)	R^2 Value	Standard Error (t/m²)	Equation Type	Sample Locations
3.6	0.87	0.42	Linear	15
4.2	0.89	0.48	Linear	18
4.8	0.86	0.54	Linear	12

In Table 5, the statistic correlation analysis is given on the relationships between RMR motivated from weather ability and mobilized rockloads (Paul et al., 2014). Values of the coefficient of determination (R^2) were between 0.86 and 0.89, reflecting strong linear consistencies among variables. These large values of R^2 are the confirmation that the CMRI-ISM RMR system by integrating weather ability parameters could predict rock load properly. The standard errors of the estimates were relatively low (0.54 to 0.42t m\-2), showing that the estimated values would be quite acceptable for practical mine engineering purposes.

Table 6: Weather ability Categories and Rock Load Relationships

SDI Range (%)	Mean RMR	Mean Rock Load (t/m²)	Category	Observations
85-88	41	5.52	High Weather ability	11
89-92	47	4.42	Moderate Weather ability	19
93-99	53	3.58	Low Weather ability	15

For the levels of weather ability, Table 6 classifies each site where it was studied the existence of crystalline structure and show clear patterns to mobilize rock load. High weather ability class (SDI range 85-88%) had mean rock load of 5.52 t/m² and it was approximately 54% higher loads than low weather ability class (SDI ranging from 93-99%) with mean rock load of 3.58 t/m² (Franklin & Chandra, 1972). The moderate weather ability group had similar behaviour with an average rock load of 4.42 t/m². This systematic deviation highlights the value of weather ability assessment to the optimization of support design.

Statistical Validation and Empirical Relationships

Regression analysis established empirical correlations between CMRI-ISM RMR values and rock loads for various gallery widths, considering effects of weather ability (Paul et al., 2014). For 3.6 m gallery width, the correlation relationship was strongly positive ($R^2 = 0.87$ and p-value < 0.05), which is statistically significant. Analogous relationships for 4.2 m and 4.8 m gallery widths resulted in R^2=0.89 and R^2=0.86, respectively, confirming consistency of weather ability effect among environmental conditions. The t-test analysis indicated that the weather ability parameter can be used as a significant factor to differentiate rock load behavior among locations. The obtained t-values exceed the critical value at $p = 0.01$ level of significance, and null hypothesis that weather ability has no influence is rejected. Validation by application to case studies confirmed the predictive power of developed relationships (Bieniawski, 1989). Means absolute error of prediction based on rock mass strength-parameter–incorporated equations was 6.8%, which is more reliable over field measured data, and the estimated values are very acceptable for practical engineering cases.

6. DISCUSSION

The findings in the study suggest that weather ability is a significant factor affecting rock loading response changes in bord and pillar mining. The observed negative relation between slake durability index values and mobilized rock loads is in line with basic rock mechanic concepts (Franklin & Chandra, 1972). More weather able rocks also experience strength loss due to wetting, which increases the severity of their weakening and self-supporting load, both requiring higher support loads (Molinda and Mark, 1996). The very high differences in rock loads between weathering classes can have significant effects on the safety and economics of a mine. Sites classified as high weather ability had average rock loads about 54% more than those of low weather ability (Venkateswarlu et al., 1989). Such a variance thus requires to make suitable amendments of the type and magnitude of support provided. An inability to properly characterize the time-dependent phenomena of weather ability degradation could lead to occurrences of roof instability with detrimental legal and financial implications for worker safety and productivity. The near constancy in the effect of weather ability on gallery widths ranging from 3.6 m to 4.8 m wide indicates the stability and strength of this relationship. Larger gallery widths led to higher absolute rock load, but the relative role of weather ability was constant (Paul et al., 2014). This result indicates that the weather ability assessment methodologies developed for standard gallery widths can be transferred to wider galleries in mechanized mining operations.

The study also revealed substantial weather ability x groundwater interaction. Sites with high weather ability (low SDI) and higher ground water seepage showed combined effects on mobilization of rock load (Singh et al., 2003). This point illustrates the significance of integrated geotechnical analysis by taking inter-relationship between various parameters into account instead of treating single factor at a time. Further comparisons with the international rock mass classification systems have indicated some common aspects of the CMRI-ISM RMR method and at the same time highlighted certain unique features of these (Ghosh &Ghose, 1992). In the U.S. coalfields, the Coal Mine Roof Rating (CMRR) system also includes moisture sensitivity as a key factor. But the CMRI-ISM RMR system uses quantitative slake durability test for weather ability estimation in a more objective way than qualitative moisture sensitivity rating. The derived empirical equations of RMR vs rock loads show application for the designing optimization of supports (Sheorey, 1997). The high statistical correlations ($R^2 > 0.85$) provide good confidence in predictive ability and low standard errors demonstrate a reliable prediction of rock load. Incorporation of such relationships into automated support design systems could potentially lead to improved efficiency in mine planning operations.

7. CONCLUSION

The present research further develops the relevant empirical base to quantify weather ability as an impactful parameter affecting rock load variance bord and pillar geo mining conditions. The completion of Indian coalfields, intrusive laboratory testing, and rigorous data analysis contributed to measuring large weather ability impact on rock load mobilization around development galleries. The study proved that higher weather ability conditions lead to approximately 54% higher mean rock load compared to lower weather ability conditions. Strong statistical relationships were discovered between varying weather ability-influenced RMR values and resultant mobilized rock loads regardless of associated galleries' widths, coefficients of determination equal 0.86-0.89. These findings prove that weather ability is recurrent, predictable, and can be reliably determined with the help of a weathering probe used in parallel studies. Therefore, the practical implications of the current study indicate that it is imperative to assess weather ability routinely during coal mine development planning. The implications of not accounting for weather ability will result in either insufficient support provision leading to safety risks or excessive over-supporting inducing unnecessary funds spending. Therefore, the empirical findings of the current study allow engineers to optimize support design through accurate assessment and application of weather ability-dependent rock load variances.

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