

Abstract

Approximately 160 coal mines in India continue to produce 35 million tons of coal annually using the Bord and Pillar mining technique. The Bord and Pillar method remains the most widely used technique for underground coal extraction in India, given the country's geo-mining conditions. This method consists of two key phases: the development phase, where galleries are constructed to form coal pillars, and the depillaring phase, during which these pillars are systematically removed to extract the coal. Both stages of underground coal mining face significant risks, with roof and side falls being common types of failures. Roof falls typically occur when the immediate roof strata detach, a result of stress redistribution around the excavation. On the other hand, side falls are more common at greater depths, where high-induced stress is prevalent. Managing strata movement is crucial for ensuring safety in underground mining operations. In underground mines, weak and layered roof strata are major contributors to roof failures, particularly in development headings, affecting both productivity and safety.

Geo-mechanical classification of the roof of an underground coal mine is of utmost importance for the assessment of the roof support requirement. 44 published cases of the Indian coalfield have been taken for analysis. It has been observed from the cases that stand-up time with *CMRI-RMR* classification is not properly correlated, particularly for short-term stable cases. After re-looking at the data set, it has been perceived that the influence of a single weak parameter is sufficient to reduce the strength of the roof rock mass. Therefore, the summation of the ratings for estimation of the overall rating of the rock mass is not appropriate. Keeping this in mind, a new geotechnical classification of the Coal Roof Index (*CRI*) has been proposed, based on the multiplication of individual parameter's rating. A multiple regression analysis has been done by considering five

independent parameters and one dependent parameter and using the developed new equation to assess the rating range. An adjustment has been proposed based on the stress conditions and dimensions of the gallery.

This study reveals that the newly developed classification system has shown a good correlation with recorded stand-up time compared to the *CMRI-RMR* classification. The range of the proposed *CRI* classification varies from 0.001 to 3000. It has been divided into five classes. An exponential correlation between the proposed *CRI* and *CMRI-RMR* has also been observed.

The numerical method is one of the most advanced tools for the prediction of roof rock behaviour and estimation of strength parameters. Generally, rock failure passes through three phases such as elastic, plastic, and strain softening. The state of failure changes with time. Therefore, to understand the behaviour of rock failure, mostly the peak strength, plastic strain at failure, and residual strength are needed. The rock failure is discussed in two parts. In the first part, to deduce the peak strength parameter in terms of proposed classification, a hypothesis was made that rock behaves elastic-perfectly plastic manner. It is well understood that plastic strain is a function of time. If the observed plastic strain is high, then the stand-up time is shorter. In the second part, the dynamic behaviour of rock mass is studied, and the strength deterioration with time is assessed considering the elastic-perfectly plastic-strain softening rock material. A time-dependent constitutive model has been developed by considering critical plastic strain for immediate failure ($\epsilon_p > 5 \times 10^{-3}$). In this study, the author has adopted the Hoek-brown failure criteria for coal galleries.

The proposed *CRI* classification is a prime input parameter. Numerical approaches take into account data from 35 stable and failed cases. The author initially determined the range of the 's' parameter based on short-term stable cases (stand-up time < 90 days) and

subsequently refined the range of the '*m*' parameter by analysing long-term stable cases (stand-up time > 365 days). The final formulation of the peak strength parameter was refined through the analysis of all 35 cases. Various function combinations of peak strength parameters were simulated, and the resulting plastic strain values were obtained. The best-fit curve was derived through back analysis, and it was proposed that the relationship between the strength parameters and the *CRI* classification follows an exponential form, enabling the estimation of the Hoek-Brown strength parameters (*m*, *s*, and *a*). Three zones of the critical plastic strain categorised for immediate roof failure cases ($\epsilon_p > 5 \times 10^{-3}$), critical plastic strain for short-term stable cases ($1 \times 10^{-3} < \epsilon_p < 5 \times 10^{-3}$), and critical plastic strain for stable cases ($\epsilon_p < 1 \times 10^{-3}$) in the immediate roof.

The study also suggested an empirical relationship for rock load at the gallery from *CRI* classification, with an impressive coefficient of determination of 0.85. The rock load is measured by the multiplication of the roof rock density and *RLH*. Thus, an appropriate support resistance can be calculated. The validation has been done by considering 5 Indian coal mine cases, among which 2 are stable and 3 are unstable.

Further, this study extended to evaluate the dynamic behaviour of roof rock with time. The effect of time-dependent properties on the reduction of roof resistance in coal mines is a significant issue that needs careful consideration. A time-dependent constitutive model has been developed to analyse the effect of time on the deterioration of rock strength. The rock mass strength properties reduce over time with plastic strain. A time-dependent elastic-perfectly plastic-strain softening (*TDEPPSS*) constitutive model of the coal is developed using the Hoek–Brown constitutive model. An *FDM*-based numerical modelling approach was considered by using *FLAC3D* to implement the proposed constitutive model. 34 Indian case studies (21 short-term stable and 13 long-term stable) were chosen to evaluate the reduced strength parameters of the coal roof using back

analysis. In the numerical simulation, the life of the failed cases was considered when vertical displacement reached 20 mm. According to field observations, when a vertical displacement of nearly 10 mm is observed, additional support is required. Therefore, critical displacement for roof failure was considered to be 20 mm in this study. The non-linear exponential function has been proposed to calculate the strength parameters (m_{rmt} and s_{rmt}) over time. The time-dependent constitutive model helps design an underground coal gallery and optimises the cut-out distance in continuous mine operation. The developed *TDEPPSS* constitutive model is suitable for assessing a coal roof's strength deterioration and creep behavior with time.