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Rib stability: A way forward for safe coal extraction in India

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A B S T R A C T

Ensuring rib stability during pillar extraction is of prime importance in bord and pillar (B&P) method of underground coal mining with caving. Rib stability has been assessed here by way of assessing factor of safety (FOS), a ratio of the strength of rib to stress on it. Earlier formulations for rib stability when applied to case studies gave very low FOS value suggesting significant ground control problems, which were contrary to the field observations. This has necessitated the need to revisit the concept of rib stability. The stress coming on the rib is estimated with the use of numerical modeling technique using the FLAC^{3D} software. The methodology of assessing rib-stability with the help of suggested rib-strength formulation has been validated at eight Indian coal mines. The outcome of this study finds relevance and importance in ensuring underground coal liquidation with improved safety and conservation.

1. Introduction

Majority of coal reserves in India are amenable to underground mining. The government of India (GoI) has an ambitious plan to increase underground coal production from 35 Mt/year (current) to 100 Mt/year (by 2019). CSIR-Central Institute of Mining and Fuel Research (CSIR-CIMFR), the only premier research institute of its kind in India, has kept "development and adoption of coal production technology (especially related to mass production) in underground mining" as an important thrust area of research. Earlier, as well as ongoing scientific studies undertaken by CSIR-CIMFR, are systematized to provide research and development (R&D) backup to the coal mining industry. However, during such studies, it was found that there is still a gap in understanding the rib (also known as a fender) stability in geo-mining perspectives. Oft-times when the gap in the past became blind spot, the accidents occurred resulting in fatalities. In this context, it may be noted that the bord & pillar (B&P) method of coal mining is most commonly practiced in India and has a lion's share (more than 95%) of current underground coal production [1]. In B&P, liquidation is based on rib-and-slice depillaring method, as shown in Fig. 1. The liquidation methodology consists of dividing a pillar into two or more stooks by driving split-roadway(s) along the level and taking 4–5 m wide slices while leaving ribs against the goaf as temporary natural supports. This reduces the quantum of erecting artificial supports to an optimum level. The ribs, being natural structures, play a vital role in understanding strata and their management. Fast re-distribution of mining-induced stresses caused due to increased mechanization like deployment of continuous miner - a mass production technology, commends the use of ribs with "optimum" stability for safe and smooth depillaring.

The "optimum" stability and aspects of rib design have always been a challenge to a rock-mechanics designer in respect of coal pillar extraction in India, more so because of uncertainties and vagaries of rock strata and their behavior. It was observed that the unsupported area (i.e., "goaf" - defined as the area where there is no lawful access) gradually increases till a "threshold" value after which the nether roof collapses. This is defined as the critical area of collapse (CAC), also known as "mainfall" in local parlance with the idea that the men and machine need to be at a safer distance before such a collapse takes place. Understandably, the characterization of overlying roof strata is essential, especially within the vertical extent of caving height varying from $4h$ to $6h$ (where h is the height of extraction in meter) on an average from the roof line of the coal seam under consideration [2]. Rock Quality Designation (RQD) became a ready-to-use rough yardstick for characterization of overlying roof rocks [3]. The selection of RQD was mainly due to the fact that it can be easily determined from the borehole lithology of the area at mine-sites. Fortuitously, a linear regression yielded the following formulations for equivalent face advance, a_{eq} (minimum exposure for mainfall to occur in meter), which is shown in Eq. (1):

$$a_{eq} = 0.59RQD + 5.2 \quad (1)$$

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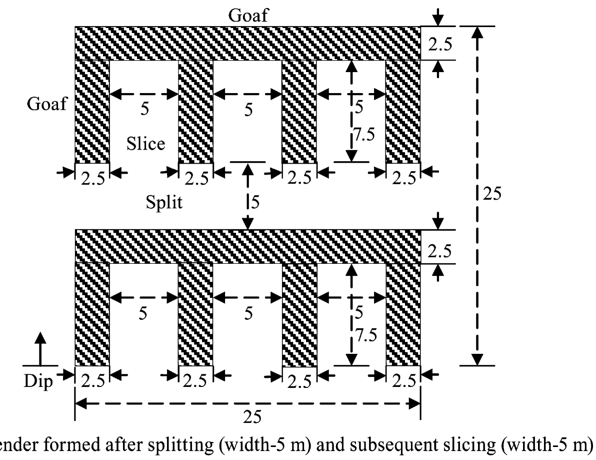

Fig. 1. Representative coal pillar (size 25 m × 25 m corner-to-corner) depillaring layout with average rib-size of 2.5 m shown by hatching (not to the scale).

Eq. (1) had a correlation coefficient of R^2 = 0.975 when the study comprised of 15 case-studies of coal extraction in Indian coal mines. The time-periods of these case-studies were confined to the period between nationalization of Indian coal mines (in 1975) and 1987. These case studies were a part of the Ministry of Coal, GoI, S&T initiatives [4].

The equivalent face advance a_{eq} is representatively shown in Fig. 2, for a diagonal line of extraction in B&P workings. a_{eq} is the linear approximation of the minimum exposure area likely to affect mainfall to occur.

The critical area of collapse (CAC) was further approximated as Eq. (2):

$$CAC \cong \frac{1}{2} \times (2 \times a_{eq})^2 \tag{2}$$

a_{eq} has provided a reasonable estimate with the experiences obtained on many mine sites, wherever CAC not exceeding their respective a_{eq} values, the actual observations were in conformity to the premise. The simple reason was that when the area of unsupported span reached CAC value, the mine officials started taking precautions of withdrawing men and machines and in the "worst-cases" the proactive initiatives of induced blasting to blast down stand-up/hanging goaf in-bye of the workings were incorporated. The mine officials did induced blasting not only for safety reason but it was also statutorily required in Indian coal mines. Therefore, Eq. (2) cannot be validated, as CAC here is only addressing the minimum value and not the actual or optimum.

Having no other option left to the authors, it was decided to consider Eqs. (1) and (2) to calculate the minimum threshold for a coal extraction proposition depending on rock characterization by RQD and further analysis using numerical modeling which has been presented in this paper. In this analysis, the estimation of stress has been made with the use of numerical modeling technique. The tributary area method is not suitable in this regard and hence, not recommended to use during depillaring. Even for development workings, this method over simplifies as it considers only pre-mining vertical stresses, overlooking the effect of stress-redistribution, mining induced stresses, abutment stresses, effect of deformation, failure in roof strata, etc. [5,6]. The strength of rib and stress coming on it are important factors for deciding rib stability. But neither stress coming on rib nor the strength of the rib alone can fully address rib stability. The factor of safety (FOS) i.e., the aspect ratio of strength to stress, should be ascertained beforehand and during extraction for this purpose. The approach described in the paper may be regarded as a conservative approach, more so because CAC being the barest minimum (based on observation) to avoid collapses. However, this approach is found to provide better insight and suggesting design of ribs as Indian coal mines are full of uncertainties and vagaries of rock strata and their behavior. Inter-alia, the frequent changes of mining practices and extraction sequences (not detailed in this paper) further complicate the matter and to err on the side of the safety, this approach may thus be adopted. Further, its veracity may be put on analysis with the recent case-studies with advanced available tools like numerical modeling.

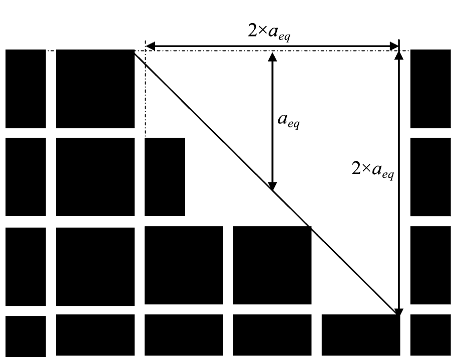

Fig. 2. Scheme of a diagonal line of extraction: area of likely mainfall in bord and pillar workings [4].

2. Assessment of rib stability

Ribs generally have low w/h ratio (w is the width and h is the height of the pillar) and are designed to fail eventually. It is very difficult to generate data related to pertinent and dominant influencing factors of rib strength on-sites [7]. This is the main stumbling block in the way of estimation of rib strength. However, the empirical formulations developed (based on case-studies of 14 failed slender pillar cases) to estimate the strength of slender pillars ($w/h < 4.0$) may be extended to provide a conservative assessment (if used) of the rib strength. As no formula is available for rib strength, it has been decided to use this conservative estimate by using the following empirical formula Eq. (3) [8], for the purpose.

$$S = 0.27 \times \sigma_c \times \frac{\sqrt{W_e}}{h^{0.86}} \text{MPa} \tag{3}$$

where S is the rib strength, MPa; σ_c the compressive strength of coal, MPa; W_e the effective width, m; and h the height of extraction, m. For ribs, the length of the rib (W_2) is much greater than its width (W_1), hence, effective width (W_e) is calculated as Eq. (4) [9]: