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

Singh Satyendra K.*, Agrawal Harshit, Singh Awanindra P.

Mining Methods and Design Simulation Research Group, CSIR-Central Institute of Mining and Fuel Research (CSIR-CIMFR), Dhanbad 826015, India

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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 FLAC3D 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.

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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. Off-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 redistribution 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):

$$a_{eq} = 0.59 RQD + 5.2$$  

(1)
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):

\[
CAC \cong \frac{1}{2} \left( 2 \times a_{eq} \right)^2
\]

\( a_{eq} \) 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 rock 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.

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.

\[
S = 0.27 \times \sigma_c \times \sqrt{W_e \times \frac{W_e}{h}} \text{MPa}
\]

where \( S \) is the rib strength, MPa; \( \sigma_c \) 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 \( (W_e) \) is much greater than its width \( (W_1) \), hence, effective width \( (W_e) \) is calculated as Eq. (4) [9]:

---

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

**Fig. 2.** Scheme of a diagonal line of extraction: area of likely mainfall in bord and pillar workings [4].
Fig. 3. The factor of safety of previously studied mines.

$$W_e = 4 \times \frac{A}{C} \text{ or } 2 \times \frac{W_1 \times W_2}{W_1 + W_2} \tag{4}$$

where $A$ is the area on plan (i.e., $A = W_1 \times W_2$); and $C$ is the perimeter on the plan, i.e., $C = 2(W_1 + W_2)$. It can be proved mathematically that in the case of rib, when $W_2 \gg W_1$, $W_e = \frac{2 \times W_1 \times W_2}{W_1 + W_2} = 2 \times W_1$.

Thus for ribs, where one side of the rib is much greater than the other (low $W_1/W_2$ ratio), the strength Eq. (3) can be modified by replacing $W_e$ in Eq. (3) with $(2 \times W_1)$, we get Eq. (5):

$$S = 0.27 \times \sigma_c \times \sqrt{\frac{2 \times W_1}{h^{27}}} \text{ MPa} = 0.4 \times \sigma_c \times \sqrt{\frac{W_1}{h^{27}}} \text{ MPa} \tag{5}$$

The FOS is calculated as Eq. (6):

$$\text{FOS} = \frac{S}{P} \tag{6}$$

where $S$ is the rib strength, MPa; and $P$ is the stress coming on the rib, MPa.

The primary objective of the rib-stability assessment is to meet the basic purpose of the rib, i.e., providing adequate safety to men and machine during depillaring workings on short term basis and providing no resistance to caving if not ‘judiciously’ reduced during retreat after the extraction is complete on the in-bye side of slice (s). Based on experience gained in B&P depillaring workings, a range band of FOS is taken as 0.6–0.9 for rib stability in case of (SDLs) and load haul dumpers (LHDs). This band is taken based on the purpose of rib and also on the fact that FOS should be less than 1.0. If FOS is less than 0.6, it suggests that the ribs are unstable and hence, may not be able to withstand the mining induced stress during active slicing [10]. The FOS more than 0.9 is not warranted as it may expectedly jeopardize the second purpose stated above. Fortuitously, the ribs so formed within the FOS band range have been empirically derived from failed cases of slender pillars and not of ribs, thus conservative. On this conservative note, Fig. 3 shows the calculated FOS values of ribs in different mines as detailed in Table 1.

3. Field observations

Contrary to the inference from Fig. 3 which suggests that the ribs are likely to fail as their FOS values are very low (less than 0.6), the actual observations at the mine-sites belowground were found to be of smooth and safe depillaring without any significant ground control problem, i.e., no roof and side falls, side spalling, floor heave, etc. As mentioned earlier, the strength of ribs is here underestimated as being conservative. This necessitated the need to revisit the concept of rib-stability for improved understanding of rib behavior during depillaring of a coal seam. A revisit of this kind has two important parameters $S$ and $P$ which need to be considered as per Eq. (6). The numerical modeling approach using FLAC3D with engineering judgments has a high potential to estimate $P$ where redistribution of mining induced stresses, extraction in nearby slices, geo-mining details, etc. are duly taken into consideration [11]. However, the aspect of estimation of rib-strength is addressed by an empirical approach with the help of recent research studies in different coal mines and thus modifying Eq. (5).

4. Numerical modeling

Numerical modeling is a popular, powerful and handy mathematical tool for solving complex geotechnical and mining related issues with availability of bespoke software. Finite difference based FLAC3D software of Itasca, USA is being extensively used in the mining industry as it offers flexibility to choose from a wide range of constitutive models [12]. It is easy to re-run and helps in result optimization [13]. FLAC3D with its time-stepping approach has been used in this study for stress analysis and assessing the influence of different geotechnical parameters on the stability of ribs [11,14].

Input parameters are vital for any numerical modeling exercises. Before applying any numerical modeling technique, all the geo-mining conditions pertaining to the basics of given geotechnical problem (here rib-stability) need to be defined [13]. These parameters mainly include the geometry of the area to be studied, rock properties (like elastic modulus, strength, RQD, etc.) for each stratum, pre-excitation in-situ field stresses, etc. [10]. Necessary boundary conditions need to be applied and meshing as per the dictate of the software is to be properly done.

The scheme of borehole lithology considered for the modeling is shown in Fig. 4 [10]. Different rock layers have been simulated in the model and loaded as per material properties, as given in Table 2 [10]. The different parameters considered during parametric analysis have been listed in Table 3 [10]. The modeling assumptions, detailed methodology, loading conditions and related aspects have not been detailed in this paper to conserve the space and it is described elsewhere [15]. The entire area coming under CAC, calculated using Eq. (2) has been made instantaneously null to simu-

### Table 1

<table>
<thead>
<tr>
<th>Name of mine</th>
<th>Depth, $H$ (m)</th>
<th>Extraction height (m)</th>
<th>Rib Width, $w$ (m)</th>
<th>Roadway width, $B$ (m)</th>
<th>Length of rib, $L$ (m)</th>
<th>$\sigma_c$ (coal, MPa)</th>
<th>CAC (m²)</th>
<th>FOS (Eqs. (5) &amp; (6))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bankola</td>
<td>85</td>
<td>3.60</td>
<td>2.60</td>
<td>4.50</td>
<td>6.30</td>
<td>28.0</td>
<td>4232</td>
<td>0.33</td>
</tr>
<tr>
<td>Shyamsundarpur</td>
<td>131</td>
<td>3.60</td>
<td>2.47</td>
<td>4.20</td>
<td>6.50</td>
<td>29.0</td>
<td>3763</td>
<td>0.25</td>
</tr>
<tr>
<td>Satgram Inc</td>
<td>110</td>
<td>2.40</td>
<td>2.17</td>
<td>4.50</td>
<td>5.50</td>
<td>37.0</td>
<td>3600</td>
<td>0.27</td>
</tr>
<tr>
<td>Gorawari</td>
<td>243</td>
<td>4.50</td>
<td>2.28</td>
<td>4.20</td>
<td>11.10</td>
<td>28.0</td>
<td>3000</td>
<td>0.10</td>
</tr>
<tr>
<td>Nandan mine</td>
<td>230</td>
<td>4.40</td>
<td>2.08</td>
<td>3.60</td>
<td>11.20</td>
<td>30.0</td>
<td>4000</td>
<td>0.11</td>
</tr>
<tr>
<td>Saoner mine</td>
<td>71</td>
<td>4.80</td>
<td>2.00</td>
<td>4.00</td>
<td>7.50</td>
<td>23.0</td>
<td>2100</td>
<td>0.24</td>
</tr>
<tr>
<td>Satpura mine</td>
<td>104</td>
<td>3.00</td>
<td>1.93</td>
<td>4.80</td>
<td>8.35</td>
<td>31.0</td>
<td>9000</td>
<td>0.25</td>
</tr>
<tr>
<td>Muralidih</td>
<td>265</td>
<td>2.85</td>
<td>1.90</td>
<td>4.50</td>
<td>10.75</td>
<td>27.8</td>
<td>5400</td>
<td>0.10</td>
</tr>
</tbody>
</table>
late maximum stress abutment coming on the in-by the most ribs. The direction of mining has been considered from goaf to solid as it is generally followed in the industry. Sheorey failure criterion has been used since it is suited for soft rocks like coal measure strata and has been developed on elasto-plastic modeling [16]. The effect of the blast-induced damage (like cracks) has not been considered, though the blast-induced cracks may propagate around 0.3 m length in pillars/ribs all along.

5. Modeling results

A recent study was taken up under Ministry of Coal, GoI, S&T initiatives. Extensive numerical modeling was done under the project generating sufficient data bank to analyze the rib behavior by way of assessing the FOS. It can be observed from Fig. 5a, that the FOS has a very low value which further decreases with increasing depth of cover applicable for different parametric variations (Table 3). A multiplying parameter \( \alpha \) was introduced in the Eq. (5) by selecting 8 (out of many) depillaring situations, where smooth depillaring was observed in each case. The modified equation is:

\[
C_p = 0.4 \times \sigma_c \times \alpha \times \sqrt{\frac{W_c}{H}} \text{ MPa}
\]  

(7)

where \( C_p \) is the rib strength, MPa; \( \sigma_c \) is the compressive strength of coal, MPa; \( \alpha \) is a multiplying parameter addressing the variation in \( K \)-ratio and increased stress concentration; \( W \) is the effective width, m; and \( h \) is the height of extraction, m.

"\( \alpha \)" can have an attributed value of 3.2 (for depth up to 160 m) and 6.9 (for depth more than 160 m). As the ratio of pre-exca-vation in-situ horizontal stress to pre-exca-vation in-situ vertical stress also known as “\( K \)-ratio” has a break even at 160 m [17]. \( K \)-ratio > 1 (for depth less than 160 m), \( K \)-ratio = 1 (at depth of 160 m) and \( K \)-ratio < 1 (for depth higher than 160 m).

A variation in FOS has been presented in Fig. 5b using modified formulations with average stress found from numerical modeling studies. The modified formulation was also tested with the case-study results in Table 1 and the observations have been presented in Fig. 6. It can be seen that the FOS value of almost all the mines lies in desired stable range and mostly within the FOS band (0.6–0.9) which propose smooth depillaring as observed during site investigations.

6. Conclusion

With technological advancements, the production programs for opencasting are now being planned for a depth of cover up to 250 m or so. Expectedly, the underground coal production has to be augmented for a depth of cover 250 m or more. Earlier estimation of the strength of ribs, based on empirical formulae developed for slender pillars, was lop-sided towards shallower depths and may not be applicable for the future underground coal extraction. In this paper, a modified formulation for calculation of rib strength for higher depths of working is suggested with the introduction of a multiplying parameter \( \alpha \). \( \alpha \) addresses the effect of \( K \)-ratio and stress concentration as the depth of workings go beyond 250 m. It was observed from earlier case studies that the FOS of ribs were low (less than the temporary stable band range of 0.6–0.9), which suggested severe ground control problems. Contrary to that, smooth and safe depillaring was observed in all the cases, as mentioned in the text. It was therefore concluded that the rib strength was being underestimated. With Eq. (7) suggested in the paper, the rib strength is being rationally estimated and so is the rib stability. It is expected to optimize coal recovery without offering any significant resistance to impending caving, ensuring proper strata management. Successful field validation of a depillaring panel with the

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**Table 2**

Material properties of different rock strata used for parametric study [10].

<table>
<thead>
<tr>
<th>Nature of floor</th>
<th>Young's modulus, ( E ) (GPa)</th>
<th>Poisson's ratio, ( v )</th>
<th>Bulk modulus, ( K ) (GPa)</th>
<th>Shear modulus, ( G ) (GPa)</th>
<th>Density, ( \rho ) (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor sandstone</td>
<td>4.000</td>
<td>0.25</td>
<td>2.67</td>
<td>1.600</td>
<td>2230</td>
</tr>
<tr>
<td>Coal Seam</td>
<td>2.000</td>
<td>0.25</td>
<td>1.34</td>
<td>0.800</td>
<td>1290</td>
</tr>
<tr>
<td>Coarse Grained Sandstone</td>
<td>3.000</td>
<td>0.25</td>
<td>2.00</td>
<td>1.200</td>
<td>2203</td>
</tr>
<tr>
<td>Medium Grained Sandstone</td>
<td>4.000</td>
<td>0.25</td>
<td>2.67</td>
<td>1.600</td>
<td>2230</td>
</tr>
<tr>
<td>Fine Grained Sandstone</td>
<td>2.000</td>
<td>0.25</td>
<td>1.34</td>
<td>0.800</td>
<td>1780</td>
</tr>
<tr>
<td>Shale</td>
<td>2.000</td>
<td>0.25</td>
<td>1.34</td>
<td>0.800</td>
<td>1290</td>
</tr>
<tr>
<td>Goaf material</td>
<td>0.605</td>
<td>0.1</td>
<td>0.25</td>
<td>0.275</td>
<td>1200</td>
</tr>
</tbody>
</table>

**Table 3**

Parameters considered for numerical analysis [10].

<table>
<thead>
<tr>
<th>Variable parameter</th>
<th>Depth of working, ( H ) (m)</th>
<th>Pillar size (m)</th>
<th>Rib size (m)</th>
<th>Seam thickness (m)</th>
<th>RQD of cavable roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed parameter</td>
<td>Gallery width (m)</td>
<td>Compressive strength of coal, ( \sigma_c ) (coal, MPa)</td>
<td>Pre-exca-vation in-situ horizontal stress, ( \sigma_h ) (MPa) [17]</td>
<td>Pre-exca-vation in-situ vertical stress, ( \sigma_v ) (MPa) [17]</td>
<td>Cavability</td>
</tr>
<tr>
<td></td>
<td>28.8, 48</td>
<td>1.6, 2.4, 3.2</td>
<td>3, 4, 6, 8</td>
<td>40, 60, 80</td>
<td>30°, 50°, 70°</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>30</td>
<td>2.4 + 0.01H</td>
<td>0.025H</td>
<td></td>
</tr>
</tbody>
</table>
modified formulation will help to get optimal rib dimensions for an underground B&P method of mining. The modified formulation has provided exciting results when tested with earlier case-studies. It would be better if a stress-estimation formula is also suggested after necessary parametric analysis. More case studies would be taken up by the authors as per future underground production program and then it may be possible to come up with a new formulation of stress estimation. Since the coal production was augmented in India by opencasting (having a share as high as 85% or so) in the past decades, the case studies of underground coal extraction could not be obtained. In general, the mines are developing around 3 times more than what they are depillaring (calculated in terms of area on plan). It is recommended to go for numerical modeling case-by-case for stress estimation. FOS band (0.6–0.9) is statutorily accepted for rib stability in India. The outcome of this study finds its relevance and importance in actual underground coal liquidation operations, in the sense that if rib has adequate stability, then, there would be less likelihood of coal left in the goaf and will ensure better strata management.

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