Rib Geomechanics : Its impacts in coal pillar extraction

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***Abstract*—In Bord & Pillar (B&P) depillaring, there are redistributions of mining-induced stresses on acontinual basis, primarily with apronounced effect on the natural supports - ribs and stooks. A rib need to be stable on temporary time-frame such that (a) it should provide adequate safety to men and machines during depillaring and (b) it should offer no resistance to caving, even in the worst situation when it is not 'judiciously' reduced during theretreat. The stability of ribs can be estimated through a well-known aspect ratio called factor of safety (FOS), which is thestrength of ribs (S) divided by stress (P) coming over it. The strength of ribs plays a pivotal role in estimating thestability of ribs, depending on geo-mining details, sequences of extraction and related technical/managerial issues in a depillaring panel. This paper suggests a modified rib strength formulation in addition to discussing related issues.Estimation of stress on ribs using numerical modeling with rational engineering judgements and pragmatic simulations have also been briefed in this paper.Case-study of depillaring panels in eight mines, having no pronounced geotechnical problems due to rib stability, have been analysed with the formula presented in this paper.**

Keywords—Underground coal mining, Rib stability, Numerical stress determination, Numerical modelling, Rib mechanics

I. INTRODUCTION

In India, more than 80 % share of coal production comes from opencast mines while the share from underground (u/g) mine is abysmal low[1]. The trend has been similar for past decades (Figs. 1-2). On the other hand, around 70% of total coal reserve now available is amenable for extraction by underground coal mining methods[2].The Government of India (GoI) has an ambitious vision of 1 billion tons coal production by 2020, which cannot be achieved without large scale augmentation of underground coal mining [3]. U/g coal production of Coal India Ltd. (one of the largest coal producing company) is targeted to increase from 36.11MT per year in 2013-14 [4] to 100MT per year by 2020. Underground mass production technology is expected to reverse the prevailing negative growth (since past decades) of underground mining in future (Fig. 3) [1].Technologically advanced methods like longwall with powered supports and mass production technology with a continuous miner (CMs) along with accessories have found great acceptance worldwide. Due to the peculiarity of Indian coal measure rocks, the longwall method though introduced a few decades ago is yet to be technically established in India [5].CM with accessories have been deployed for depillaring in bord and pillar (B&P) workings in Indian coal

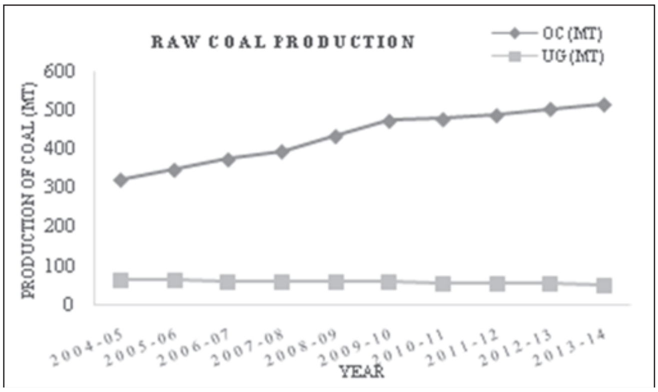

Fig. 1. Comparison of raw coal production from opencast vs underground mines [1]

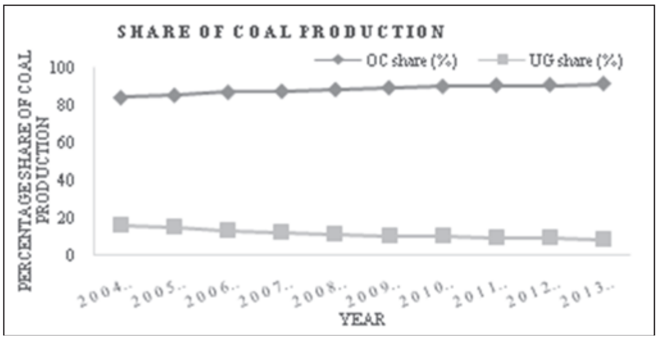

Fig. 2. Comparison of coal production (%) from opencast vs underground mines [1]

Fig. 3. Growth chart of opencast and underground coal mine production [1]

mines, using predominantly pocket-and-fender or split-and-lift method [6]. Till date, a single lift height of depillaring has been restricted to maximum 4.5m with CM deployment, even in the case of a seam being ‘thick-seam’ and developed along the floor. The thick seam may be defined, in India, as a seam having a thickness more than 4.8m [7].

In B&P pattern, the seam is developed by driving galleries/bords on all sides forming pillars.During depillaring, pillars so formed is divided into two or more stooks by driving split (one or two nos. depending on the size of the pillar). The stooks are extracted by taking slices with simultaneous forming of ribs suitably.In the case of high production methodologies like Wongawilli, Christmas tree method, etc. ribsystem of mining isbeing followed without affecting the blockpillar formation and subsequent splitting [8]. The ribsystem of mining means a larger block of rib, which is called here as fender or stooks, having a dimension of length 50-70m, width as high as 11m and height 4.5m. The extraction in such high production methodology is suitably planned with putting in place the successive slicing with rib-dimension similar or higher in comparison to conventional methods. The reduction of these ribs is inbuilt in the methodology. Judicious reduction of the rib is a statutory requirement by the Indian inspectorate [Director General of Mines Safety (DGMS)] [9]. However, it has been observed in a large number of Indian case studies by researchersthat ribs in the range of 2.0-3.0m width (w)are in vogue, serving the purpose (a) and (b) above.

The stability assessment of ribs is of paramount importance, especially when judiciously reduced during retreat i.e., after completion of extraction in the immediate out-bye slice. Before any detrimental nether roof collapse, etches occur on the rib sides especially on the goaf side and consequent fractures provide enough symptoms and warning in order to withdraw men and machines. Moreover, the ‘judicious’ rib extraction is episodic in nature and many time researchers regard ribs being minnows in depillaring operation. However, it may be asserted that proper rib stability will ensure better coal recovery during depillaring. Consequently, the coal not left in the goaf will ensure less likely fire hazards. The aspect of estimation of rib-strength is addressed by an empirical approach with the help of earlier research studies in different coal mines and a new formulation is suggested in this paper.

II. Rib Pillar System

Ribs are formed during depillaring after a pillar is splitted and subsequently sliced. During depillaring, the highest risk is in ribs adjacent to active lift (slicing) and along its in-bye side. The depillaring method is so planned that the span between two consecutive ribs should not cave before in-bye rib is judiciously reduced. The goaf-edges in conventional depillaring are supported by skin-to-skin than 2.0m rib size are construed to be not adaptable, perhaps regarded as unsafe rib dimension. On the other hand, the rib dimension more than 3.0m are not acceptable due to the following reasons.

timber cogs with props at the corners in semi-mechanized depillaring and by bolted breaker lines, i.e., designed 2-3 rows of resin bolts at a denser gridspacing in mechanized depillaring. The idea is also to prevent men from entering in the goaf inadvertently. The purpose of the goaf-edges is to confine caving to the in-bye of the goaf-edge support (skin-to-skin cogs or bolted breaker lines). By and large, a successful rib-pillar extraction can be planned to keep due diligence to the following factors [10, 11].

- Uniform ribs formation
- Length of ribs, dependent primarily on working depth of cover and height of extraction
- Possibility of complete extraction of ribs/stooks, if possible by ‘judicious’ extraction on retreat
- Correct installation of supports (like breaker line) at goaf edges
- Proper dealing of geological anomalies and their special treatment in terms of planning the sequence of extraction and rib-dimension
- Maintaining steady rate of extraction-retreat, as fast as possible.

The enigma remains about estimating the stability of rib during depillaring. Often rib stability is assessed using pillar strength formulations for stress and strength. But the purpose of ribs and those of pillars are different. Ribs are designed for a short-term while, a pillar is generally formed for long-term stability. The higher the width/height (w/h) ratio of pillars, the better is the core confinement and consequently the more is the stability of the pillar under consideration. On the other hand, w/h ratio for ribs are low (slender in nature) and there is hardly any core confinement occurring in ribs. The factor of safety (FOS) of developed pillars should be more than 2.0 during development as mandated for Indian coal mines. While ribs are formed just before final extraction and are for very short period. Many times, the designers have to propose a pillar dimension higher than the statutory requirements (CMR-1957, Reg. 99 (4)) [12], not from FOS point of view but for better-expected ground control during depillaring by the formation of suitable ribs. The earlier researchers used to apply the strength formula of a slender pillar [13] for a depth less than 200m as follows:

$$S = 0.27 * \sigma_c * \frac{\sqrt{w_e}}{h^{0.86}} MPa \qquad (1)$$

Where, S is the rib strength (MPa), w_e is the effective rib width (m),σ_c is the compressive strength of coal (MPa), andh is the height of extraction (m) such that w/h $\leq$ 3.0.

Equation (1) was developed statistically fitting the equation with the 14 failed pillar cases and it was extended to estimate rib’s strength. There is practice in vogue that less

- During the retreat, these ribs are difficult to be judiciously reduced, in the case of drilling and blasting with intermediate technology (i.e., with the deployment of SDL/LHDs). The methodology is inherently slow-paced and of slowretreat nature, but predominantly adopted in India.

- The Indian coal seams have a lower value of incubation period (i.e., the time duration between the first fall after void creation due to extraction and the indication of fire). Increased chances of fire may happen due to spontaneous heating, if coal is left say by not judiciously reducing the ribs.
- The ribs, if not judiciously reduced (say if more than 3.0m), would provide resistance to impending caving. There would be the likelihood of unpredictability at goaf edges resulting into likely 'chase-outs'.

III. Numerical Modelling Analysis

Numerical modelling is a popular, powerful and handy mathematical tool for solving complex geotechnical and mining related issues with availability of bespoke software. The extraction in neighbouring slices, pillars and panels play an important role in numerical modelling. Being a time-stepping procedure, the redistribution of stresses are taken into account simulating the excavation at the minessite belowground after each step. By rational simulation, it is possible to estimate the mining-induced stress. FLAC3D (Fast Lagrangian Analysis of Continua in Three Dimensions),a finite-difference software has been extensively used in the mining industry as it offers flexibility to choose from a wide range of constitutive models [14]. It is easy to re-run and helps in result optimization [15]. The authors have used this software gainfully for simulation of u/g excavation,stress analysis, assessing the influence of different geotechnical parameters on the stability of ribs and subsequent stability analysis [16, 17, 18].

Input parameters are vital for any numerical modeling exercises. Before applying any numerical modelling technique, all the geo-mining conditions and the influencing parameters need to be clearly defined. These parameters mainly include the geometry of the area to be studied, rock properties [like elastic modulus, strength, rock quality designation (RQD), etc.] for each stratum, pre-excavation in-situ stresses, etc. [19]. Necessary boundary conditions need to be applied and meshing as per the dictate of the software is to be properly done [14]. In the model developed for analysis, an excavation block is 'nulled' step-wise representing depillaring operations. Iterations are conducted to ensure that equilibrium conditions are met prior to the subsequent 'nulling' (excavation) [20]. Instantaneous nulling is done to simulate the worst-case scenario of stress coming on the rib. In practice, the extraction is progressive. The rate of depillaring in actual mine scenario can have very slow pace of retreat in case of intermediate technology to comparatively faster in the case of mass production methodology.

It was ensured that the modelling conducted was in line with the field observations and geo-mining geometry. At the same time, it was also ensured to simulate correct mode of deformation and failure [21]. The behaviour of different parameters like depth of working, in-situ stress conditions, pillar sizes, width-to-height (w/h) ratio of ribs, seam thickness, the height of extraction, etc. should be analysed to assess their influence in deciding stability of the ribs and subsequently the mine workings. Numerical models are incomplete representation of real world behaviour [22]. The modeling assumptions, detailed methodology, loading conditions and related parametric analysis results have not been detailed in this paper to conserve the space and it is described elsewhere [6, 19, 23].

IV. Field Observations

Data from field investigations done under a Grant-in-aid project by CSIR-CIMFR were used for analysis (Table 1) [24]. The concept of pillar stability was used to assess rib stability during depillaring in eight different mines. The FOS plot is shown in Fig. 4 suggests ribs likely to fail as their FOS values are very low (less than 0.6) and severe ground control issues. Contrary to the inference from Fig. 4, 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 since, it has been calculated using slender pillar formula. Overdesigning the ribs is not justifiable from coal conservation and subsequent goaf settlement point of view. 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- strength'S'and stress 'P' which need to be considered.

TABLE I. Detail Of Mines For Case-Study

Name of Mine	*Depth (H), m*	*Extraction height, m*	*Rib Width (w), m*	*Roadway Width (B), m*	*Length of rib (L), m*	*σ_c(coal), MPa*	*FOS*
Bankola	85	3.60	2.60	4.50	6.30	28	0.33
Shyamsund-arpur	131	3.60	2.47	4.20	6.50	29	0.25
SatgramInc	110	2.40	2.17	4.50	5.50	37	0.27
Gorawari	243	4.50	2.28	4.20	11.10	28	0.10
Nandan mine	230	4.40	2.08	3.60	11.20	30	0.11
Saoner mine	71	4.80	2.00	4.00	7.50	23	0.24
Satpura mine	104	3.00	1.93	4.80	8.35	31	0.25
Muralidih	265	2.85	1.90	4.50	10.75	27.8	0.10

During depillaring, there is a continuous redistribution of stresses on stooks and ribs, so formed. It is difficult to consider these effect in empirical formulations forcalculating the load on ribs. Tributary area theory (TAT) is an oversimplified approach for calculating load, where the influencing parameters related to redistribution stress during depillaring and subsequent deformations vis-à-vis type and characteristics of roof strata are not considered [25]. Therefore, TAT can not be used for estimation of load on ribs. The numerical modeling approach using FLAC3D with

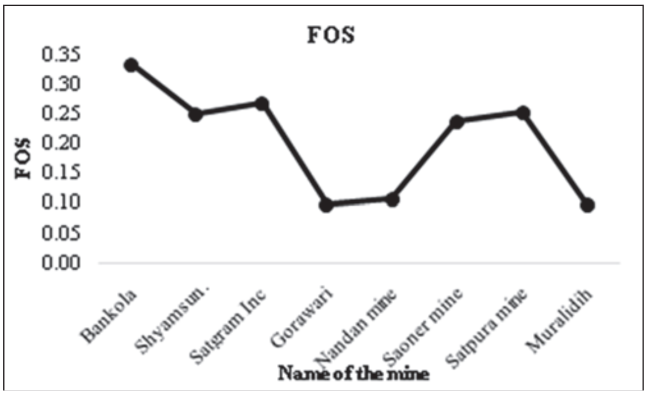

Fig. 4. Factor of safety of previously studied mines

engineering judgements 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 [20].

V. Modification of Strength Formula for Ribs

The slender pillar strength formula (1), was developed based on case-studies of 14 failed pillar casesas described elsewhere [13]. However, the failed pillars considered empirically had a variation of width ranging from 2.8m to 19.8m. These dimensions are unlikely to occur as far as ribs in B&P are concerned, especially at the applicable shallow depth of cover (i.e., <150m). The ribs generally vary in Indian depillaring situation from 2.0m-3.0m. The modification is needed because the ribs generally have low w/h ratio. Its length (w2 – say) is much greater than the width (w1 - say). For such ribs, effective width (we) is calculated as below[26]:

$$w_e = \frac{4*A}{C} \text{ or } \frac{2*w_1*w_2}{w_1+w_2} \tag{2}$$

where,A = Area on plan (i.e. = w1 x w2), C = Perimeter on plan [i.e. = 2(w1 + w2)],

It can be proved mathematically that in case of rib,

when w2 >>w1, $\frac{2*w_1*w_2}{w_1+w_2} \rightarrow 2 * w_1$

Thus, for long ribs, where one side of the rib is much greater than the other (low w_1/w_2ratio), thestrength(1) can be modified by replacing w_e in (1) with,$2 * w_1$, we get,

$$S = 0.27 * \sigma_c * \frac{\sqrt{2*w_1}}{h^{0.86}} = 0.4 * \sigma_c * \frac{\sqrt{w_1}}{h^{0.86}} MPa \tag{3}$$

where, w_1 is the rib width (m).

A multiplying factor ‘α’,for addressing the variation in K-ratio [ratio of pre-excavation in-situ horizontal stress (σ_h) to pre-excavation in-situ vertical stress (σ_v)] and increased stress concentration at higher depths needs to be incorporated [27].It is needed to keep the option open about the nature of variation of pre-excavation in-situ stresses and related factors in the strength formula for ribs.

Thus, Equ.(3) can then be modified as,

$$S = 0.4 * \sigma_c * \alpha * \frac{\sqrt{w_e}}{h^{0.86}} MPa, \tag{4}$$

Where, S is the rib strength (MPa), σ_c is the compressive strength of coal (MPa), α is a multiplying parameter addressing the variation in K-ratio and increased stress concentration. w_e is the effective width (m), and h is the height of extraction (m).

VI. Discussion

Based on experience gained in B&P depillaring workings, a band range of FOS is taken as 0.6-0.9 for rib stability in case of intermediate technologies with the use of SDLs and LHDs. This band is taken based on the purpose of rib and also on the fact that FOS should be less than 1.0. FOS < 0.6, suggests that the ribs are unstable and hence, may not be able to withstand the load even during active slicing. The proposition of FOS band i.e., 0.6-0.9 has a higher gullibility in the sense that the Indian inspectorate stick to these values while providing statutory approval of depillaring in some semi-mechanized B&P workings. Fortuitously, the ribs so formed had not resulted in mine accidents in depillaring districts, till date in Indian coal mines. In absence of any scientific basis to prove that this FOS band (0.6-0.9) may need to be modified, the authors have taken this band as inviolable at the moment and thus considered for the rib-stability.

The stress increases as we go deeper. It was observed during numerical modelling that the stress increases and FOS decrease continuously with increase in depth. The lower value of FOS suggestslikely ground control problems which are not always the case. 2.0-3.0m rib dimensions are in vogue in Indian Coalfields. As far as case-studies are concerned, the FOS value from the earlier formulation as shown in Fig. 4,suggested abysmal conditions and severe ground control problems contrary to field observations. As per new strength equation, the same mines were analysed and from the comparative graph shown in Fig. 5, it can be inferred that the ribs are in the temporary stable range of 0.6-0.9, hence, smooth depillaring is expected, as was observed in the field.

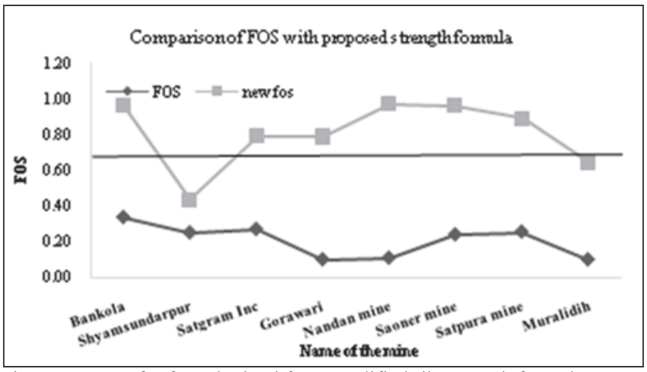

Fig. 5. Factor of safety obtained from modified rib strength formula

With the introduction of CM with accessories in depillaring, the FOS band for temporary stable ribs may be modified to 0.5-0.8. It is to be noticed that there is no scientific basis for this, except for the fact that the CMs deployed to extract stooks (after completion of splitting andnecessary supporting), may extract the complete stooks within one shift or less i.e., very fast in comparison to the scenario of intermediate technologies. The lower datum is therefore reduced from 0.6 to 0.5 in latter case applying engineering judgements and experience gained in Indian coal mines. The inspectorate is providing approval for depillaring with CM deployment in many mines like Jhanjhara colliery (R-VII seam), Eastern Coalfields Limited (ECL), Tandsi mine, Western Coalfields Limited (WCL), etc. with such FOS values.

A modification of (1) has been suggested (4). The incorporation of $'\alpha'$has brought depth of working into account which was not considered in (1). The modified formula provides quick hand calculation for the mine operators to determine stability of the given rib dimension starting from 3.0m and decreasing to 2.0m but not less than the latter. Equation (4) addresses the rib stability in a focused manner. From the result of parametric numerical analysis, 'α' can have an attributed value of 3.2 (for depth upto 160m) and 6.9 (for depth more than 160m). As the K-ratio has a break even at 160m [27]. K-ratio>1 (for depth less than 160), K-ratio =1 (at depth of 160m) and K-ratio<1 (for depth higher than 160m) [23].

VII. Conclusion

The purpose of ribs and pillars are different, so, stability formulations for pillars assessment cannot be extended to rib stability assessment. The rib strength formula presented in the paper may be regarded to play a 'cameo' role in the assessment of rib stability in total perspective of depillaring. A number of case studies, physical observations and related data-collection from a scheme of designed geotechnical instrumentation would further enhance the confidence in determining rib stability using the modified approach as presented in this paper.

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