Rib/snook design in mechanised depillaring of rectangular/square pillars

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Abstract

A field study at different mechanised depillaring (MD) operations in Indian coalfields (with depth ranging from 60 to 377 m and caveability Index variation from 2300 to 10500) found mixed performances of adopted sizes of the ribs/snooks. Formation of an irregular shaped rib/snook during MD of the existing square/rectangular pillars by a continuous miner and uniqueness of the existing geo-mining conditions limit scope of application of the conventional rib/snook design approaches. Taking guidance from the field studies, a parametric investigation is conducted in laboratory on the calibrated simulated models using FLAC^{3D}. An analysis of stress redistribution for different stages of the MD in simulated models provided a different characteristic of an irregular shaped ribs/snooks failure. Presence of moderate roof strata is found to be, relatively, more significant for the rib/snook design. Based on the simulation results, an attempt is made to provide a model for the rib/snook design in MD.

Keywords: Rib/snook, Depillaring, Continuous miner, Area based design, Simulation.

1. Introduction

Existing facts and figures about different developed coal seams (standing on pillars) find depillaring as a vital extraction technique [1] for the Indian coal mining industry. The industry has adopted large scale semi-mechanized depillaring operations (using drilling and blasting for coal winning and equipment, such as Side-Discharged-Loaders/Load-Haul-Dumpers for coal haulage) with the help of indigenous resources only [2]. However, the industry finds this depillaring approach challenging [3] for further improvements in production, productivity and safety. A mechanised depillaring (MD) operation (using a continuous miner (CM) for coal cutting and shuttle/ram car for fast coal haulage) possesses good potential for improved performance of the underground pillar extraction. The Indian coal mining industry introduced a MD operation in February, 2003 [4] and since then; at

least, six different coal mines [5] have used this approach for fast underground pillar extraction. On an average, each of these MD operations produced around 2000 t of coal per day and the observed goaf velocity (pace of extraction) approached close to 1.0 m per day. Most of these MD are adopted for the developed coal seams, where the existing widths (nearly 4.2 m) of galleries are widened to 6.6 m to suit the machine movement. As the Coal Mines Regulations (CMR) of India provides, relatively, larger size of pillars therefore the existing pillars are, generally, split before slicing. Here, the line of pillar extraction is ideally kept straight or linear. But, due to the machine maneuverability limitations, the existing square and rectangular shaped pillars produce irregular shaped ribs/snooks against the goaf. The resulted irregular shape of a rib/snook (Fig. 1) makes compliance with the required linear design difficult.

The risk of goaf encroachment during slicing of a fender (split part of a pillar) is overcome by leaving a rib against the goaf (Fig. 2). Again, final slicing in a fender of the pillar is done ahead of four/three way intersections of the galleries. Here, the role of size/shape of the most out-bye rib (also called snook), to be left against surrounding galleries intersections, becomes vital for the safety of a depillaring operation [6]. Potential falls of competent roof inside the goaf during the depillaring operation or encroachment into the working area should be avoided [7]. Such an attempt of encroachment gets support from the inherent existence of different openings along the goaf line of a depillaring panel. To restrict such an encroachment, an effective support system is erected in these openings along the goaf line (generally called goaf edge support). All these openings, along the goaf edge, are supported by the roof bolt based breaker line support (RBBLS)[8]. Different field studies by CSIR-CIMFR found that the RBBLS works effectively during the depillaring under the shadow of stable rib/snook/fender only [9]. Therefore, the design of a rib/snook becomes an important component of the MD operation.

A rib/snook is a temporary natural support and should be sufficiently large to protect the slicing from goaf and surrounding gallery intersection. But, at the same time, the rib/snook should be small enough so that they do not inhibit the caving of roof strata inside the goaf with an advance of the working. Design of a rib during conventional depillaring is performed as per Directorate General of Mines Safety (DGMS) circulars. But use of this design approach is complicated for MD operations, for the following four reasons: (1) irregular shape of rib/snook, (2) straight line of extraction, (3) fast rate of extraction and (4) application of high capacity, pre-tensioned, stiff and resin grouted roof bolts as support system. A number of previous studies are reported [10][11] [12] for the design of a rib/snook

in MD. However, the applicability of these studies in Indian coalfields is limited, mainly, due to two reasons: (1) uniqueness of the rock mass and (2) complex geo-mining conditions.

In absence of an indigenous design norm for a rib/snook, different field applications of the MD in Indian coalfields have adopted the previous reported methods for this purpose. Existing differences in the site conditions, however, made this adoption difficult. The reported design norms have considered, mainly, two extreme conditions of the roof strata and the presence of a narrow snook is found to be suitable [12] for both the conditions. However, in Indian coalfields, a large amount of coal seams are developed below moderate roof strata, which is not properly addressed in the reported studies. Further, field performance monitoring of these adopted designs in Indian coalfields noticed some successes [4] [5] and some failures [3][13]. Therefore, under the guidance of different available design norms and the field performance monitoring results, numerical modelling has been utilised to investigate the performance of a rib/snook under different varying conditions for the MD operations. An analysis of the simulation results, taking into consideration the results from field and laboratory studies, has been used to develop a preliminary model for the design of a rib/snook for the MD operations in Indian coalfields.

2.0 Indian depillaring scenario

Indian coalfields are known to encounter difficult overlying strata during underground mining [14]. But for a depillaring operation, both, highly laminated/weak and massive/strong overlying strata are termed as difficult because both of these conditions adversely interact with the broken nature of the conventional semi-mechanised depillaring. Reported poor efficiency [2] and safety [15] of the conventional depillaring operations for underground pillar extraction are considered by the Indian coal mining industry to phase-out this approach. A fully mechanised depillaring is however providing a faster rate of extraction [16] and improved safety along with increased production and productivity of a depillaring operation, which is obviously attractive for the coal mining industry of the country.

2.1 Site conditions

Underground extraction of the existing developed pillars by MD operation was first started at Anjan Hill Mine in 2003. Experiencing excellent performance of this approach [4] during the first field trial, at least, six different Indian mines have extensively used this approach for the depillaring. CSIR-CIMFR conducted extensive field investigations at four of these MD sites. On the basis of these investigations and published data of the other two MD sites [13][17], Table 1 gives a summary of these six MD operations in the coalfields. Depth of cover of these MD sites in the country varied from 60 m to 377 m. The nature of overlying

strata of these panels also varied widely: ranging from easily caveable and laminated roof of Pinoura Mine to massive and strong overlying strata of VK7 Mine. Caveability Index (*I*) is one of the established approach for the assessment of the overlying strata [18], which is defined as:

$$I = \frac{\sigma l^n T^{0.5}}{5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where: σ = Uniaxial Compressive Strength in kg/cm^2;

l = Average length of core in cm;

T = Thickness of the strong bed in m and the factor *n* has a value of 1.2 in the case of uniformly massive rocks with a weighted average of RQD of 80% and above. In all other cases n = 1.

An assessment of Caveability Index was performed to understand the nature of overlying strata through examination and testing of core samples of the different sites. Available geo-mechanical properties of the core-samples of overlying strata at Tandsi and Jhanjra are used for estimation of *I* at these two sites. Fresh core samples of overlying strata were procured at VK-7, GDK-11, Anjan Hill and Pinoura mines. These procured core samples were tested in a laboratory for their physical and mechanical properties for estimation of *I*. The observed spectrum of *I* for the mechanised depillaring sites is shown in Fig. 3.

2.2 Field performance

On the basis of the field performance studies, MD operations at Anjan Hill, Jhanjra and Pinoura are found to be, more or less, successful but not without difficulties. For example, in the first MD panel at Jhanjra, the left out ribs/snooks inhibited the caving of the moderate roof strata inside the goaf considerably with an advance of the working. This panel did not experience roof fall even after a goaf area exposure of more than 10000 m^2 (Fig. 4). Under this condition, the working in the panel was stopped due to the apprehension of air-blast. Taking advantage of shallow cover (125 m), the hanging roof strata inside the goaf is managed through long hole drilling and blasting from the surface [13].

Working below the easily caveable roof of Pinoura caused a number of roof falls and burial of the CM inside the cuts. During recovery of the CM, the extent of fall was observed up to 20 m inside the roof but a left out rib of around 2 m width was found to be intact even against this height of the fall. But a roof fall of 5 to 6 m height only at VK-7 Mine (competent roof strata) caused crushing of a more than 4 m wide rib. This was the deepest MD panel in the county at around 377 m of cover. The MD at Tandsi Mine was practiced below

incompetent roof strata at nearly 260 m depth of cover. Here, the MD experienced strata control problems at the goaf edge during full extraction resulting in adoption of a partial extraction method [17]. GDK 11 Incline Mine at around 325 m of cover witnessed extraction of total thickness of the seam (6 m) in single pass by the Continuous Miner (CM). The machine could win 4.6 m height directly, while 1.4 m floor coal is taken at final stage through ramp during the retreat. Again, here a mixed performance of the rib/snook was observed. Caving of the competent roof inside the goaf could not be inhibited by the left out ribs/snooks of increased height but, at a number of occasions, the roof fall encroached the working area.

2.3 Available guidance

The three popular rib/snook design approaches are based on: (a) width or width to height ratio (b) safety factor and (c) area of a rib/snook. As per DGMS circulars, a rib of 1.5 m width should be left against the goaf during a slicing operation of the depillaring in Indian coalfields. Further, this size of the left out rib should be judiciously reduced during retreat. Such circulars are for the convention depillaring only and there is mention about MD, where an uniform width of the rib/snook is difficult to be maintained. An analytical calculation by Van-der-Merwe (2005) found that the optimum rib/snook width may vary between 2.5 and 4 m as per variation in the site conditions. Shepherd and Chaturvedula (1992) identified that width to height ratio (w/h) of the rib/snook is an important parameter for the design. Suggested range of w/h for the rib/snook varied from 1 to 2 for different site conditions of the depillaring [10]. However, the shape issue makes it difficult to be applied for depillaring of the exiting square/rectangular pillars by CM. Safety factor based approach is adopted by Moolman and Canbulat (2003) [21] and recommended that the geometries and slice width of depillaring are varied for each depth until a safety factor of 0.35 is obtained for remnants (rib/snook) of a depillared pillar. This approach uses the conventional tributary area method for load estimation and Salamon and Munro (1967) [22] pillar strength formula for load bearing capacity of the snook/rib. Here, irregular shaped rib/snook makes it difficult to apply the conventional formula for the strength calculation and estimation of the load does not consider the influence of goaf.

Literature survey shows that, generally, an area-based design of a rib/snook is typically adopted [10] during depillaring of a square/rectangular pillar by CM. A major problem with the area-based design is length to width ratio. If this ratio is quite large/small then the validity of such a design may be compromised. However, this aspect of the design approach is automatically being taken care by the ability of the currently available CM for the MD. These CMs, generally, have a cut-out-distance (maximum length of cut inside the slice)

equal to 11 to 12m only. Therefore, wider pillars are split into fenders to fit the length of a rib/snook around this value of the cut-out-distance.

Relatively, high speed of extraction during the MD alleviates the magnitude of strata dynamics in and around a slicing operation but an understanding of interaction of the rib/snook with overlying strata is vital for its design. As per the basic design norm for a temporary support, the size of a rib/snook is not to be increased proportionately with depth of cover as it happens for a pillar. But, as per the above given field studies, the two major influencing factors for the area of a rib/snook during the MD are depth of cover and competency of the overlying strata. Different field trials of MD in Indian coal mines applied a variety of area of ribs/snooks ranging from 20 m^2 to 125 m^2 (Fig. 5) to cover the changing conditions of different sites. This range of the area of ribs/snooks is considered during the parametric study on simulated models.

3.0 Parametric study

Although size of a rib/snook is not to be increased proportionately with depth of cover as is the case for more conventional pillar design, field observations showed that depth of cover and competency of the overlying strata are the two major influencing factors for the area of a rib/snook. But a systematic field experimentation of varying these parameters for different sizes of the rib/snook would be difficult. Therefore a detailed parametric study for the rib/snook design is performed with numerical models to assess the impact of parameter variation on model performance.

3.1 Numerical modelling

A continuum analysis software package: $FLAC^{3D}$ [23] was untilised for numerical modelling of the varying rib/snook geometry. CSIR-CIMFR has successfully used this software [24] for different geo-technical investigations. Bedding planes are represented through interfaces, which are the main discontinuities of the proposed study. Rock Mass Rating (RMR) [25] evaluations of the varying strata was undertaken to compare site conditions. The Mohr-Coulomb Strain-hardening/Softening (MCSS) within $FLAC^{3D}$ was chosen for the parametric study following comparison of initial depillaring results obtained through elastic and plastic models. Various strength and elastic properties, necessary for numerical modelling used in the strain softening model, are: (a) Elastic constants; (b) Peak and residual shear strength and the variation in between with the shear strain (c) Peak and residual angle of internal friction and the variation with the shear strain and (d) Angle of dilation and its variation with shear strain. The shear strength and friction angle were estimated using Sheorey's (1997) failure criterion for rock masses [26]. This criterion uses

the 1976 version of RMR of Bieniawski [25] for reducing the laboratory strength parameters to give the corresponding rock mass values. This criterion is defined as:

$$\sigma_1 = \sigma_{cm}(1 + \frac{\sigma_3}{\sigma_{tm}})^{b_m} \qquad \text{……(2)}$$

where,

$$\sigma_{cm} = \sigma_c e^{(\frac{RMR-100}{20})}$$

$$\sigma_{tm} = \sigma_t e^{\frac{(RMR-100)}{27}}$$

$$b_m = b^{\frac{RMR}{100}}$$

σ_1 = Tri-axial strength of rock m ass (MPa), σ_3 = Confining stress (MPa), σ_c = Compressive strength of intact rock (MPa), σ_t = Tensile strength of intact rock (MPa), b = exponent in failure criteria, which controls the curvature of triaxial curve, σ_{cm} = Compressive strength of rock mass (MPa), σ_{tm} = Tensile strength of rock mass (MPa) and RMR = Biniewiski's Rock Mass Rating. In the above equations, the subscript m stands for the rock mass.

From laboratory testing, the value of the compressive strength (σ_c) was known. Then the tensile strength $\sigma_t = \sigma_c/15$ and b = 0.5 were taken as the most representative values, as seen from a large number of published test data [26].

The factor of safety (*SF*) is defined as:

$$\left.\begin{array}{ll} SF = \dfrac{\sigma_1 - \sigma_{3i}}{\sigma_{1i} - \sigma_{3i}} & for\ \sigma_3 < \sigma_t \\ SF = \dfrac{\sigma_t}{\sigma_3} & for\ \sigma_3 > \sigma_t \end{array}\right\} \qquad \text{……..(3)}$$

Where, σ_{1i} = Induced major principal stress (MPa) and σ_{3i} = Induced minor principal stress (MPa).

From these, the rock mass shear strength τ_{sm}; the coefficient, μ_{0m} and the angle of internal friction, ϕ_{0m} are obtained as:

$$\tau_{sm} = \left(\sigma_{cm}\sigma_{tm} \frac{b_m^{b_m}}{(1+b_m)^{1+b^m}} \right)^{1/2} \qquad \text{…….. (4)}$$

$$\mu_{0m} = \frac{\tau_{sm}^2(1+b_m)^2 - \sigma_{tm}^2}{2\tau_{sm}\sigma_{tm}(1+b_m)} \text{ ..... (5)}$$

$$\phi_{0m} = \tan^{-1}(\mu_{0m}) \text{..... (6)}$$

It was, however, found that the values of rock mass shear strength, τ_{sm} and friction angle, ϕ_{0m} so determined had to be changed slightly to account for the fact that the MCSS Plasticity model in FLAC3D uses the linear Mohr– Coloumb criterion while the Sheorey criterion is nonlinear. The value of τ_{sm} obtained from the Sheorey criterion was increased by 10% and that of ϕ_{0m} was reduced by 5˚ to use them as Mohr–Coloumb parameters.

The MCSS model also requires parameters describing the rate of cohesion and/or friction drop as a function of plastic strain in the post-peak region. The determination of the MCSS parameters for a rock mass is a difficult task, but carried out empirically by performing back analysis. Different test pillar models were run with various sets of MCSS parameters for determination of pillar strength and compared with pillar strength value, calculated through an empirical formula. The best match was selected for the subsequent modelling of MD panel.

3.2 Site details

A parametric study within [26] can easily be performed by considering typical site conditions of the mining with hypothetical systematic variations in different parameters. However, assumptions for typical site conditions for underground coal mining can be difficult. Therefore, the actual site conditions of a representative MD are considered for the modelling within the current investigation. Accordingly, dimensions of the considered block for the modeling are 252 m, 252m and 115m along the X, Y and Z directions respectively. Total 150m width of the block is used for mining around a barrier of 51m thickness. Height of the working is kept 4.0 m with a pillar size of 30m x 30m (corner to corner) and gallery width equal to 6.0 m. As usual, cubic and cuboids meshing are used for the formations of different mining structures in the model. Height of the simulated model is kept to be 59m above the working the and thickness of the modelled floor below the working seam is kept to be 52m only. Truncated Load (γH) is applied on the model as per actual depth cover of the coal seam. The interval of mesh is considered 0.5 meters in coal seam and 1 meter in the other layers. Different layers of this model, including the coal seam was simulated as per the observed column of stratigraphy (above and below the coal) through a coring bore-hole data

of the site. The boundary condition in the numerical model has been defined in such a way that the vertical wall of the model in X and Y direction and the floor of the model in Z direction are fixed.

Physico-mechanical properties of coal and overlying/underlying rock strata are derived through field and laboratory testing of freshly procured core samples. Other required properties were estimated according to Murli Mohan *et al*. [24], as mentioned in Tables 3 and 4. *In situ* stress values were estimated as per Sheorey [27], which are given as:

$$S_v = 0.025\ H \quad \text{MPa} \quad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

$$S_h = S_H = 2.4 + 0.01H \quad \text{MPa} \quad \ldots\ldots\ldots\ldots\ldots\ldots(8)$$

where, H = Depth of cover in metres, S_v = Vertical *in-situ* stress, S_h = Minor horizontal *in-situ* stress and S_H = Major horizontal *in-situ* stress.

3.3 Simulation results

The parametric study covered testing of nearly 250 models in laboratory. Stable size of a rib during slicing is studied for different stages of the depillaring for different values of depth of cover and CMRI-RMR [29] of overlying strata as given in Table 5. The CMRI-RMR value is taken as a parameter to study the effect of the nature of the immediate roof strata over the rib/snook size because this parameter is frequently used in Indian coal-fields for immediate roof categorisation. Size of the rib was varied for a chosen set of depth of cover and CMRI-RMR to find out a lower value of the stable size of rib/snook. As per the boundary conditions of the considered site and results of the field observations, the three sizes of the rib/snook considered for this investigation are: 42 m^2, 78 m^2 and 114 m^2 respectively. More variations in the sizes of ribs/snooks were not considered necessary as part of this initial investigation. Experimentations with these three sizes of ribs/snooks, showed that the size of a rib/snook needs to be fixed for a given site conditions (Fig. 6). Here stress concentration over three different sizes of ribs/snooks shows that the smaller size rib/snook (42 $m^{2)}$ has experienced considerable induced stress, even some failure in its thinner part, for 150m depth of cover and 40 CMRI-RMR of the overlying strata. While the other two sizes of ribs/snooks (78 m^2 and 114 m^2) are, almost, relaxed for the same conditions of the site.

3.4 Shape effect

Mark and Zelanko [10] suggested a "method of slices" to estimate strength (bearing capacity) of an irregular shaped rib/snook. This method was suggested because it is difficult to use the existing pillar strength formulae to estimate the strength of a snook/rib due to its shape. They assumed that any pillar element is a function of its distance from the nearest pillar rib. They defined pillar stress function (σ_v) as:

$$\sigma_v = S_1 [0.64+2.16(x/h)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where, S_1=*In situ* coal strength, x=Distance from the nearest pillar rib, h=Pillar height.
They also defined a parameter called "Stability Factor", which is a bearing capacity-to-load ratio of a rib/snook. It is suggested that a yielding snook should have a stability factor value equal to 2.5. On the basis of these assumptions they provided stress profiles over a rib/snook (Fig. 7).

Field studies found that an irregular shaped rib/snook encounters instability in its thinner portion after experiencing stress concentration due to increased width of the excavation. After sufficient increase in the width of the extraction in a simulated model, an observed typical failure of the thinner part and concentration of induced stress in the core of the rib/snook is shown in Fig. 8. This nature of the observed stress redistribution over a rib/snook during depillaring does not exactly match with that in different slices given by Mark and Zelanko [10]. Numerical modelling found that nearly one third length (thinner part) of the left out rib/snook does not provide much resistance to lowering of the roof strata. Symmetrical nature of the stress distribution over all along the area of an irregular shaped rib/snook is found to be difficult for the coal mass. Major part of the stress concentration takes place only in the wider part of the left out snook/rib. Mark and Zelanko's approach of stress profiling seems to be valid for an elastic material only.

Observed variation of stable rib/snook size with depth of cover and CMRI-RMR is shown in Fig. 9. It is observed that the moderate roof strata generate more loading over the rib/snook than the strong and weak roof strata. These observations, conducted for only three different sizes of the rib/snook, found that the design of rib/snook is more important for moderate roof strata than strong/massive or weak/laminated roof strata. Observed increase in the area of the stable rib/snook with depth of cover is, more or less, an accepted practice for the design. But an increase in the area of the stable rib/snook with CMRI-RMR in the beginning and then decease in the area of the stable rib/snook with CMRI-RMR is found to be interesting from strata mechanics point of view.

4.0 Conceptual model

It is difficult to cover all possible site conditions during a simulation study and, therefore, a practical bandwidth of the geo-mining conditions are considered for the parametric study using the numerical models. However, the obtained results can provide a good conceptual idea or guidelines regarding the rib/snook loading during the MD.

4.1 Strata mechanics

An attempt to develop a conceptual model for the rib/snook design on the basis of the stress distribution study on the simulated model requires an understanding of the strata mechanics phenomenon in and around a depillaring operation. A depillaring operation includes three important mining structures: (a) Pillar/fender, (b) goaf and (c) applied support. Left out ribs/snooks also work/perform like applied support for a depillaring operation. The response of these mining structures keeps changing with progress or during the life of the depillaring operation in a panel. In a depillaring panel, generally, the area around intact pillars (standing ahead of the extraction line) does not experience much strata dynamics. However the area, in and around the goaf, encounters considerable amount of strata dynamics and is the main source of stress redistribution over pillars ahead of the extraction line. Here, it is important to study the interaction between roof and pillars around the goaf edge under the existing site conditions. Generally, in the beginning of the pillar extraction, a beam of overlying strata (clamped at both ends) is formed over the goaf. After a sufficient increase in the dimension of the goaf, the beam of roof strata fails and a cantilever is formed at the goaf edge. Now, splitting/slicing work for the progress of the depillaring is done under the cover of this cantilever. Although the major load of the overhang is transferred to the solid pillars (standing around the goaf edge) at this situation, there is a possibility of local instability in the lower horizon of the cantilever due to the inherent nature of the formations. Therefore, the characteristic of the cantilever is, mainly, governed by the nature of the overlying strata. Here a systematic design and planning of rib/snook to control the local instability of the lower horizon of the cantilever (to cover the span over the proposed slice/slices for the depillaring) is important. Stress concentrations over a rib/snook, formed after one and four rows of pillar extractions, are shown in Fig. 10 to visualise the effect of progress of a depillaring operation. Observed nature and amount of stress concentration over three different sizes of ribs/snooks provide important guidance/guidelines for their design.

4.2 Parametric co-relations

The above mentioned literature review and field studies indicate that the design of a rib/snook is influenced by depth of cover and nature of the roof strata. Accordingly, an attempt is made to understand the influence of these two parameters on rib/snook design through different simulation results.

The numerical simulation study showed that the development of cuts under competent immediate roof strata caused, relatively, smaller load development over the neighbouring snook/rib (Fig. 11). Good competency of the roof strata might have securely covered the complete span over the slice/slices and most of the loads might have transferred to adjacent

solid pillars/fenders. In case of moderate strata, there was a decline in the competency of roof over the span of slice/slices, which made it difficult to transfer the major overhanging load towards the solid pillar. A dilution in competency of the exposed roof strata over the slice/slices may induce deformation before the solid pillars/fenders, which might have developed more loads over the left out rib/snook. Therefore, the nature of deformation of the moderate roof strata and the width of slice/slices are, mainly, controlled by an efficient design of the snook/rib. In the presence of an extremely weak/laminated roof stratum a relatively smaller width/span of slice/slices is adopted and good settlement of overlying strata is observed inside the goaf. The observed extending nature of the competent roof strata is found to be absent here during its caving. This resulted in less load development over the neighbouring rib/snook. These observations show that the complete band width of moderate roof strata created a relatively higher load over the rib/snook in comparison to, both, extremely weak and strong roof strata.

As per results of the numerical modelling, there is an increase in the stable rib/snook (Fig. 9) size with an increase in depth of cover. This finding is not exactly in tune with the assumption that a rib/snook is like an applied support for a small period of time. However, it is an observed fact that a natural support-such as a pillar/fender experiences side spalling at deeper cover and the rib/snook is formed from these natural supports only. Under the side spalling condition, some area of the formed rib/snook may not be good resistive to the roof strata. Therefore, the observed increase in stable size of a rib/snook with depth of cover seems to be in tune with the existing site conditions.

Obtained stable sizes of ribs/snooks for different depth of cover and nature of the roof strata (in terms of CMRI-RMR) are subjected to a multivariate regression analysis. This analysis provided a relationship to estimate the stable size of the rib/snook (S), which is given as:

$$S = 0.52\, H^{0.74}\, R^{0.23} \quad \text{m}^2 \quad \ldots\ldots\ldots\ldots(10)$$

where, H=depth of cover, m

R= CMRI-RMR

It would be interesting to correlate CMRI-RMR with the caveability index to make the above mentioned findings of numerical models more useful in the field.

4.3 Conceived model

It is observed that the depth of cover and nature of roof strata affected the rib/snook size differently. Movement/caving of a strong/massive roof stratum is, mainly, governed by fender or pillar, while that of a weak/laminated stratum is controlled by the properties of the

immediate roof and difficulty in generation of load over the rib/snook. It is moderate roof strata, which offers excessive loading to a rib/snook during the slicing operation of MD. An attempt is made to develop a conceptual model (Fig. 12) on the basis of the observed rib/snook size variations with the nature of immediate overlying strata. Presence of moderate roof strata induces considerable amount of load over the rib/snook. Therefore, relatively, larger sizes of ribs/snooks are required during MD under such type of roof strata in comparison to the weak or strong roof strata. However, at the time of retreat, there is a need to dilute the competency of these ribs/snooks by judicious reduction in their size for smooth caving of the roof strata inside the goaf.

5.0 Conclusions

Field performance studies of the adopted rib/snook design at different MD operations in Indian coalfields have provided mixed results. Position and shape of a rib/snook in MD make it difficult to apply a design approach based on width or estimation of strength to load ratio. Literature review finds an area-based approach for the design of an irregular shaped rib/snook is normally adopted but, generally, two extreme ends of the nature of roof strata are considered for this design. Results of the undertaken numerical simulation show that the band width of the moderate roof strata creates more loading over the rib/snook than either the strong/massive or weak/laminated roof strata. At a fixed depth of cover 150m, a rib size of 42 m^2 is stable for 20 CMRI-RMR but the size of a stable rib increases to 78 m^2 for 40 and 60 CMRI-RMR values and, finally, decreases to 42 m^2 for 80 CMRI-RMR. Again for a fixed CMRI-RMR 40, stable sizes of rib varied from 42 to 114 m^2 for 150 to 550 m depth of cover. Results of the numerical simulation do not support the conventional assumption about a rib/snook to work exactly like an applied support during the slicing operation. This finding of the simulation matches with field observations, where deterioration in the intactness of the outer portion of a pillar/fender is often noticed at higher depth of cover. Observed nature of variations in the area of a stable rib/snook under different types of the roof strata provide an interesting strata mechanics phenomenon, which helps in conceptualising an approach for the rib/snook design. On the basis of the results of the numerical modeling study, a conceptual model is presented for the design of a rib/snook in MD under varying geo-mining conditions.

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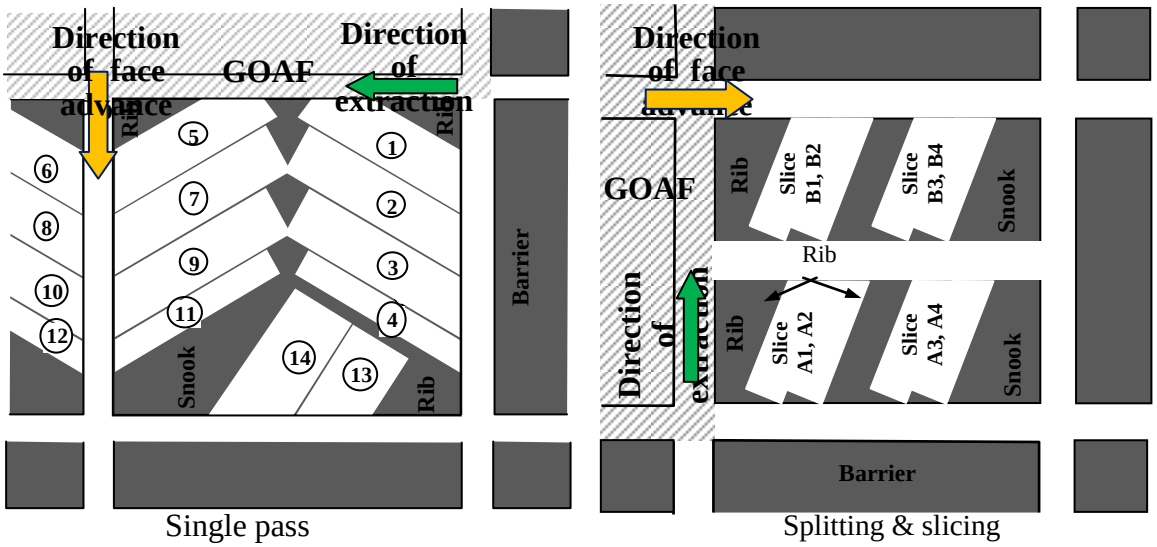
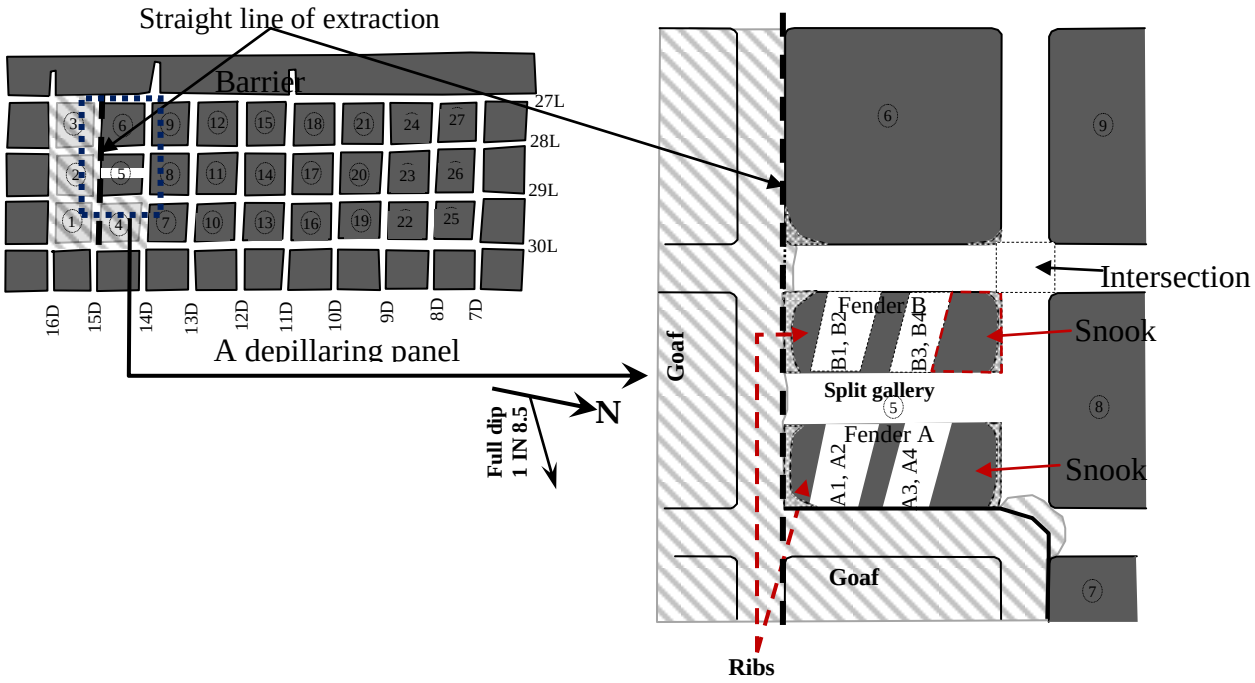


Fig. 1 : Formation of irregular shaped rib/snook in two popular manners of pillar extraction: (A) Single-pass extraction of total pillar and (B) Splitting and slicing.



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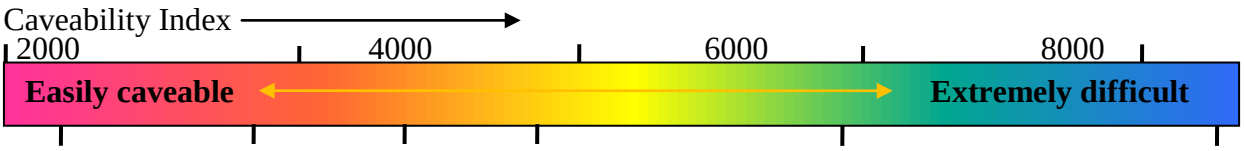

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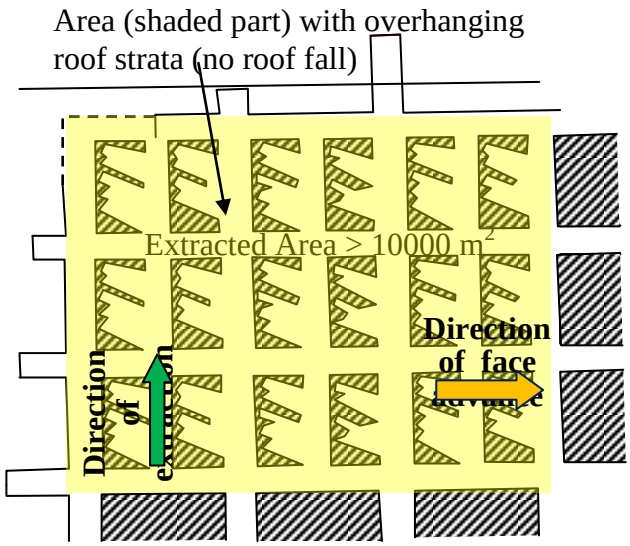

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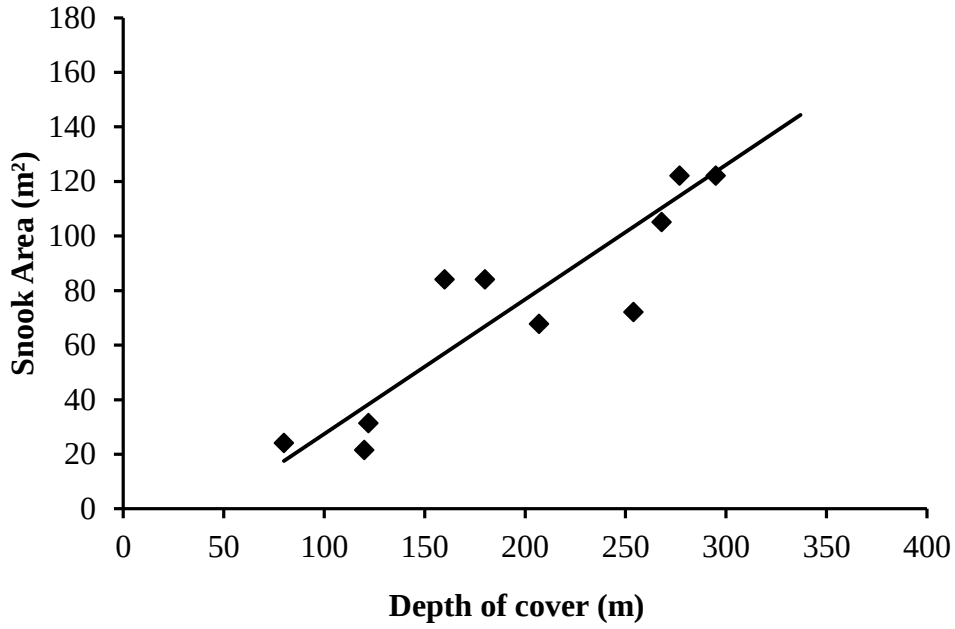

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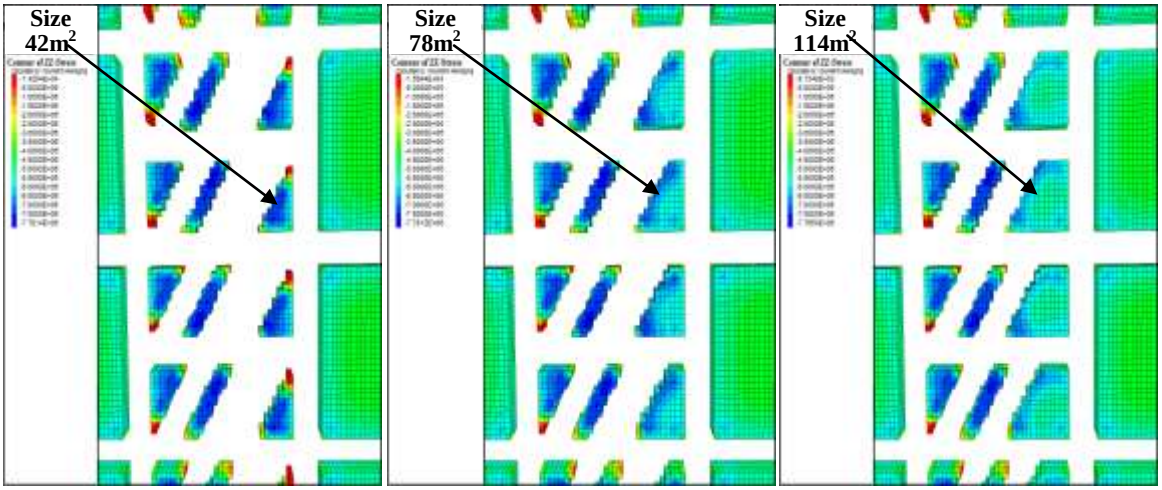

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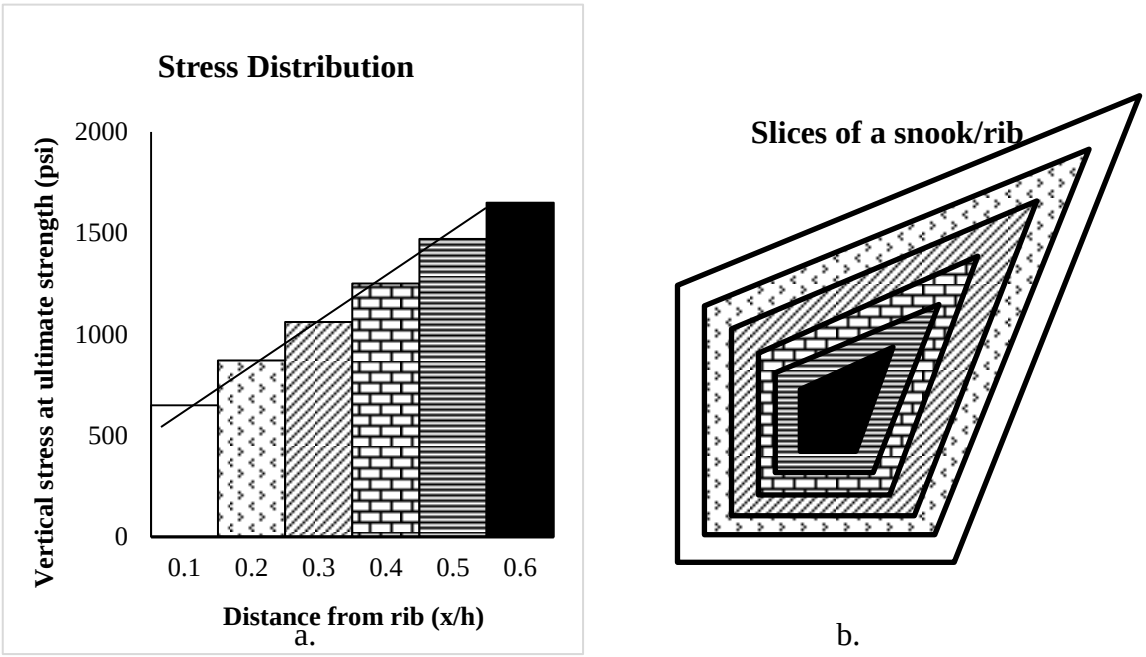

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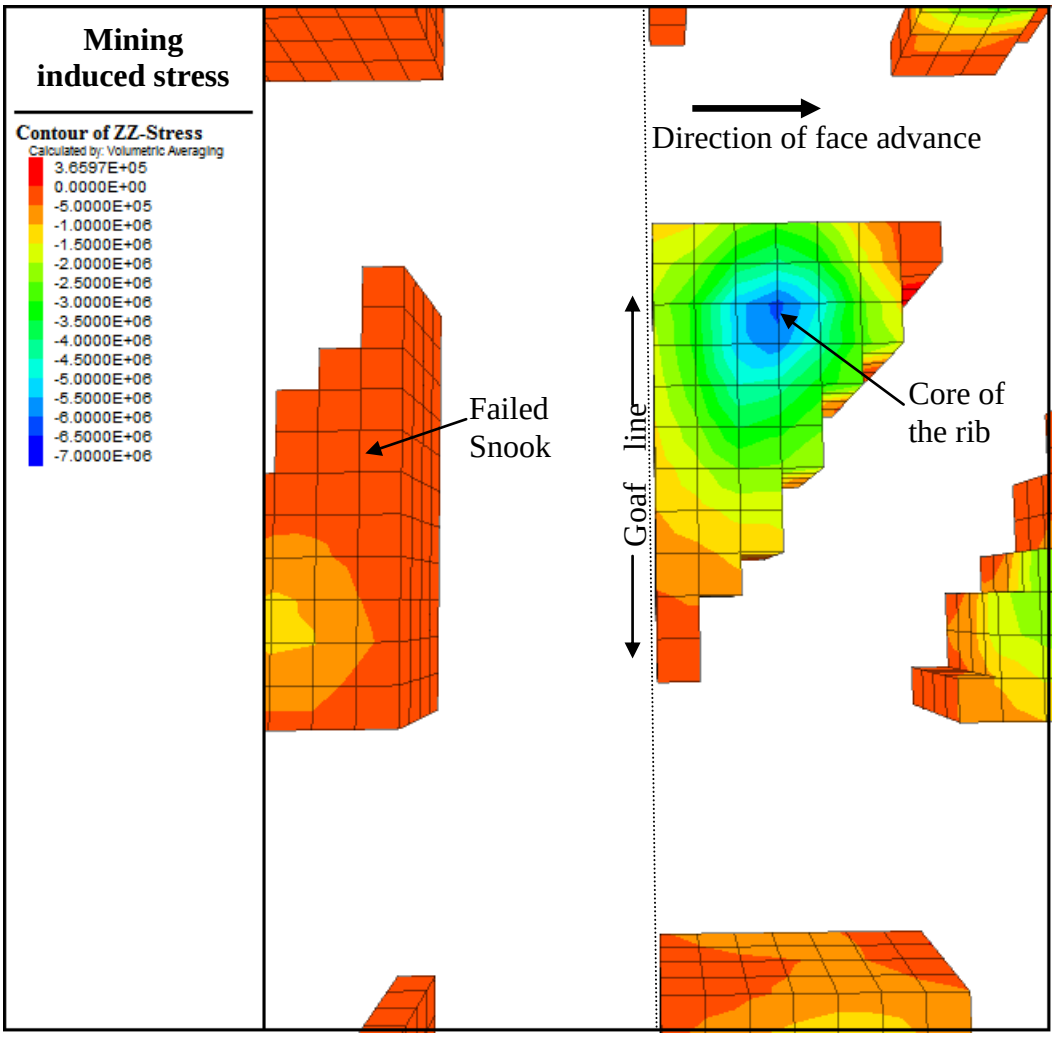

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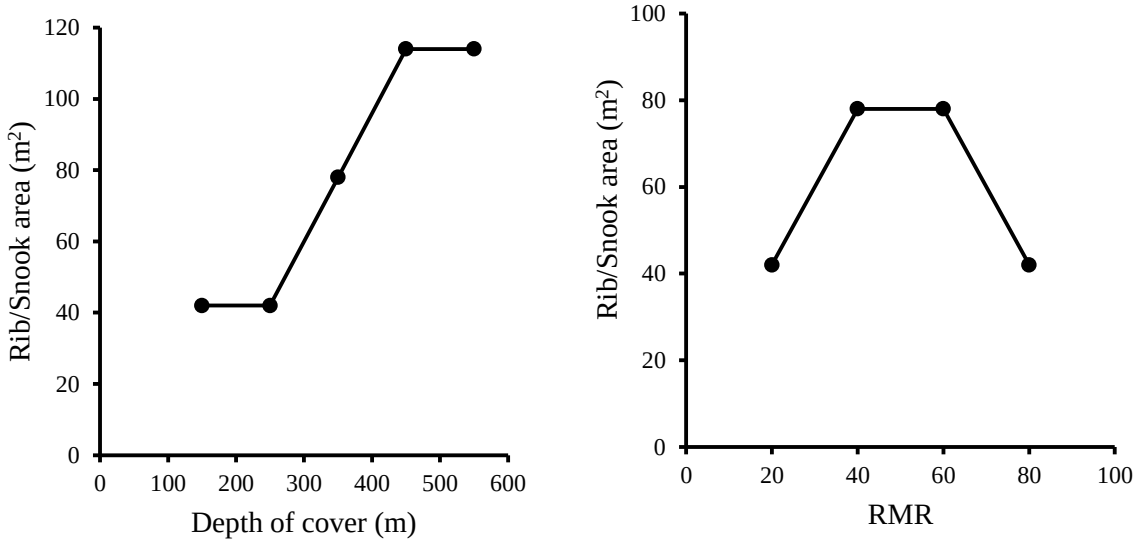

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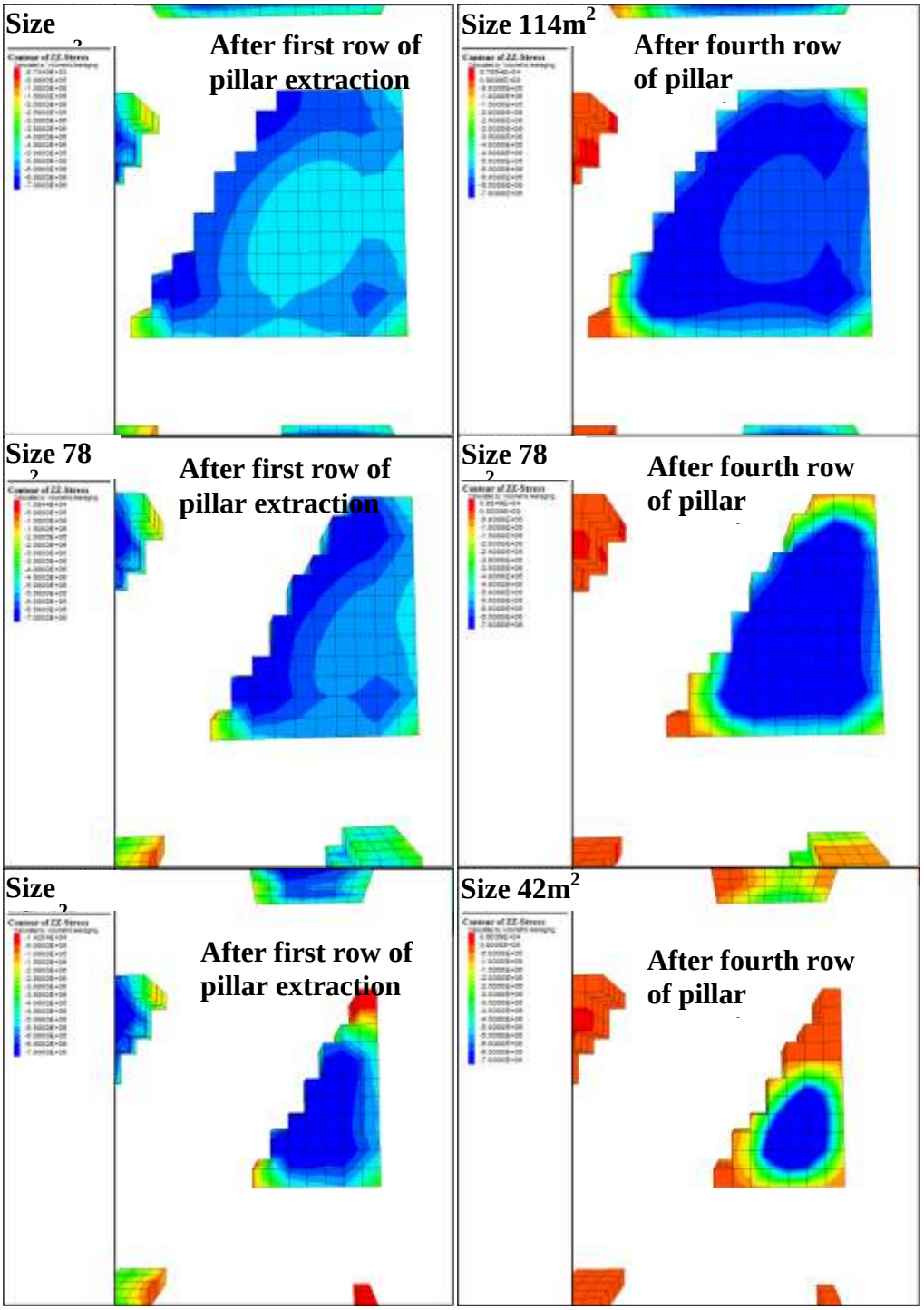

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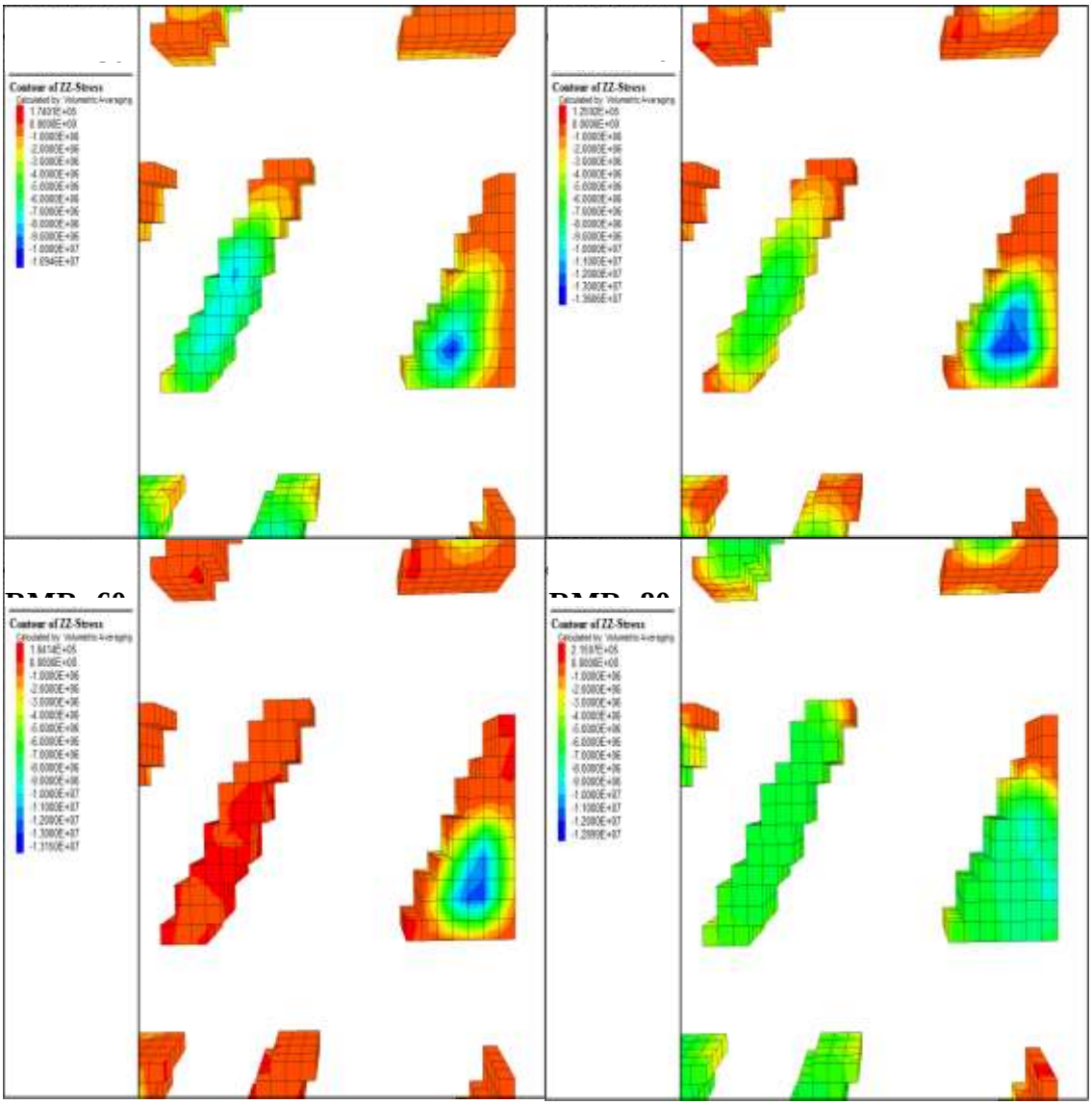

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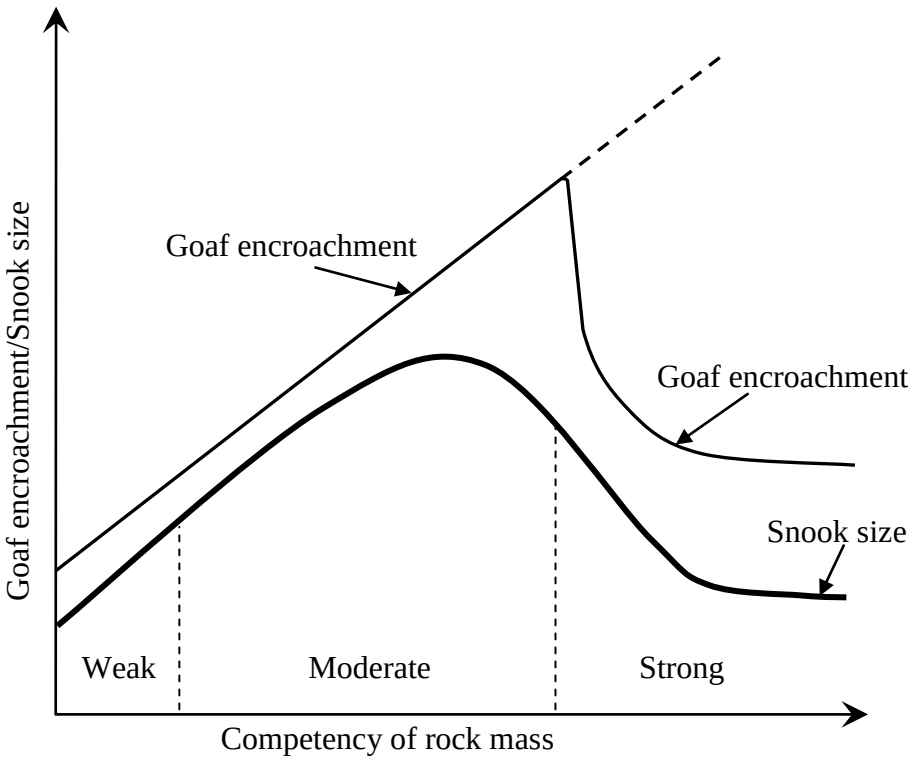

Fig. 12: A conceptual model for the rib/snook design under varying competency of the roof strata.

Table 1: Summary of different MD operations in Indian coalfields.

Name of mine	Geo-mining parameters of different mechanized depillaring faces							
	Depth cover, m	Pillar size, (corner to corner), m	Bord width, m	Working height, m	Overlying strata		Manner of extraction	Performance *
					I	Nature of caving		
Pinoura	60	18.5 x 19.5	6.5	3.0	2332	Easily	Single pass	Success
Anjan Hill	85	28.2 x 28.2	6.6	4.5	4762	Moderate to difficult	Splitting & slicing	Success
Jhanjra	125	26.0 x 26.0	6.0	4.2	5672	Moderate to difficult	Splitting & slicing	Delayed caving
VK-7	377	40.0 x 40.0	5.0	4.6	10522	Extremely difficult	Splitting & slicing	Roof collapse
Tandsi	260	40.0 x 40.0	5.0	3.0	3879	Unstable roof strata	Splitting & slicing	Partial extraction
GDK-11	325	48 .0 x 46.0	6.0	4.6 - 6.0	7798	Difficult	Splitting & slicing	Success

*Performance of different depillaring operation, mentioned in this column, is as per field observations of production, productivity and safety.

Table 2: Incorporated variation of different parameters in the Mohr-Coulomb strain-hardening/softening model.

Shear strain	Cohesion (τ_{sm}) (MPa)	Friction angle (ϕ_{0m})($^\circ$)	Dilation angle (ψ)($^\circ$)
0.000	$1.1\tau_{sm}$	$\phi_{0m} - 5$	15
0.005	$1.1\tau_{sm}/5$	$\phi_{0m} - 7.5$	5
0.01	0	$\phi_{0m} - 10$	0
0.500	0	$\phi_{0m} - 10$	0

Table 3: Elastic parameters of the rock-mass for the modelling.

Strata	Thickness (m)	Young's modulus (GPa)	Shear modulus (GPa)	Bulk modulus (GPa)	Poisson's ratio
Floor: mgsst	50.00	5.70	2.28	3.80	0.25
Coal seam	6.00	2.00, 3.00	1.20	2.00	0.25
Roof Layer 1: mgsst#	0.5	7.00	2.80	4.67	0.25
Roof Layer 2:mgsst#	1.50	5.25	2.10	3.50	0.25
Roof Layer 3: cgsst##	6.00	4.80	1.92	3.20	0.25
Roof Layer 4: shale	1.00	5.70	2.28	3.80	0.25
Roof	50	4.80	1.92	3.20	0.25

mgsst: Medium grained sandstone, ##cgsst: Coarse grained sandstone

Table 4: Physico-mechanical properties of the rock-mass for the modelling.

Strata	Density (Kg/m^3)	Cohesion (MPa)	Friction angle (Degree)	Uniaxial compressive strength (MPa)	Tensile strength (MPa)
Floor: mgsst	2310	2.17	37.44	55.80	3.72
Coal seam	1400	0.78	36.50	32.00	2.10
Roof Layer 1: mgsst#	2500	2.43	39.23	60.60	4.83
Roof Layer 2:mgsst#	2210	1.38	34.88	53.50	3.50
Roof Layer 3: cgsst##	2310	0.85	42.73	38.20	2.54
Roof Layer 4: shale	2310	2.43	39.23	60.60	4.83
Roof	2310	2.17	37.44	55.80	3.72

#mgsst: Medium grained sandstone, ##cgsst: Coarse grained sandstone

Table 5: Range of parameters considered for the modeling study.

Depth (m)	CMRI-RMR	Area of rib/snook (m^2)
150	20, 40, 60, 80	42, 78, 114
250	20, 40, 60, 80	42, 78, 114
350	20, 40, 60, 80	42, 78, 114
450	20, 40, 60, 80	42, 78, 114
550	20, 40, 60, 80	42, 78, 114