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Rib/snook competency in mechanised depillaring of the conventionally developed coal seams

The stability of a natural support like pillar, fender, rib/snook is fundamental for the success of a bord and pillar mining. In fact, the stability of these supports becomes more important at the time of depillaring than the development. An application of mechanised depillaring, utilising continuous miner (CM), provides faster rate of extraction and, therefore, the roof is not supported during the slicing operation. However, the slicing of an existing square or rectangular type pillar provides irregular shaped rib/snook. Available conventional approaches are difficult to be applied for the design of such a rib/snook. Even the scope of application of a foreign design approach for the rib/snook design is limited, mainly, due to the uniqueness of rock mass and site conditions of Indian coalfields. Considering these facts, a systematic study on numerical models in laboratory is undertaken to understand the required competency of a rib/snook at different stages of a mechanised depillaring operation. Giving a brief background of different important field trials of the mechanised depillaring in Indian coalfields, this paper describes the modelling approach and presents results of these models to show the effectiveness of different sizes of ribs/snooks at different stages of the depillaring. Considering the scope of strata dynamics at the goaf edges, some practical considerations for rib/snook design are also discussed on the basis of different field experiences.

Introduction

Bord and pillar method is dominating for underground coal mining in Indian coalfields. Here, development of a coal seam on pillars is found to be techno-economically favourable for the industry. This caused development of a number of coal seams, locking large amount of coal in these pillars (Dixit and Mishra, 2010). Final extraction i.e. depillaring of these developed coal seams is an uphill task for the Indian coal mining industry, mainly, due to the efficiency of the conventional depillaring. The conventional depillaring is, generally, semi-mechanised and follows slow rate of extraction through broken nature of different mining operations. The slow rate of extraction attracts considerable amount of overlying strata movement (Singh et al., 1996), which becomes threat for the safety of the depillaring. In last ten years, coal mining industry of the country has introduced a number of fully mechanized operations for a faster rate of depillaring. These depillaring operations in different coalfields of the country encountered wide variations in site conditions ensuing mixed outputs (Oldroyd, et al., 2006; Mishra, et al., 2013). On the basis of different field studies (Ram et al., 2015{a}), Table 1 gives a brief summary of these applications of CM based depillaring in Indian coalfields.

Existing developed pillars of square/rectangular shape are, relatively, bigger in size for the suitability of a CM machine. Therefore, the pillar is generally split into two or more fenders before the slicing. An encroachment of working area by a roof fall inside the goaf during slicing of a fender (splitted part of a pillar) is overcome by leaving a rib against the goaf (Fig. 1). Again, final slicing in a fender of the pillar is done around a four/three way intersection of galleries. Therefore, the role of size/shape of the most out-bye rib (also called snook or final stump to be left against the galleries intersections) becomes vital for the safety of a depillaring operation. In fact, a depillaring operation inherits a number of openings along the line of extraction. These openings provide least resistance path for a roof fall inside the goaf to encroach the working areas. Erection of an effective support system is essential in these openings along the goaf line (generally called goaf edge support) to arrest the encroachment possibilities. In a mechanised depillaring, goaf edge is supported by the roof bolt based breaker line support (RBBLS) (Petho, et al., 2012). Different field studies by CSIR-CIMFR (Ram et al., 2015[b]) found that roof reinforcement during depillaring works effectively under the shadow of stable rib/snook/pillar only (Singh et al., 2001). Therefore, effectiveness of a RBBLS also depends on the design of the surrounding ribs/snooks.

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TABLE 1: DETAILS OF DIFFERENT MECHANIZED DEPILLARING FACES OF INDIA.

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*
					Caveability index	Nature of caving		
Pinoura	60	18.5 × 19.5	6.5	3.0	2332	Easy to moderate	Single pass	Success
Anjan Hill	85	28.2 × 28.2	6.6	4.5	4762	Moderate to difficult	Splitting and slicing	Success
Jhanjra	125	26.0 × 26.0	6.0	4.2	5672	Moderate to difficult	Splitting and slicing	Delayed caving
VK7	377	40.0 × 40.0	5.0	4.6	10522	Extremely difficult	Splitting and slicing	Roof collapse
Tandsi	260	40.0 × 40.0	5.0	3.0	3879	Unstable roof strata	Splitting and slicing	Partial extraction
GDK 11	325	48.0 × 46.0	6.0	4.6-6.0	7798	Difficult	Splitting and slicing	Success

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

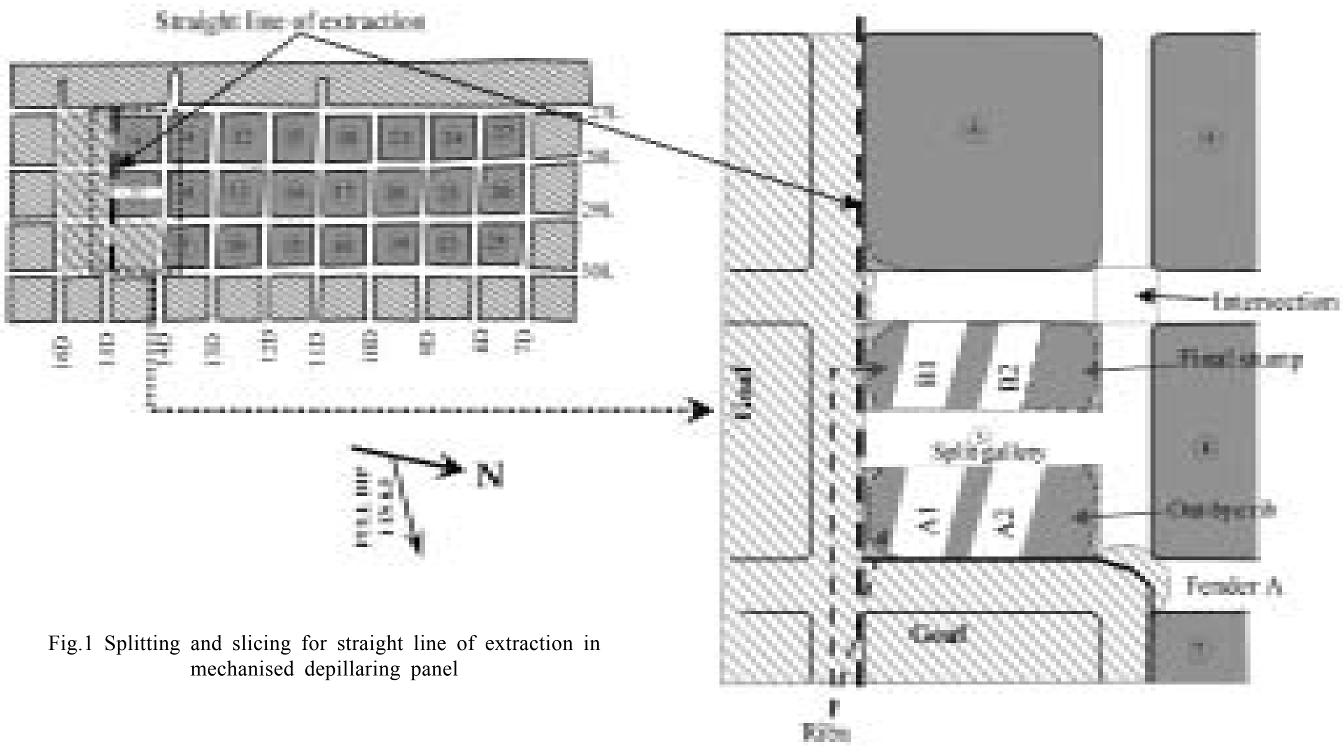

Fig.1 Splitting and slicing for straight line of extraction in mechanised depillaring panel

Directorate General of Mines Safety (DGMS) circulars (Kaku, 2004) provides an idea about the size of rib/snook during conventional depillaring. But a mechanised depillaring encounters different conditions, mainly, due to 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. Although considerable amount of work is done for rib/snook design in foreign countries (Mark and Zelanko, 2001; Lind, 2002{a}), there is an apprehension about success of these design norms in Indian coalfields. Two important reasons for this apprehension are: (a) uniqueness of rock mass and (b) complex geo-mining conditions of Indian coalfields. Therefore, it is realised to conduct an investigation to see the performance of rib/snook under varying conditions of depillaring operations. Considering difficulties of such a study in the field, numerical modelling is adopted to investigate performance of rib/snook for different stages of a depillaring operation. Obtained guidelines from a review of different types of available design approaches are utilised to plan different investigations on numerical models. Calibration of modelling parameters is done with the help of a widely accepted empirical formulation for pillar strength. On the basis of the results of numerical simulations, done for different conditions of a mechanised depillaring, this paper attempts to visualise the crucial role of a rib/snook during the depillaring. It is realised that the area based design approach for the rib/snook has advantages over the safety factor based design approach.

Mechanised depillaring

Indian coal mining industry is, mainly, practising semi-mechanized depillaring operations for underground pillar extraction. This approach of depillaring is fully saturated and there is hardly any scope for further improvement in production, productivity and safety by this approach. A fully mechanized depillaring is providing faster rate of extraction (Singh et al., 2014), which improves safety along with production and productivity of a depillaring operation. Therefore, the coal mining industry of the country has introduced a number of fully mechanized depillaring operations (Ram et al., 2015[b]) in last ten years only. A mechanized depillaring operation has many operational and technological differences with the conventional one as discussed below.

Method of extraction

A mechanized depillaring operation, generally, follows straight line of extraction (single row of pillars) from dip side of the panel. Such a single row of pillar extraction below the competent roof strata does not give enough width for the beam over the void to break. On the other hand, the length of the void increases as per width of the panel, which results large amount of overhanging roof strata inside the goaf for a wider panel. This overhang needs to be, primarily, managed either by induced caving of the roof strata or through an increase in the width of the depillaring. However, an important factor for the safety of the depillaring operation is an appropriate competency of the snook/rib at different stages of the depillaring (as per overhang inside the goaf).

Manner of pillar extraction in mechanised depillaring is dependent upon the site conditions including shape and size of pillars (if developed). Some special methods like Wongawilli (Lind, 2002[b]) and Navid (Lind, 2005) method are adopted under certain specific conditions but the three main manners of extraction for mechanised depillaring are: (a) Outside lift (b) Christmas tree and (c) Split and fender (Mark and Zelanko, 2001) (Fig. 2). Outside lift is used for small size of pillar and there is no need to split the developed pillars. Christmas tree method is adopted for moderate size of pillars and it also does not need splitting of the developed pillars during the depillaring. In this method, a coal pillar is taken in single pass by left and right slicing from the existing galleries (Chase et al, 1997). Generally, no rib is left between the slices of this method but design of snook is essentially required to restrict the effect of immediate intersection. Split and fender (pocket and fender) is adopted for bigger size of pillars, where a pillar is first splitted into fenders and then each fender is extracted by slicing. Here, requirement of support in the split gallery at the time of depillaring slows the speed of a depillaring operation. A rib is left out between slice and goaf while a snook is carefully designed to restrict the effect of immediate galleries intersection over the last slice. Also, a solid pillar/fender is always present at the back of the CM operator for safety. Outside lift and Christmas tree work without splitting and, therefore, do not require application of roof bolt support at the time of depillaring. However, the dimensions of the developed coal pillars in Indian coalfields, generally, needs splitting to suit the operational limits of the CM. Therefore, split and fender (pocket and fender) is the most suitable manner of extraction for the existing developed pillars.

Rib/snook mechanics

All methods of pillar extraction are bound to leave rib against the goaf. A rib is to protect the running slice from roof fall inside the goaf. A snook of, relatively, bigger in size is the

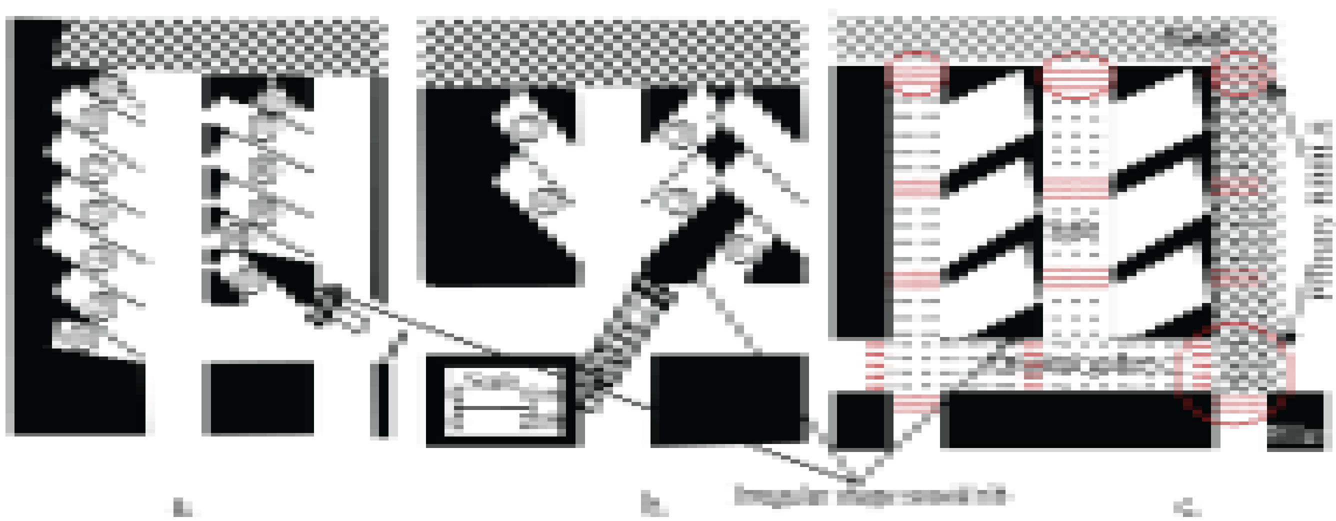

Fig.2 Pillar extraction mining methods: (a) Outside lift (b) Christmas tree (c) Split and fender

most out-bye rib of a fender/pillar (Fig.3), which is left to protect the last slice of the fender/pillar from adjacent intersection of galleries. A rib/snook is to carry maximum anticipated rock load in presence of an adjacent intersection of galleries (Mckensey, 1992). Thus rib/snook works like an applied support for a small period of time, taken by the slicing process. Depillaring leaves a number of snooks/ribs inside the goaf, which provide resistance against hanging goaf. Freshly exposed roof span over the width of a slice or consecutive slices rests over a rib/snook during the progress of the slicing in a fender. Instability of a rib/snook during slicing directly threats safety of the working.

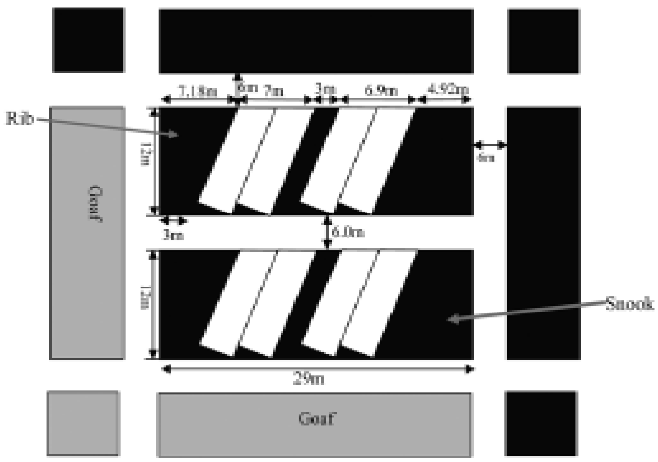

Fig.3 Positions of rib and snook for a typical manner of extraction of a pillar during mechanised depillaring

Generally, a pillar formed by a CM attains rhombus shape. These types of pillars provide regular shaped snooks/ribs after slicing. Support resistance of such snooks/ribs can be estimated through existing formulations. However, application of CM for a developed coal pillars of square/rectangular shape results irregular shaped snooks/ribs. Strength estimation of these irregular shaped snooks/ribs becomes a difficult task. In absence of an indigenous norm for rib/snook, different field applications of mechanised depillaring in India have adopted trial and error method of the design. Field performance monitoring of these designs noticed some successes (Ram et al., 2015[a]) and some failures (Mishra et al., 2013; Singh et al., 2011). Uniqueness of rock mass and existing complexities of geo-mining conditions of Indian coalfields restricts direct adoption of any foreign design. Frequent encroachment of working areas by goaf during caving of the inherent competent roof strata is a typical problem of Indian coalfields.

Pillar extraction i.e. depillaring is a dynamic phenomenon, where the response of all associated mining structures keeps changing with progress of the extraction. Three main mining structures during depillaring are (a) pillar/fender, (b) goaf and (c) applied support. Left out ribs/snooks also works like applied support for a depillaring operation. For a successful pillar extraction, the rib/snook should be large enough to support the intersection/exposed roof and, at the same time, it should be small enough so that it does not inhibit the caving with the progress of the depillaring. In a depillaring panel, generally, the area around intact pillars (standing ahead of extraction line) does not experience much strata dynamics. But the area inside the goaf and around the goaf edge (line of extraction) encounters considerable movement of strata and stress redistribution. The interaction between roof and pillars around the goaf edge needs to be investigated for a given site conditions. In the beginning of the pillar extraction, a beam of overlying strata (supported at both ends) is formed inside the goaf. After a sufficient increase in the dimension of the extraction, 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 influence of this cantilever. Although the major load of the overhang is transferred to the solid pillars (standing around the goaf edge), 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 overlying strata but the local instability of lower horizon of the cantilever to cover the span over the proposed slice/slices for depillaring is controlled by systematic design and planning of rib/snook.

Numerical modelling

Site conditions of an actual CM based depillaring panel are considered to study the effectiveness a rib/snook at different stages of a mechanised depillaring. It is decided to use continuum analysis software package FLAC3D (Itasca, 2000), mainly due to the available experiences of modelling at CSIR-CIMFR. This package can easily take care of bedding planes through interface, which are the main discontinuities of the proposed study. It is also decided to use rock mass rating (RMR) (Bieniawski, 1976), which could automatically take care of the discontinuities. Mohr-Coulomb strain-hardening/softening (MCSS) model of FLAC3D was chosen on the basis of a comparison of initial depillaring results obtained through elastic and plastic models (Fig.4). Various strength and elastic properties, necessary for numerical modelling used in the strain softening model, are listed below:

- Elastic constants;
- Peak and residual shear strength and the variation in between with the shear strain;
- Peak and residual angle of internal friction and the variation with the shear strain and
- Angle of dilation and its variation with shear strain.

Some of the required properties were obtained through laboratory testing of the procured core samples from the site and other properties were estimated according to Murli Mohan et al. (2001), as mentioned in Tables 2 and 3. In situ stress values were estimated as per Sheorey (1994).

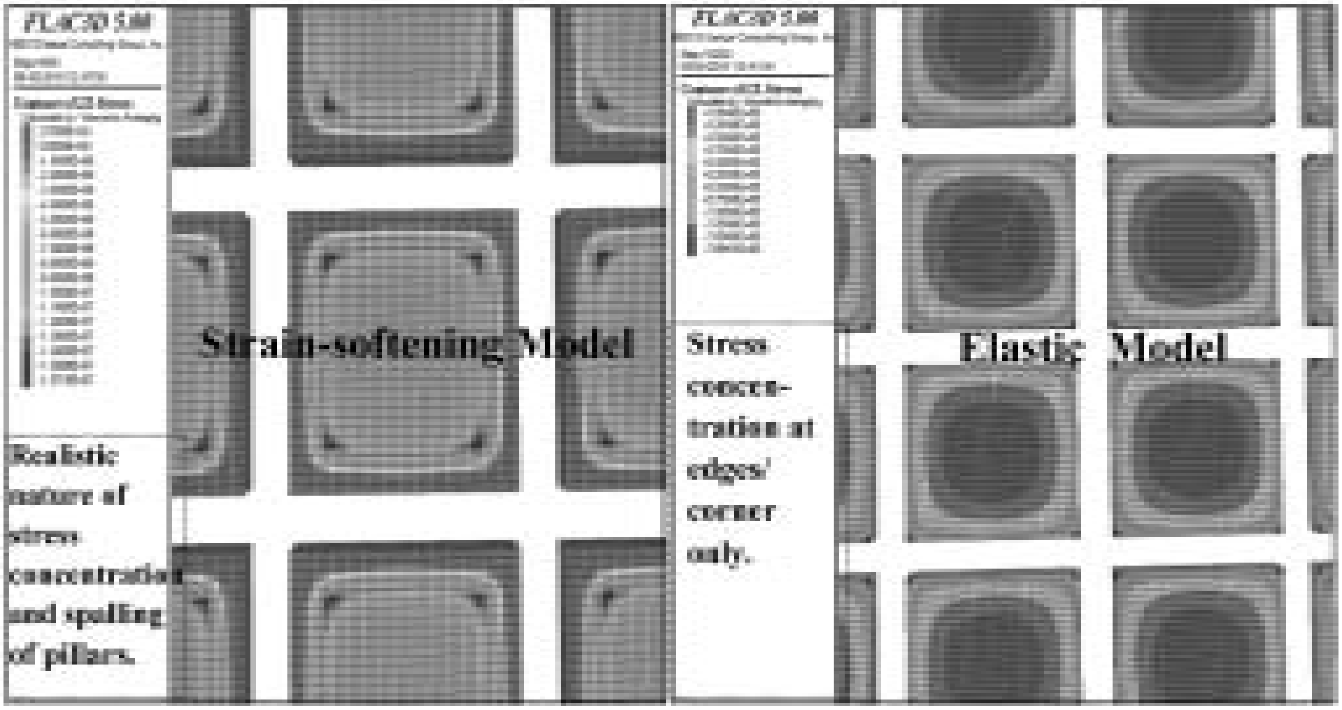

Fig.4 Comparison of initial modelling (development of pillars) results obtained through elastic and plastic models

Determination of the MCSS parameters for a rock mass is a difficult task in real practice but an empirical back-analysis makes it simple. For this back-analysis, different test pillar models were run with various sets of MCSS parameters for determination of pillar strength for matching it with the calculated pillar strength value through an empirical formula (Fig.5).

Simulation results

Considering the geo-mining conditions of the chosen site, a number of models were tested in laboratory for this study. A stable size of a rib is studied for different slicing operations, taking place at changing stages of the depillaring. As per the existing operational conditions of the mechanised depillaring, it is only area of the rib/snook was varied to see their effectiveness at different stages of the depillaring.

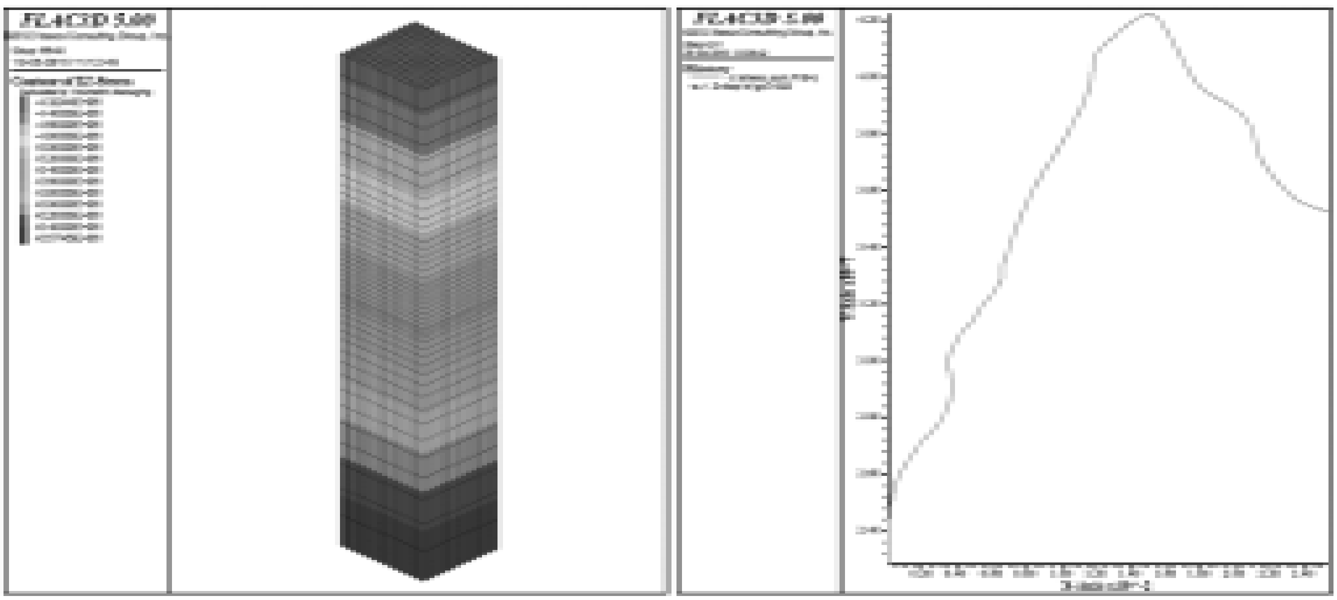

Fig.5 Generated grid pattern and obtained curve of stress-strain variations during test model study of pillar strength in a room and pillar environment

TABLE 2: 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

TABLE 3: PHYSICO-MECHANICAL OF THE ROCK-MASS FOR THE MODELLING.

Strata	Density (kg/m^3)	Cohesion (MPa)	Friction angle (degree)	Uniaxial compressive strength (MPa)	Uniaxial 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

Accordingly, size of the rib/snook was varied for the chosen site conditions to find out a lower value of the stable size of rib/snook. It is to be noted that only three sizes of ribs/snooks were considered for this experimentation, mainly, due to the time constraints and guidance available from the field experiences. From the results of this simulation, it is observed that the size of a rib/snook needs to be fixed for a given site conditions (Fig.6). A simple advantage of the calibration of the simulated model is that the observed stable size of the rib/snook matched with the field results. Fig.7 shows stability of various ribs/snooks, left in the depillaring process, for different stages of a mechanised depillaring panel. Here, pillar extraction up to fourth row of pillar extraction is studied. This study finds that the ribs/snooks, left during first row of pillar extraction, are failing when fourth row of pillars are extracted. From these results, it is evident that the left out ribs/snooks did not experience excessive stress over their core till completion of the second row of pillar extraction. Therefore, judicious reduction of, at least, first two rows of ribs/snooks is not difficult for the chosen site conditions. This judicious reduction of these ribs/snooks is important for smooth caving of the roof strata during further progress of the depillaring.

A magnified view of stress concentrations over a rib/snook after first row and fourth rows of pillar extractions are shown in Fig.8. This figure shows the contours of mining induced stress over three different sizes of ribs/snooks. A typical failure of thinner part of the rib/snook is observed with concentration of the induced stress over their core after sufficient increase in the width of the extraction. Mark and Zelanko (2001) attempted to provide the nature of stress redistribution over such a

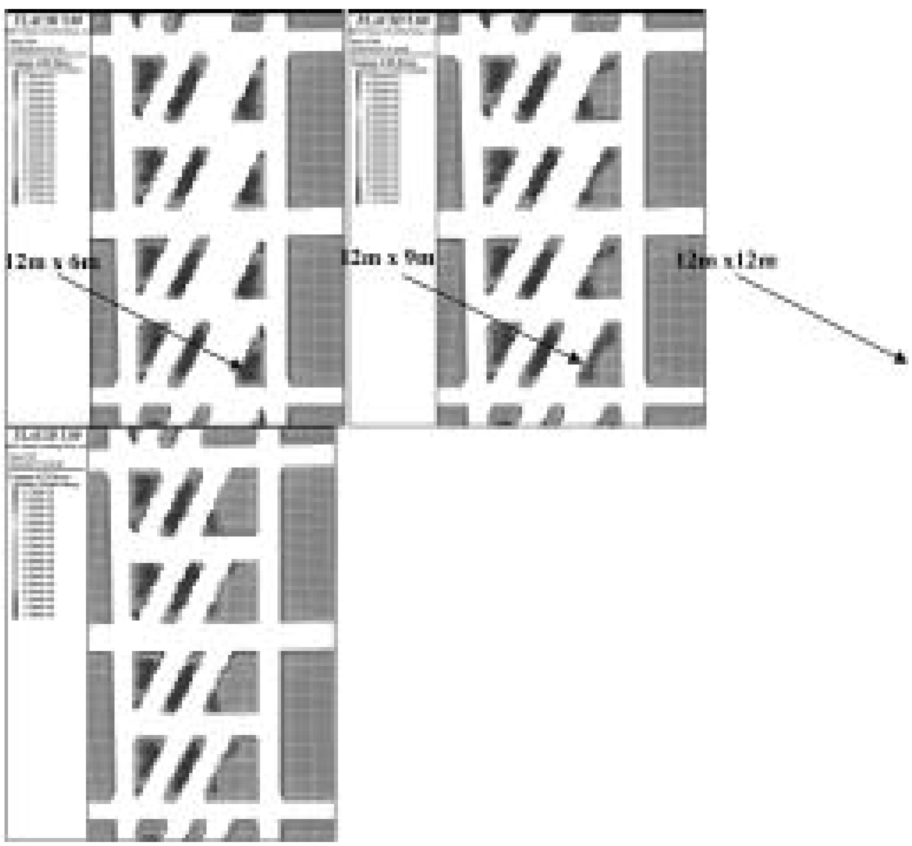

Fig.6 Stress development on different sizes of rib at 150m and 40 RMR after first row of extraction in the panel

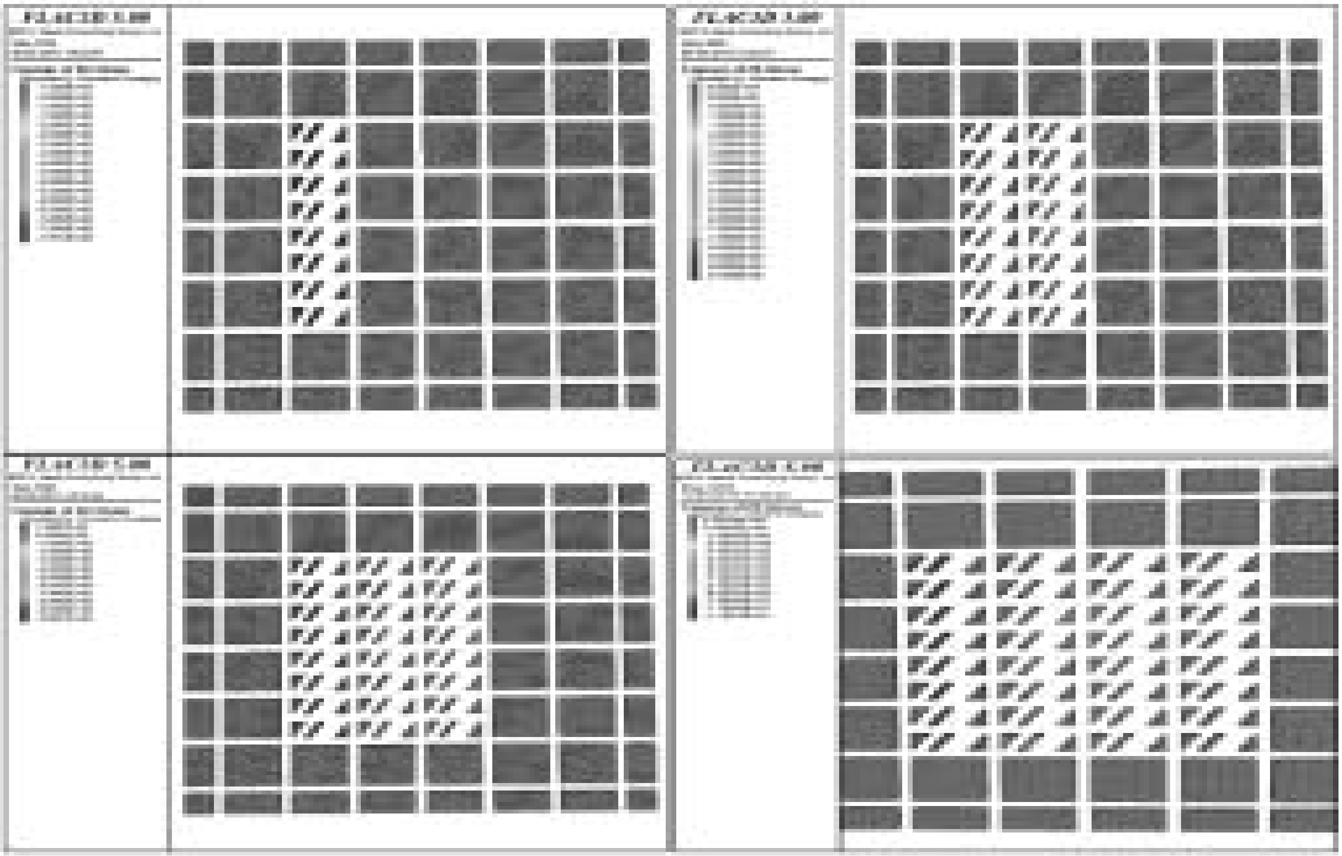

Fig.7 Conditions of different left our ribs/snooks inside the goaf after 1st, 2nd, 3rd and 4th rows of pillar extraction

shaped rib/snook (Fig.9). However, the observed nature of the stress redistribution by this numerical modelling over such a rib/snook during depillaring does not exactly match with that in different slices given by Mark and Zelanko (2001). Probably, Mark and Zelanko (2001) considered an ideal effect of the shape and material properties, which hardly happen during an actual practice in the field. Stain softening behaviour is quite close to an actual rib/snook loading and failure phenomenon in the field.

Rib/snook dilution

Above presented simulation study shows that the effectiveness of competency of the left out ribs/snooks inside the goaf varies with the progress of working in the panel. Presence of these ribs/snooks inside the goaf may delay caving of the roof strata. Even DGMS circulars allow judicious reduction of these ribs/snooks during the retreat. As the reduction of ribs/snooks is dependent upon the stability of the overlying beam/cantilever, it is difficult to have a uniform pattern of the rib/snook size reduction throughout the depillaring panel. A simulation based decision for the size reduction may be a better option but such detailed studies are not done for each depillaring site. Therefore, in absence of such a simulation study, it is a prerogative of the face supervisor to take a decision for the judicious reduction of the out-bye rib. Mechanised depillaring operation provides three main cutting options for the rib/snook size dilution.

Cut along the existing slice side

When a cut is made in the rib/snook along the final slice then the effective size of the left out snook is reduced (Fig. 10). Such a cut for the reduction of snnok size creates a remnant under shadow of the intact rows of pillars. This position of the remnant provides, relatively, better resistance during caving of a moderate roof hanging inside the goaf. For this operation, it is necessary to ensure that the roof strata over the in-bye slices are stable. This type of reduction supports caving inside the goaf and the stability of out-bye gallery is not thoroughly compromised. However, if the overlying strata are laminated and weak, then this type of reduction may be avoided. Under competent roof conditions this manner of judicious snook reduction may be adopted because the position of the remnant may reduce the chances of goaf overriding during the retreat.

Central cut in the snook

There are a number of occasions during a depillaring operation, where the efficacy of the left out snook needs to be considerably diluted. If a cut is made in the central portion of the snook (Fig.11) then the efficacy of the resulted remnants to resist caving of the roof strata is considerably reduced. Both the left out remnants of the snook are thin with, relatively, poor resistance capacity in comparison with the

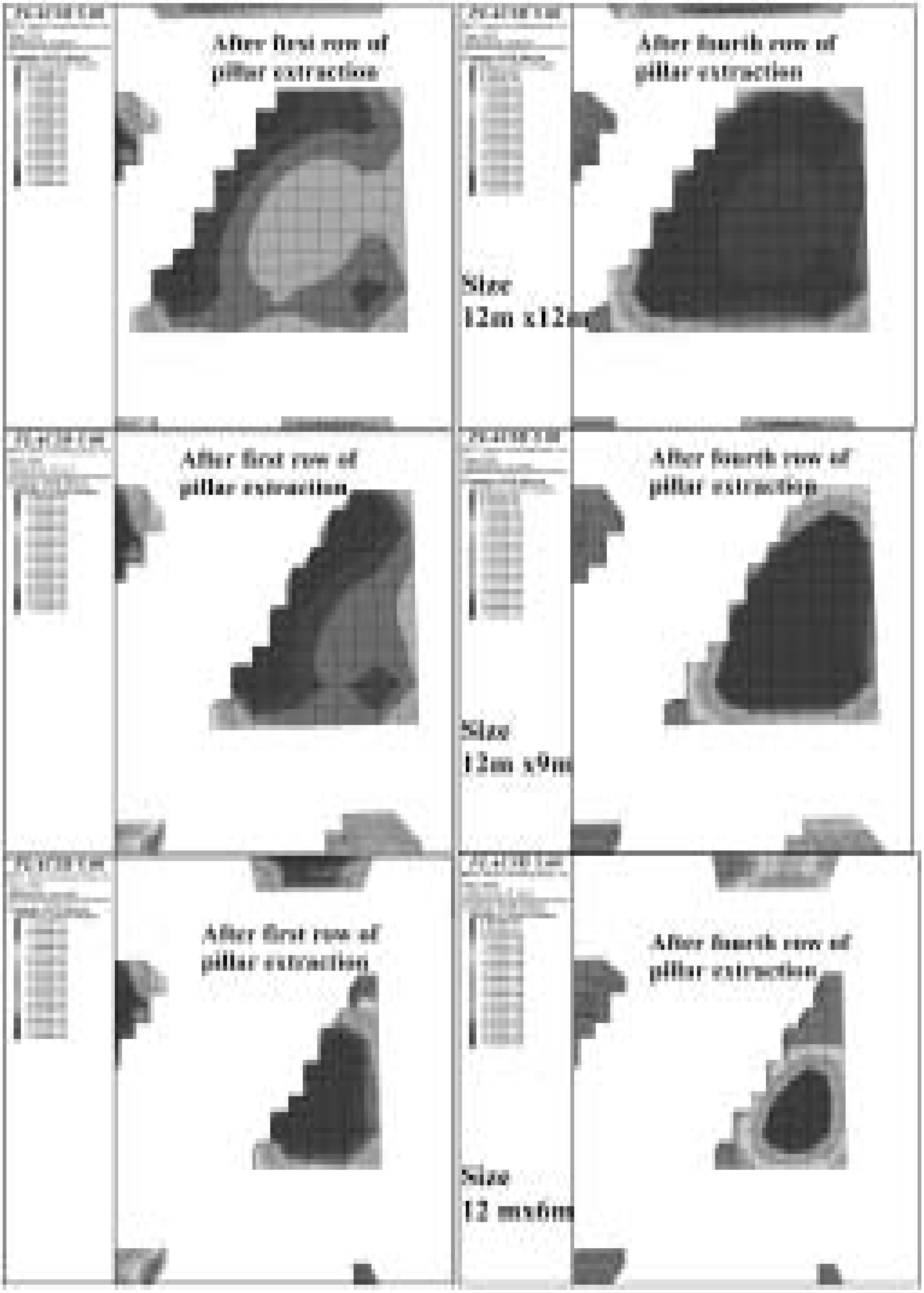

Fig.8 Magnified view of stress concentrations over a rib/snook after first and fourth rows of pillar extractions

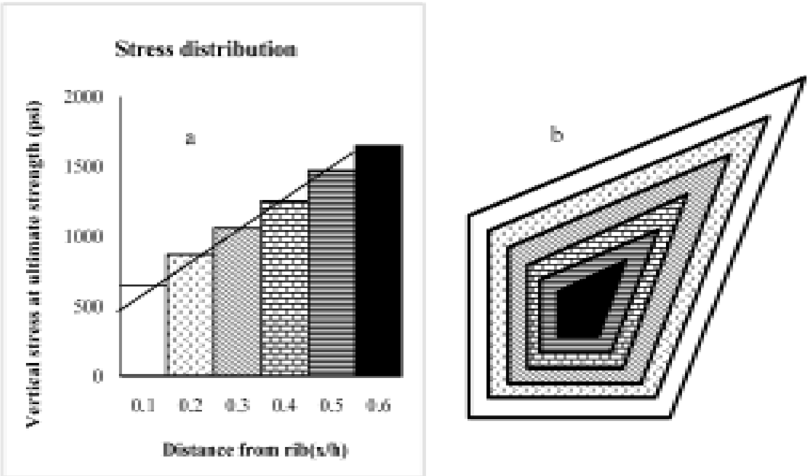

Fig.9 (a) Rib/snook stress distribution (cross-section to the core) and (b) Plan view of the stress distribution in different slices [after Mark and Zelanko, 2001]

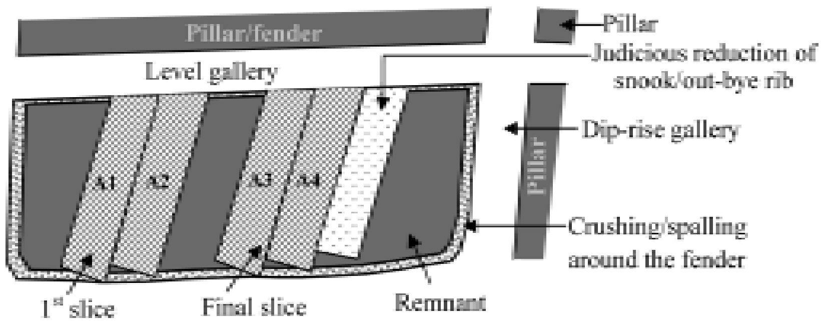

Fig.10 Reduction of a snook along existing slice side during the mechanized depillaring

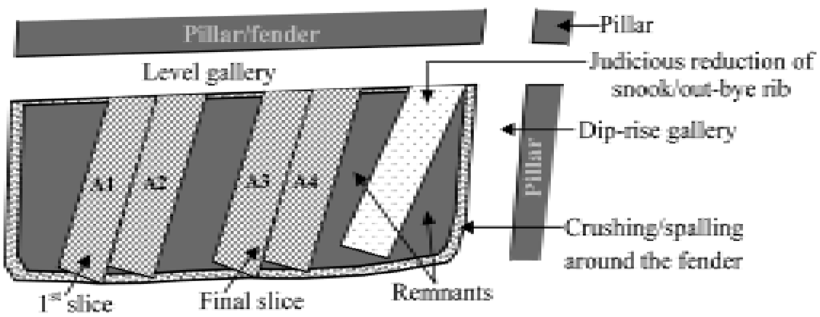

Fig.11 Reduction of a snook through a central cut in the snook during the mechanized depillaring

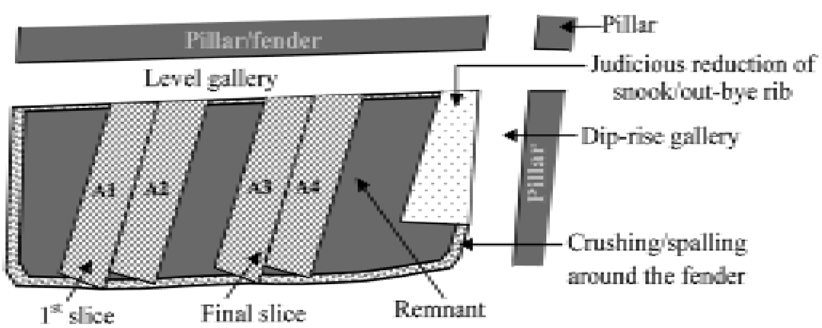

Fig.12 Reduction of a snook through a cut along existing dip rise gallery side in the snook during the mechanized depillaring

formation of a single remnant through side cutting. Such an approach of the snook reduction is followed, generally, in the beginning of the depillaring operation. In the beginning, there is no overhang of roof strata inside the goaf and the chances of extension of the roof fall up to the surrounding junction are remote. This manner of snook reduction is also adopted under weak/laminated roof strata because here an additional increase in the width of the final slice/slices needs to be avoided.

Cut along the existing dip-rise gallery side

Presence of an overhang of roof strata inside the goaf due to the existence of competent overlying strata may compel to reduce the size of a snook through a cut along the existing out-bye gallery (Fig.12). Here, size of the snook is diluted through widening of the existing supported gallery, under the shadow of intact pillars. This approach of the size reduction avoids core dilution of the snook/out-bye-rib and provides a, relatively, competent remnant. Position of the machine is, relatively, safe during the judicious reduction because of the shadow of the intact pillars and protection by the remnant from the goaf side. Here, coal recovery is little less in comparison with the other two options but the core of the out-bye rib is to remain intact. Such a reduction of the snook may be adopted when the machine finds danger in cutting along the existing slide side due to roof overhang and there is a need leave, relatively competent remnant.

Conclusions

Mechanized depillaring of the developed pillars, generally, provides irregular shaped ribs/snooks. These ribs/snooks work like a temporary support because their competency is vital during the progress of the neighbouring slice. However, after completion of the slice, competency of the ribs/snooks needs to be diluted. Due to irregularity in the shape of the rib/slice, area based design approach is preffered over width to height ratio (w/h) or safety factor based approaches. Available experiences of field trials of the mechanized depillaring in different coalfields have given some idea about the area of the rib/snook to be left for a chosen site conditions. However, the competency of these left out ribs/snooks needs to be diluted at different stages of depillaring in a panel. Development of a calibrated numerical modelling approach provides good estimation of performance of these ribs/snooks at different stages of the depillaring. Results of such modelling study help in deciding the effectiveness of a rib/snook competency at different stages of depillaring in a panel. However, the cutting approach to dilute the size of a rib/snook needs to be fitted with the existing conditions of the roof strata inside the goaf.

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