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Chapter

Developments Made for Mechanised Extraction of Locked-Up Coal Pillars in Indian Geomining Conditions

Ashok Kumar, Dheeraj Kumar, Arun Kumar Singh, Sahendra Ram, Rakesh Kumar, Mudassar Raja and Amit Kumar Singh

Abstract

Bord and Pillar method of underground mining has been used extensively to develop Indian coal seams into pillars and galleries. This results in only 20–30% recovery of coal and rest coal remain locked up in developed pillars. Indian coalfields are famous in the world for its uniqueness and complexity of the geomining conditions which makes the extraction of the locked-up coal pillars a difficult and hazardous activity using different underground mining methods. Indian mining industry has introduced mechanisation since last 10 years to deal with the various underground rock mechanics issues in order to improve the efficiency and safety during recovery of locked-up coal pillars. But mere introduction of mechanisation did not solve all the rock mechanics problems due to requirement of indigenous design of different involved geotechnical elements for Indian geomining conditions. CSIR-CIMFR is a national research organisation engaged in improving conditions of underground coal mines. It has developed rock mechanics advances, namely, design of irregular shaped heightened rib/snook, roof bolt-based breaker-line support, warning limit of roof sagging, and cut-out distance for continuous miner-based mechanised depillaring. This chapter presents the developments made and highlights challenges to pursue future research studies for mechanised depillaring-based mass coal production from Indian underground mines.

Keywords: continuous miner, mechanised depillaring, rock mechanics issues, roof sagging, rib/snook, breaker-line support, cut-out distance

1. Introduction

Around 96% of the total coal production in India is currently being produced by opencast mining method and the contribution of underground mining is on a declining trend from 22% in 2001 to 4% in 2019. Opencast is favoured due to availability of reserves at shallow depth of cover and heavy earth moving mechanised technologies over underground as the former has rock mechanics issues as only slope/dump stability. However, opencast mining method has limitations of depth and associated environmental concerns. Underground mining is a way forward towards clean coal production technology and sustainable development. Depletion of coal at shallow depth is paving the way towards underground mining.

Indian coal mining industry had rampantly developed a number of coal seams using Bord and Pillar (B&P) mining method on square/rectangular pillars and galleries with around 20–30% coal recovery as per Regulation 111 of the Coal Mines Regulation [1]. Development of coal seam using B&P mining method requires less technical knowledge of rock mechanics. Depillaring of the developed coal pillars becomes challenging due to complex geomining conditions of Indian coalfields namely nature of roof, geological discontinuities and surface/subsurface structures. Conventional depillaring (CD) using drilling-blasting faced issues of goaf encroachment, high induced stresses and failure of underground structures. Coal producing industries started looking for suitable mass coal producing underground technologies to meet the desired coal production. Longwall mining method was introduced long back in India during 1970s but did not get success due to the direct application of foreign technology in Indian complex geomining conditions without any *in-situ* field investigation.

Continuous miner (CM) based mechanised depillaring (MD) has been introduced as a mass coal producing technology to extract the standing coal pillars. It has proved to be successful in India and CM has been deployed in a number of Indian coal mines and many more are yet to come. It has gained the faith of industry by proving its potential of safety and production. Reason of success of CM based MD in Indian coalfields are indigenous design of different geotechnical elements like irregular shaped heightened rib/snook, roof bolts-based breaker-line as goaf edge support, warning limit of roof sagging in geotechnical instrument and cut-out distance in different geomining conditions. Average daily production from a CM face is around 2000 t which is around 10 times of the daily production from a CD face using drilling-blasting. Success of any underground mining method depends upon the performance of underground structures under extreme difficult high induced stress condition. **Table 1** shows the details of MD during development and depillaring in Indian coalfields using CM.

Name of mine	Depth	Pillar size (m × m)	Gallery width (m)	Immediate roof	Manner of pillar extraction	Snook size (m^2)	Roof sagging limit in AWTT (mm)	Cut-out distance (m)
A	50–163	33 × 33	6.6	Sandy shale	Split and slice	26	5 mm as both warning and withdrawal limits	14 m in split and 10 m in slice
G	160–325	35 × 36	6.0	Sandstone	Split and slice	102	5 mm as warning and 10 mm as withdrawal limits	15 m in split and 12 m in slice
P	50–120	18.5 × 19.5	6.6	Shale	Christmas tree	22	5 mm as warning and 8 mm as withdrawal limits	12 m in split and 9.5 m in slice
V	50–100	18.5 × 19.5	6.6	Shale	Christmas tree	22	5 mm as warning and 8 mm as withdrawal limits	12 m in split and 9.5 m in slice

Table 1.
Details of mechanised depillaring operations at different Indian coalfields.

2. Rock mechanics challenges in mechanised depillaring

Underground mining in India has not boomed to that extent due to the less rock mechanics advances in B&P mining method. Depillaring continues to be one of the most challenging and hazardous activities in underground coal mining due to different accidents by roof/side falls and poor performance of structures. It is the main stage of production with around 60–80% of coal recovery. MD was first introduced in 2003 at Anjan Hill Mine of Chirimiri Area of South Eastern Coalfields Limited a subsidiary of Coal India Limited. Irregular shaped rib/snook created during pillar extraction and resin grouted roof-bolts are used as goaf edge support for the first time in India. Due to non-availability of empirical formulation to design such rib/snook and roof bolts-based goaf edge support, MD achieved mixed results in Indian coalfields. Also, the time interval between flashing of light in auto warning tell-tale instrument and roof fall was recorded to fix a warning threshold limit of roof sagging. It was successful at Anjan Hill Mine and MD was further introduced at a number of Indian coal mines to extract standing coal pillars and virgin coal seams.

It was found that the resin grouted roof-bolts as breaker line support (RBBLS) installed directly at the goaf edge did not work effectively and the roof fall extended inside the working and caused collapse of rib/snook and burial of CM [2, 3]. A small increase in area of rib/snook by 20–40% increased the stand-up time of roof in goaf by 5–10 hours. Hanging roof is a serious problem during MD as it creates the issue of front abutment stress causing goaf encroachment and burial of CM. Safety and productivity are the main concern during the underground mining. Geotechnical investigations found that caveability of overlying strata and size of remnants are the two important factors which affect the safety and productivity. Insufficient knowledge of geological discontinuities further aggravates these issues. Rock mechanics challenges at the goaf edge during MD are very complex which needs to be addressed indigenously.

2.1 Irregular shaped heightened rib/snook

Natural supports (pillar/fender/rib/snook/stook) are an important element for the success of MD. Size of pillar remnant is critical for the regular caving of overlying hanging strata in goaf during MD. Different countries used different nomenclature for the remnants like snook/stook 'x'/final stump/rib/narrow fender (**Figure 1**). Risk of sudden major roof falls is reduced by leaving a proper sized rib/snook against the goaf. It acts like a barrier between the slicing operation and goaf. Pillar is split into two equal halves and each half is called fender/stook. After splitting, one fender keeps supporting the slicing operation in another reduced sized fender. Rib/snook is remains of fender left to temporarily support the cantilevering/beaming roof to permit safe extraction and fall gradually after the extraction is completed. Stability and competency of fender and rib/snook is important for the maximum possible extraction during MD. Natural supports provide more support to the roof than any artificial designed support (cog/chock/bolt/mobile breaker-line roof support). Interaction between the support (natural/artificial) and roof determines the safety and efficiency of the MD.

During the retreat rib/snook created are further reduced judiciously for regular caving of roof in the goaf which involves dangerous risk of accident. Narrow rib/snook crushes easily compared to wider snook and size of snook decides the fall area, pattern and filling. Massive/strong overlying strata are more affected by the rib/snook size compared to weak/laminated strata. The practice of leaving too large and too many rib/snook in the goaf over supports the roof cantilever/beam resulting

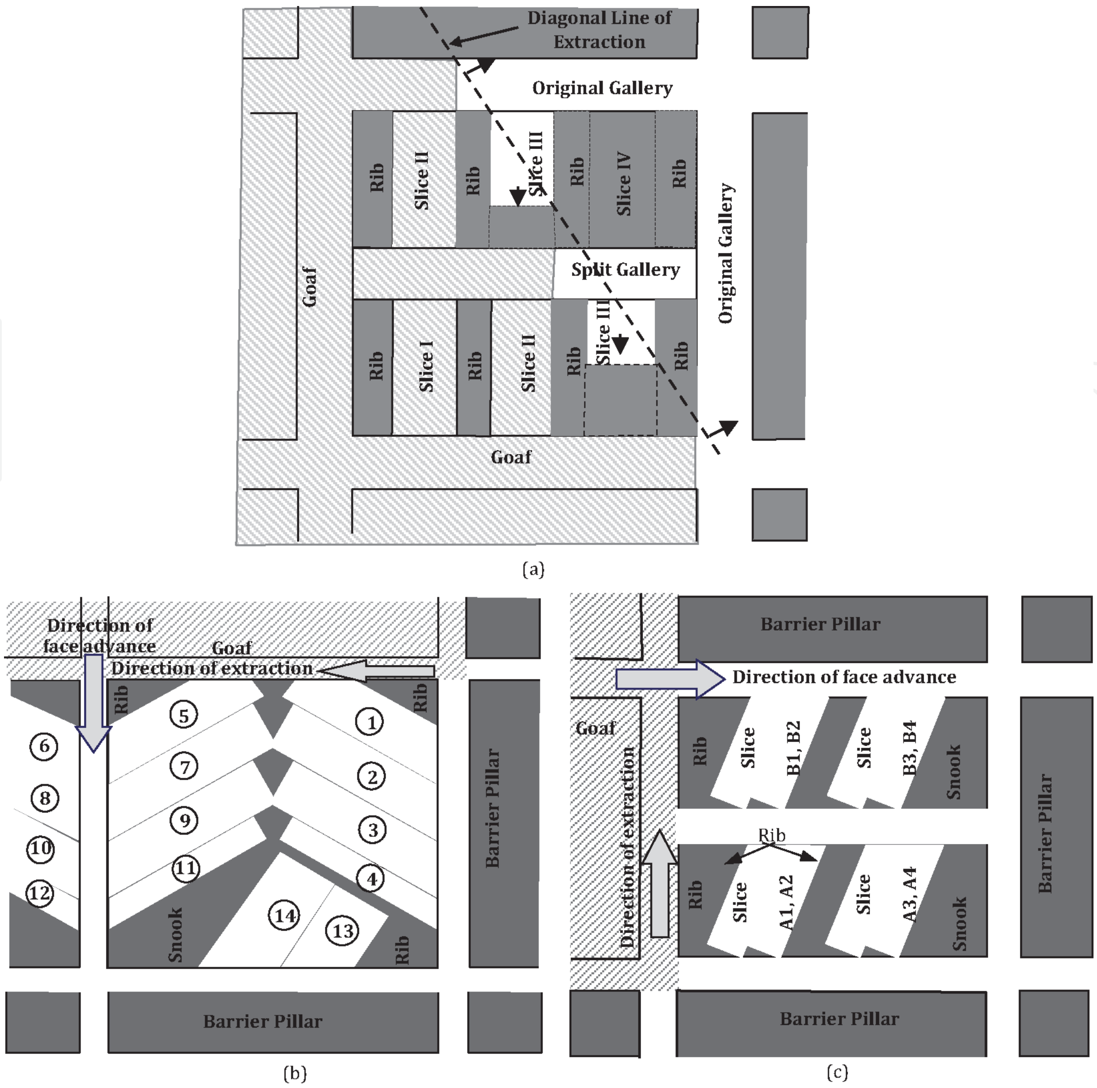

Figure 1.
Different sizes of rib/snook created during the conventional and mechanised depillaring (modified after Singh et al. [4]). (a) Manner of extraction and regular shaped rib during conventional depillaring. (b) Single pass extraction/fish-bone/Christmas tree. (c) Splitting and slicing/pocket and fender.

in increased stand-up time of roof. This results in transfer of abutment stress towards fender and solid pillars in the working. Laminated/weak strata and shallow depth cover strata have less tendency of bridging compared to strong/massive at higher depth of cover. For weaker strata even a small rib/snook acts like a solid pillar at shallow depth of cover.

Small increase in area of rib/snook may lead to increased stand-up time of roof. Different shapes and sizes of rib/snook created during the three different manner of extraction are shown in **Figure 1**. The shape of rib/snook is often irregular in shape due to the manoeuvrability of CM and existing rectangular/square pillars. Shapes and estimation of area of such shapes of rib/snook formed during CD and MD is shown in **Figure 2**. No empirical formula is applicable or available to estimate the strength of such irregular rib/snook **Figure 2(b)** and **(c)**. Seam height, depth of cover and nature of roof strata plays important role in deciding the competency of a given size of rib/snook. A conceptual model is developed for establishing a relationship of stand-up time of different nature of roof with the different sizes of rib/snook during MD as shown in **Figure 3**.

Singh et al. [4] studied the performance of rib/snook at different underground mines practising MD at different depths and nature of roof. CM carried out the slicing operation under the shadow of created competent rib/snook. Therefore,

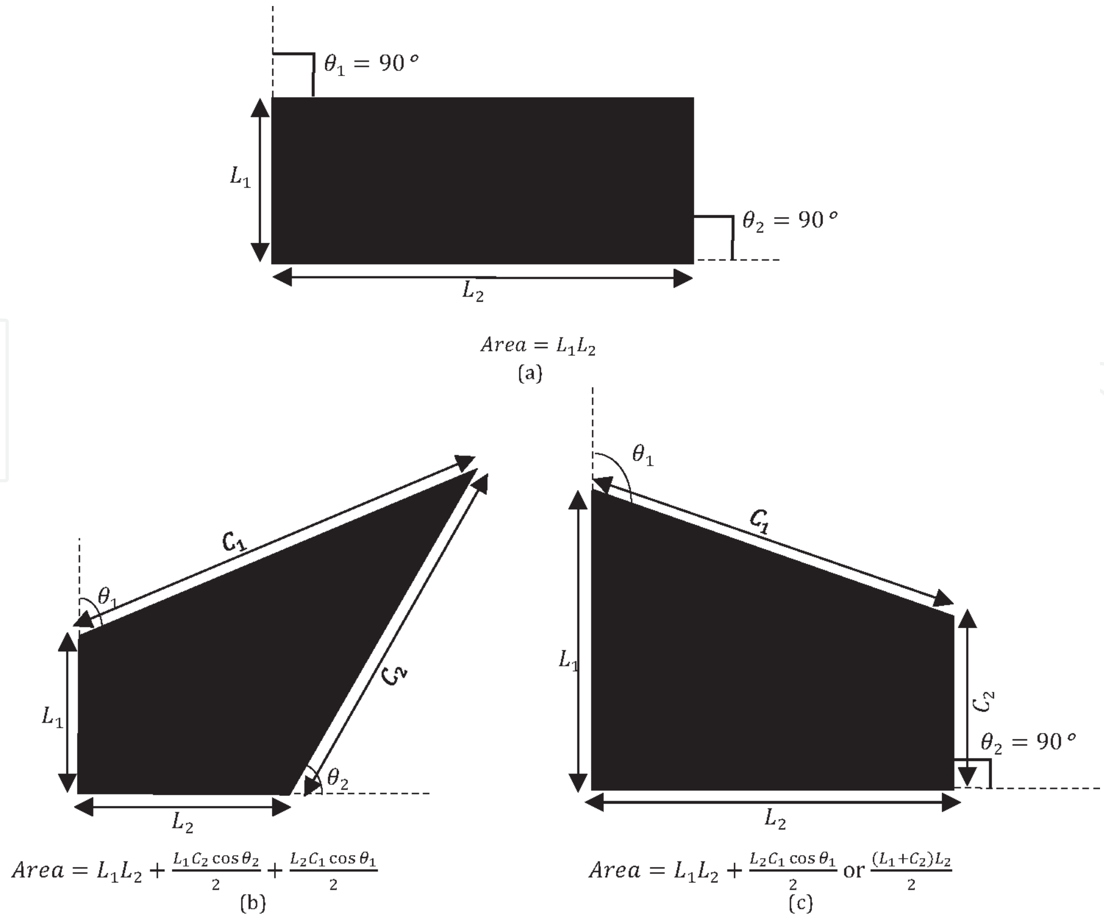

Figure 2.
Area of different shapes and sizes of rib/snook created during the conventional and mechanised depillaring. (a) Shape of snook during conventional depillaring method. (b) Shape of snook during Christmas tree/fish bone method. (c) Shape of snook during split and fender method.

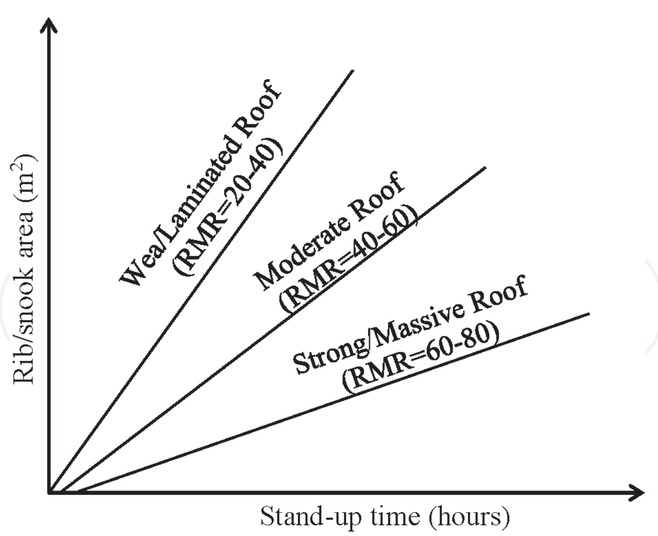

Figure 3.
Stand-up time of different nature of roof in goaf with variation with rib/snook area.

stability of rib/snook becomes a concern for the safety of men and machineries. Some cases of burial of CM occurred at few mines due to failure of incompetent rib/snook explained in Singh et al. [2]. Singh et al. [4] conducted a parametric study based on the field studies on numerical models by varying the nature of roof and depth of cover. This study found to be useful in designing a competent rib/snook during MD.

2.2 Roof bolt-based breaker-line as goaf edge support

Goaf edge during MD poses a challenging rock mechanics issue especially during the reduction of fender into rib/snook. Rib/snook formed cannot alone act against the goaf encroachment as it needs the support of breaker/hinge-line to break the bridging beam/cantilever roof. Performance of RBBLS in different mines had been monitored visually and also, using instrumented roof bolt. It was found that the position of hinge/breaker-line is affected by the nature of roof rock and size of competent fender/rib/snook/stook 'x', split gallery and out-bye intersections. Function of the hinge/breaker-line is to enhance the strength of rib/snook against caving roof and prevent the encroachment inside the working.

RBBLS forms an important geotechnical element of MD for its success. Pillar/fender at the goaf edge experienced fracturing of its sides (called spalling) which leads to shifting of position of RBBLS by 0.5–2.0 m towards the out-bye side depending upon the extent of spalling. After shifting the position, the efficiency of RBBLS enhanced (**Figure 4**). Ram et al. [5] designed the roof bolts-based breaker line as goaf edge support in Indian MD coalfields using the field and numerical simulation studies based on parametric variation of nature of roof and depth.

2.3 Warning limit of roof sagging in geotechnical instrument

Auto warning tell-tale is a geotechnical instrument which has a LED light for flashing in dark environment when the roof sagging crosses the threshold limit fixed in it. There are two important factors which decide success of AWTT in MD, namely, setting of safe roof sagging threshold limit and the fixation of anchorage point. Generally, the anchorage is fixed at a horizon of 10 m in the roof which is found to be a successful practice as the roof below it is vulnerable to failure during local fall after extraction. Roof sagging value is found to be varying in different methods of mining and factors like size of remnant, thickness and elasticity of roof affected it. Therefore, Kumar et al. [6] studied the roof sagging limit set in AWTT at different MD faces. Further, a parametric study to estimate a safe warning roof sagging limit is decided based on field studies and numerical simulation.

A typical observation by AWTT is shown in **Figure 5** indicating the time-interval between flashing and roof fall in a MD panel. Initially, due to the support by barrier pillar from three sides and solid pillar from one side, the time taken for roof fall is the maximum. As the extraction progresses away from the barrier on dip-side, the time-interval between flashing of AWTT and roof fall reduced due to the

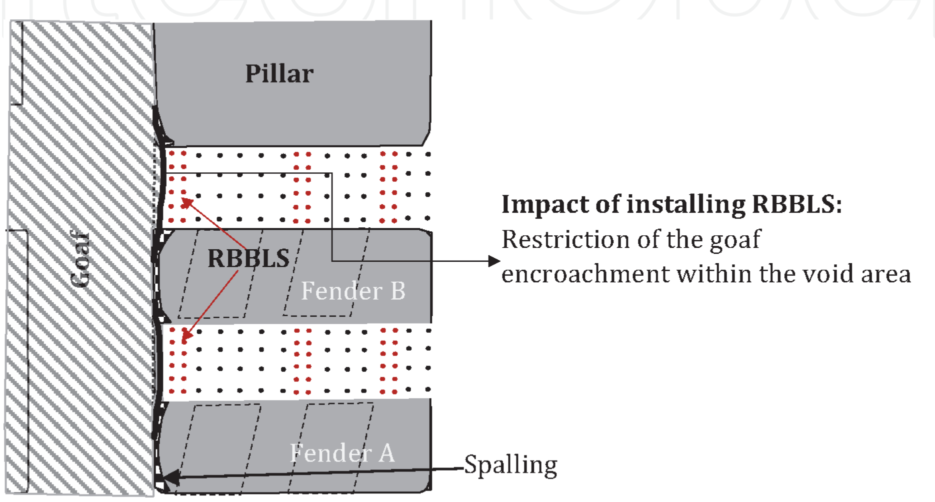

Figure 4.
Controlled caving inside the goaf after placement of an efficient breaker line supports at the goaf edge.

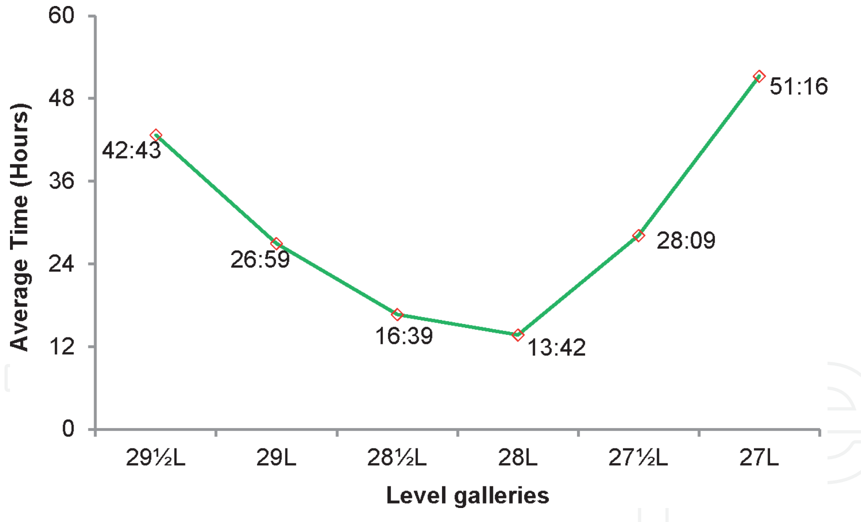

Figure 5.
Time-interval between flashing and roof fall in a MD panel measured using auto warning tell-tale.

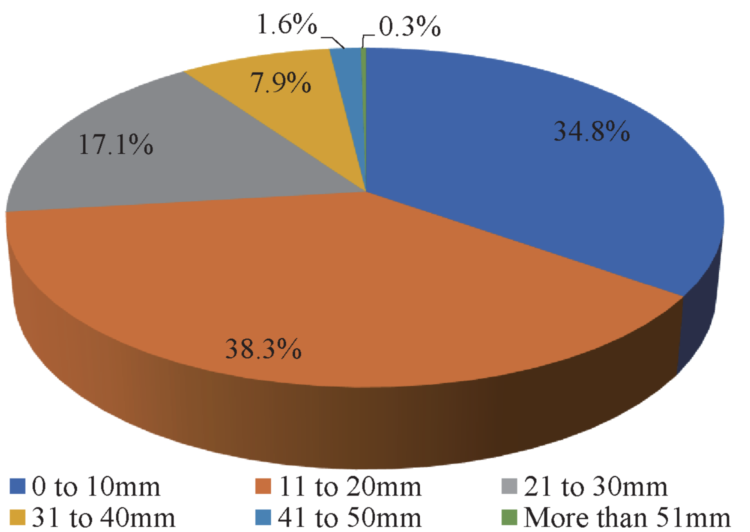

Figure 6.
Range of roof displacement observed in a panel through tell-tales.

formation of cantilever from beam. Variation in recording of roof displacement is studied in a MD panel through tell-tales (auto warning/single height/rotary). Most of the observations of roof sagging is found to be between 11 and 20 mm (**Figure 6**) as recorded from different tell-tales used in the mine.

2.4 Cut-out distance

Rock load height increases with increase in width of a gallery and found to be independent of its height. Cut-out distance defines the productivity of CM; therefore, it becomes an important geotechnical element to be designed in a panel. It is defined as the safe and stable span for a fixed width of gallery excavated by CM in a single lift without application of any applied/reactive support. Field studies are conducted at a number of Indian MD coalfields. It is found that width of the excavated gallery and nature of overlying strata are the two most influencing parameters which affects the cut-out distance to be practised in a given geo-mining conditions.

It has been also found that cut-out distance is to be kept different for a development and depillaring operations. Lesser rock mechanics issues are encountered during development activity by CM whereas depillaring involves dynamic activity where overlying strata are highly vulnerable to large induced stresses compared to development. However, it is kept to be a constant value in both development and depillaring operation for easier practice and understanding by the miners. It can be increased during development for faster preparation of the panel and reduced during depillaring for safety and productivity of the mine.

2.5 Thickness of coal seam

Thickness is a serious issue in Indian coalfields as a major amount of coal is lost due to unplanned development of a seam along roof/floor/middle horizon. A number of thick coal seams in the country are left developed along different horizons locking huge amount of coal [7]. Extraction of full thickness of a thick coal seam at a time is important for Indian underground coal mines. Earlier blasting gallery (BG) method was used by the Indian industry to extract the complete thickness of a thick coal seam in a single lift [8, 9]. But this method failed to improve the safety as well as faster and efficient recovery of coal extraction from BG panels. Height of the pillars at the goaf edge increased from the inbye side due to full extraction of the coal seam thickness during BG. Barrier pillars and pillars at the goaf edge in the panel were vulnerable to goaf encroachment and their premature collapse occurred due to strength dilution by indirect increase in height. Stability of heightened coal pillar was studied by Kumar et al. [10] using numerical simulation and established a relation between strength estimated through numerical modelling with that of CSIR-CIMFR formula, shown below.

$$S_{CMRI} = 1.28\, S_{NM} - 9.5 \tag{1}$$

where S_{NM} = pillar strength estimated through numerical modelling and S_{CMRI} = pillar strength estimated through empirical formulation.

Modification in manner of pillar extraction by CM helped in complete recovery of a 6 m thick coal at a time. CM extracted the floor coal up to 1.5–2.0 m during retreat in a slice. This created an issue of heightened irregular shaped rib/snook. Stability of such heightened rib/snook during MD was studied by Kumar et al. [7] by changing the heights of rib/snook from 3.0 to 6.0 m for a given area, nature of roof and depth. It needs to be further studied by changing the depth of cover and nature of roof with the variation in heights of rib/snook.

2.6 Issues of stress and pillar design at higher depth

Depth is a major issue for design of underground mining structures as B&P mining method is no more feasible at overburden cover greater than 400 m. Longwall is feasible at such depth of cover but indigenous design of barrier/chain/rib pillar is important. A new concept of barrierless design of longwall panel has been introduced in China. Similar concept can be used in B&P for the design of barrier pillars. Optimum design of pillars helps in maximum coal recovery and minimum wastage as left-out remnants in goaf. Worldwide available empirical formula for estimation of pillar strength does not explain the effect of depth on their strength except Sheorey [11]. Higher depth creates the case of high value of vertical in-situ stress which affects the performance of underground structures [12]. Available empirical formulation becomes redundant for the strength estimation of underground structures at higher depth. CSIR-CIMFR empirical strength formula may be used to estimate pillar strength but it did not consider the failed and stable cases of pillar at such high depth of cover [13].

Experiences of working at higher depth are important for the Indian industry as it is planning to go deeper for coal extraction in near future. Recent experiences gained by IGN, Czech Republic in collaboration with CSIR-CIMFR, are beneficial for the Indian mining industry. Underground structures at higher depth of cover needs to be designed judiciously for the maximum coal recovery by leaving less amount of coal in the goaf. Further, it would not create the issues of spontaneous heating, goaf encroachment and coal bump. Also, there is a need to design an optimum barrier pillar at higher depth of cover exceeding 300 m which crushes with retreat of working in the panel. Concept of rib/snook design in MD needs to be used for design for pillar at higher depth of cover. It should be capable to support the roof and stand stable till the extraction is over under its shadow and should fail in a controlled manner in goaf due to increase stresses. Following such design norm would help in sustainable development with maximum utilisation of resources with less wastage.

2.7 Goaf span and caveability

Different nature of overlying strata has different unsupported span for its caving. During first row of coal pillar extraction in MD, the goaf span is not sufficient for caving and therefore it is suggested to go for the maximum possible extraction due to the support from barrier and solid pillars from all the sides. Generally, roof fall is experienced when the length of the goaf span is equal to the panel length. Presence of thick difficult to cave massive competent strata does not cave even after this span due to the higher strength and thickness [14]. Hanging of such strata creates issues of goaf encroachment, over riding of pillars and sometimes air blast and coal/rock bump.

Different techniques have been used to deal with such strata during MD. MD is practised in Pinoura and Vindhya mine having easily caveable roof with frequent roof fall to VK-7 and Churcha mine having massive Deccan trap/sill delaying roof fall. Bulking factor plays a major role in caving of roof and estimation of subsidence on the surface. Sometimes the difficult to cave massive strata is located after a parting in the roof. In this case the bulking of the caved material fills the void. If the roof is difficult to cave-in and present as immediate strata then it remains hanging in goaf for a longer span of exposure and remedial measures like induced blasting or small panel (non-effective width) technique is adopted. High induced stress is created due to large span of overhang in the goaf. **Figure** 7 shows the area of exposure and progressive area of fall in a MD panel.

The value of caveability index (I) decides the easiness/difficulty hanging overlying strata to cave in goaf. It was established by Sarkar and Singh [15] for characterisation of the overlying strata in Longwall mining method. It is defined as:

$$I = \frac{\sigma l^n T^{0.5}}{5} \tag{2}$$

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.

This caveability index developed for Longwall mining is not applicable in case of MD as it has a number of openings around the goaf edge and left-out ribs/snooks. There is a need to develop such index for MD which would help to extract coal by CM especially under extremely difficult to cave massive strata.

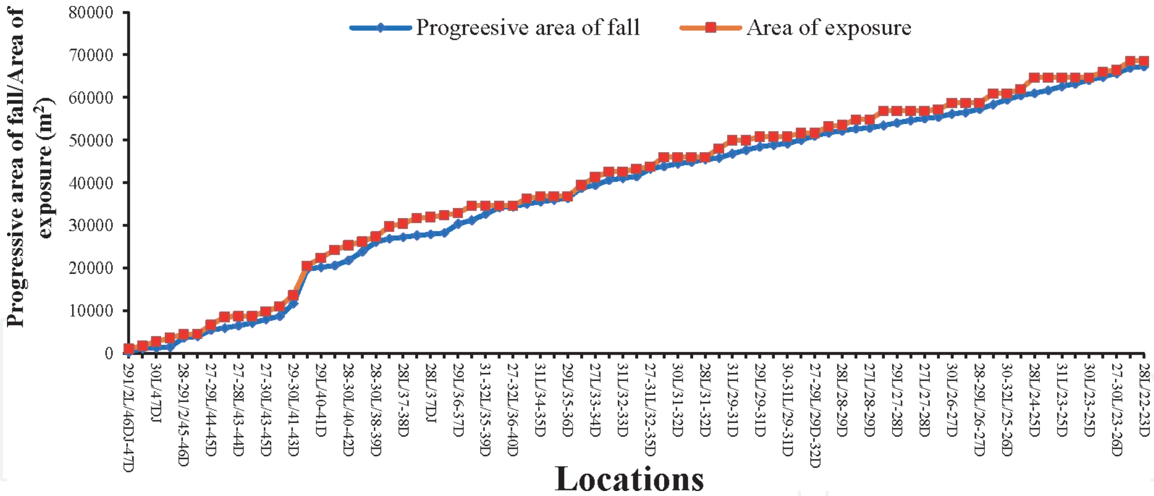

Figure 7.
Details of area of exposure and roof falls occurred in MD panel.

2.8 Geological discontinuities under influence of in-situ stress

Underground mining operation has witnessed failure of roof during widening and heightening of the developed galleries for adaptability and manoeuvrability of CM (**Figure 8**). This failure occurs due to hidden joints/slips with wash-outs, intercalation, and cross-stratification of shale and sandstone (**Figure 8**). Further, this failure was controlled by using the appropriate support system as per the results of numerical simulation and field investigations. Support becomes an important element under such disturbed nature of roof. Artificial supports in the immediate roof are installed generally after a length of 12 m (cut-out distance of CM) in a gallery width of 6 m. Geological discontinuities (hidden slips, wash-outs, cross-stratifications and intercalations of shale and sandstone) in immediate roof strata affected the advancement of drivages using CM in a panel. Freshly exposed immediate roof strata up to 1.8 m failed over the remotely operated CM. The local fall was dangerous to the drivages as it affected the safety, production and productivity of the mine. After the roof fall, cut-out distance was reduced to 4 m but the roof instability continued in the drivages. Further, support system was redesigned (increased density and length of bolts with wire mesh) to successfully control the roof instability for the reduced cut-out distance of 4 m.

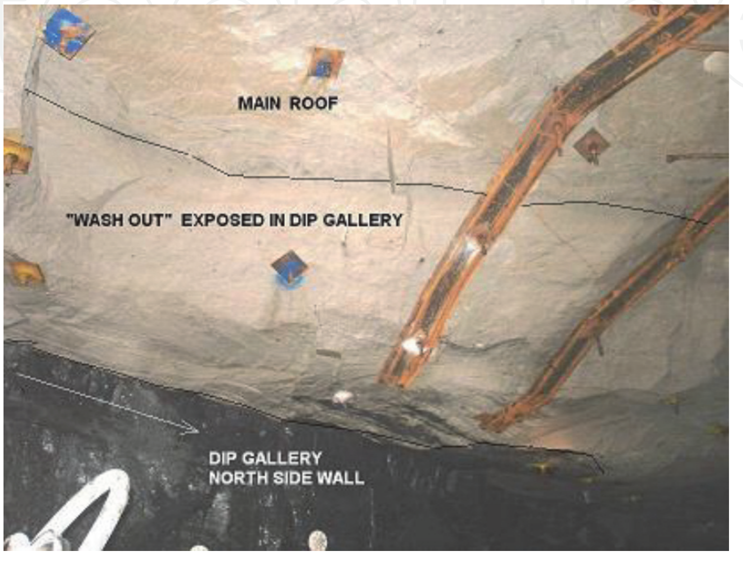

Figure 8.
Wash-outs exposed in the roof of dip rise gallery reduced the cut-out distance of CM during development.

2.9 Determination of in situ strength of rock mass

It is easier to estimate the physico-mechanical properties of coal and rock in the laboratory using different rock testing equipment. These properties do not reflect the actual properties of in-situ coal/rock mass. There is available Sheorey failure criterion but it is age old and needs to be re-established for the higher depth of cover cases. Also, the strength estimated in laboratory are on a higher side and if these are considered for design of underground structures then there are likely chances of an under design which is vulnerable to fail.

Strength of rock mass is important for the stability of underground structures in rock and its realistic assessment for coal measure strata presents a unique challenge. Rock mass classifications have tried to quantify the behaviour of the rock mass. Failure criterion is helpful in prediction of strength of rock mass. But, the anisotropic and inhomogeneous behaviour of coal pillar restricts the scope of rock mass failure criteria for higher depth of cover. There is a need to revisit RMR classification system for failure criteria of intact coal measure formations at higher depth of cover.

2.10 Rock burst/coal bump

Stress concentration on underground structures results into accumulation of strain energy inside it resulting into coal bump/rock burst. Coal measure formations have the capability to store large amount of strain energy before failing. It involves the violent failure of rock/coal around an excavation causing severe injury to the miners. Indian coalfields have rare experience of dealing with coal bump/rock burst due to working under moderate nature of roof at shallow depth of cover. Some incidences of coal bump/rock burst have been experienced due to hanging of overlying strata for a longer span in goaf after pillar extraction which creates high abutment stresses over the solid pillars. It is difficult to deal with such strata as their sudden caving lead to sometimes air blast.

Deep coal mines with massive/strong roof and high stress-conditions experience coal bump/rock burst. Severity of the rock bump increases with increase in depth and stress. Instrumentation and monitoring using geotechnical instruments and micro seismic methods are helpful in understanding and prevention of such occurrences. Energy stored depends upon the physico-mechanical properties of strata. Various destressing techniques have been practised worldwide to deal with such issues.

3. Rock mechanics advances in mechanised depillaring

3.1 Design of rib/snook

Parametric study by varying the nature of roof and depth of cover was carried out in FLAC^{3D} by Singh et al. [4] to estimate the size of irregular shaped rib/snook during MD of existing square/rectangular shaped pillars. Further, height of rib was also varied [7] during extraction of complete thickness of a thick coal seam at a time using numerical simulation to estimate a stable competent size. Results of field and numerical simulation were used to estimate a competent rib/snook. Conceptual model was formulated to have a general idea about variation in size of rib/snook with depth of cover and nature of roof strata.

Area of competent sizes of ribs/snooks with variation in depth of cover and nature of the roof strata are analysed through a multivariate regression. A relationship is developed based on the analysis to estimate a competent size of the rib/snook (S), which is given as:

$$S = 0.52\, H^{0.74}\ \ R^{0.23}\ \mathrm{m}^2 \qquad (3)$$

where H = depth of cover (m) and R = CMRI-RMR.

3.2 Design of goaf edge support

Rock load height (RLH) estimated at the goaf edge using numerical models with variation in RMR and depth of cover and analysed using multivariate regression by Ram et al. [5]. Based on field studies and numerical simulation observations, relationships are developed for the design of RBBLS at three different locations around the goaf edge which are given below.

For 0 m out-bye from goaf edge

$$RLH = 11.67\, H^{0.58}\, R^{-1.14} \qquad (4)$$

For 1 m out-bye from goaf edge

$$RLH = 66.32\, H^{0.31}\, R^{-1.26} \qquad (5)$$

For 2 m out-bye from goaf edge

$$RLH = 115.22\, H^{0.12}\, R^{-1.20} \qquad (6)$$

3.3 Prediction of roof sagging limit for roof fall

Kumar et al. [6] did a multivariate analysis of the roof sagging recorded from the numerical models with variation in thickness and elastic modulus of immediate roof, size of remnants and distance from the goaf edge. This analysis helped in derivation of an Eq. 9 to calculate the limiting roof sagging value as:

$$C = 26.63 - 0.12\mathrm{D} - 1.12\mathrm{E} - 0.14\mathrm{A} + 0.23\mathrm{T} \qquad (7)$$

where C is the roof sagging observed in model (mm), D is the goaf edge distance (m), E is the elastic modulus of immediate roof (GPa), A is the size of remnants left in or around goaf edge (m^2), and T is the immediate roof thickness (m).

Taking into account the anisotropic and heterogeneous natures of rock, a safety factor of 2 is selected for fixation of the sagging value for a warning limit in AWTT which is given as:

$$S = 0.5\mathrm{C} \qquad (8)$$

where S is the warning value of roof sagging (mm) to be fixed in an AWTT.

3.4 Design of cut-out distance

CM does not damage the surrounding roof like drilling-blasting during cutting of coal. Cut-out distance in field has been practised based on trial and error in field. Numerical models based on a safe and stable roof sagging value of 5 mm are used to study the cut-out distance with varying nature of roof and width of gallery [7]. Elastic constitutive model is used to study the cut-out distance based on field studies in $FLAC^{3D}$ by fixing the allowable range of roof sagging to 5 mm (**Figure 9**). Roof sagging values for a 6 m width of gallery by varying the cut-out distances are shown in **Figure 9** on numerical models. **Figure 9** also depicts that the cut-out distance can be further extended beyond 12 m during development using CM for faster extraction.

Based on the results of numerical model and field studies, a relationship is established to estimate the cut-out distance with variation in nature of roof and gallery width, which is given as:

$$S = 14.61 + 1.98E - 2.12W \tag{9}$$

where S is the length of cut-out distance (m), W = width of gallery (m), and E = elastic modulus of immediate roof (GPa).

4. Future rock mechanics issues

Apart from abovementioned issues for B&P mining method using CM based MD, there are challenges of rock mechanics in Indian coalfields at higher depth of cover for the characterisation of rock mass, response of underground structures to high in-situ stresses, design of underground structures, economics, subsidence, complete extraction of difficult coal seam at a time, failure criterion of rock mass, fixation of warning limit for stress and convergence in different geotechnical instrumentation and so forth.

Despite being the second largest producer of coal in the world, Longwall top coal caving method of mining is still not practised in Indian coalfields whereas China produces around 90% of the coal using this technology. Most of the Indian coal is being produced using opencast method which is not sustainable for longer duration

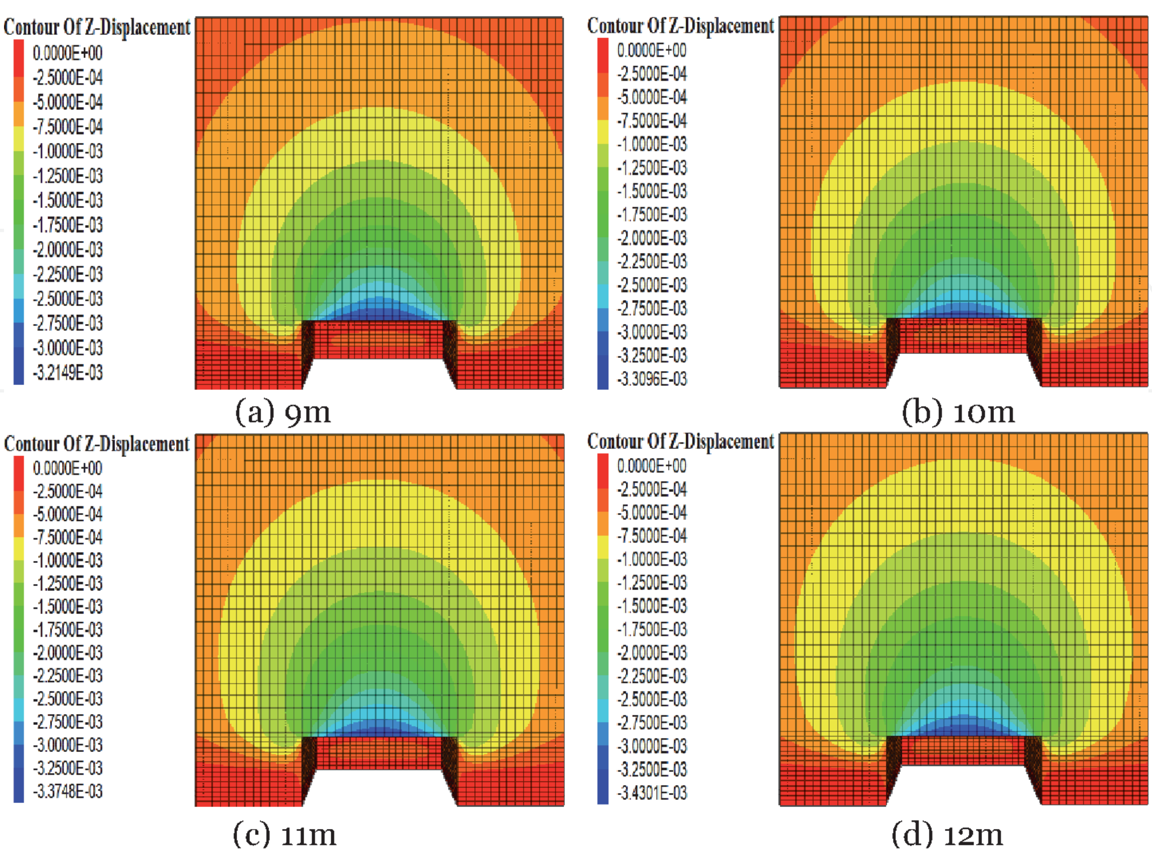

Figure 9.
Roof sagging value for different cut-out distance in $FLAC^{3D}$. (a) 9 m, (b) 10 m, (c) 11 m, and (d) 12 m.

due to its different limitations. Solutions to these future problems lie in carrying out R&D for each such issue on priority basis for the Indian coalfields.

5. Conclusions and recommendations

Mechanised depillaring using continuous miner technology has proven its potential in improvement of production and safety since last 10 years. A number of Indian coal mines are preferring mechanised depillaring over conventional technique to extract the locked-up coal pillars. Field study found that geo-mining conditions and design of geotechnical structures created during mechanised depillaring affect the performance of this mass coal producing technology. Rock mechanics developments in design of geo technical such as breaker-line support, rib/snook, cut-out distance/lift length and determination of roof sagging limit in instruments at the goaf edges has improved the performance of mechanised depillaring operations. However, rock mechanics issues like complete extraction of a thick coal seam, large span of overhang, caveability of difficult overlying strata, geological discontinuities, depth of working and pillar design at higher depth remains a challenge for this technology. Efforts are being made to deal with these issues in Indian coalfields as per their confrontation.

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Conflict of interest

The authors declare no conflict of interest.

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