remnant pillar has been commenced by simulating the panel at a critical depillaring stage and depth of cover for different combination of pillar width and snook widths.

Chapter 6: The simulation results in terms of vertical stress and yield profile for all the models have been presented in the sixth chapter. The cases of panels and remnant pillar satisfying the design criteria have been chosen for further analysis. Based on the analysis, a nomograph has been prepared for the panel design. The guidelines for designing the remnant pillar design were also provided in this chapter.

Chapter 7: Significant outcomes drawn from different chapters and contributions from the study has been summarized in the seventh chapter.

Chapter 2

LITERATURE REVIEW

2.1.General

The bord and pillar system is the most popular underground coal mining method in India concerning the geo-mining complexities. The conventional mining practices adopt a cyclic process of drill and blast to extract the coal. Numbers of technical advancements have been witnessed in the underground coal mining sector during the last two decades (mainly mechanization and instrumentation) to extract coal more safely and productively. The *CM* is an emerging technology nowadays in the bord and pillar mining system. The *CM* can either be deployed in virgin patches of coal or already developed panels for the depillaring operation. Adopting the *CM* technology increases the production rate as a compared to conventional techniques of drill and blast. Strata issues have been observed in few bord and pillar panels of Indian coalfields during the mechanized depillaring operation using *CM*. Assessment of the strata's behavior becomes essential before commencing the mechanized depillaring operation. The design of pillars and remnant pillar plays an essential role in providing safe mining conditions. Varieties of extraction patterns have been practiced in a mechanized depillaring panel during the final extraction of coal using *CM*. The optimum design of the panel, pillars, and remnant pillar (ribs/snooks) is the prime necessity for a successful depillaring operation. This chapter provides a detailed literature survey concerning strata behavior, extraction schemes, and designing techniques.

2.2.Strata behavior

The strata in the underground coal mines were generally present in layers or beds of different physicomechanical properties and geological discontinuities. The underground mining activity disturbs the natural state of equilibrium and understanding the strata behavior before depillaring is essential concerning safe mine workings. The depillaring operation in the bord and pillar mining system is performed either by caving or stowing (filling of the goaf with sand). Most of the country's underground coal mines prefer caving of the strata over stowing due to the unavailability of stowing material (mainly sand), and it also imposes an extra cost to the industry. The caving process plays a vital role in resuming the stable state of equilibriums by releasing the strata pressure (Sheorey P.R., et al., 1995; Singh G.S.P., 2015; Bin Y., 2016). The biggest challenge in underground coal mining is synchronizing the caving process with the advancement of depillaring operations.

2.2.1. Caving phenomena

The depillaring operation results in the formation of goaf and changes the strata dynamics of the overlying strata. The overlying strata become highly stressed and behave as a cantilever or beam during the depillaring operation. Failure of the overlying strata occurs if the stress value exceeds the threshold limit, and the phenomenon is known as caving. The caving of the strata takes place in phases during the depillaring operation, i.e., failure of the immediate strata (local fall) and afterward main strata (main fall). Global stability is mainly concerned with the stability of the panel (including pillars/barriers) and the main strata, whereas local stability is concerned with the stability of the remnant pillar and immediate strata. The stability of the structures like pillars/barriers depends mainly on their design and the nature of the overlying strata. The number of parameters governs caving phenomena, mainly thickness and stiffness of the strata, sequence of excavation, rate of extraction, size of the intact pillars, size of remnant pillars (ribs/snooks), and geological discontinuities. The caving process is mainly governed by the design of the underground structures and the strata's characteristics. Weak overlying strata are readily cavable, while strong and massive strata always found difficulty in caving. Induced caving is performed in situations where overlying strata is difficult to cave naturally. The most preferred mining condition is the one that provides global as well as local stability. It is essential to design the panel (including pillars/barriers) and remnant pillar (ribs/snooks) wisely, considering the strata's nature to obtain smooth caving in the area.

Early caving of the strata results in the pillars' overriding, whereas the delay in the caving process raises the chances of air blast in the area. Thus, the strata's regular caving is of utmost importance for men and machinery's safety in the workings area. Peng et al. (1984) explain the caving process graphically w.r.t. main and periodic weighting during face advancement (fig. 2.1). Fig. 2.1 shows a progressive caving of the strata with the advancement in depillaring operation (i.e., Stage ‘A’ through stage ‘E’). Fig. 2.2 shows a typical layout of a bord and pillar panel showing the behavior of the immediate strata (cantilever formation) during the depillaring operation.

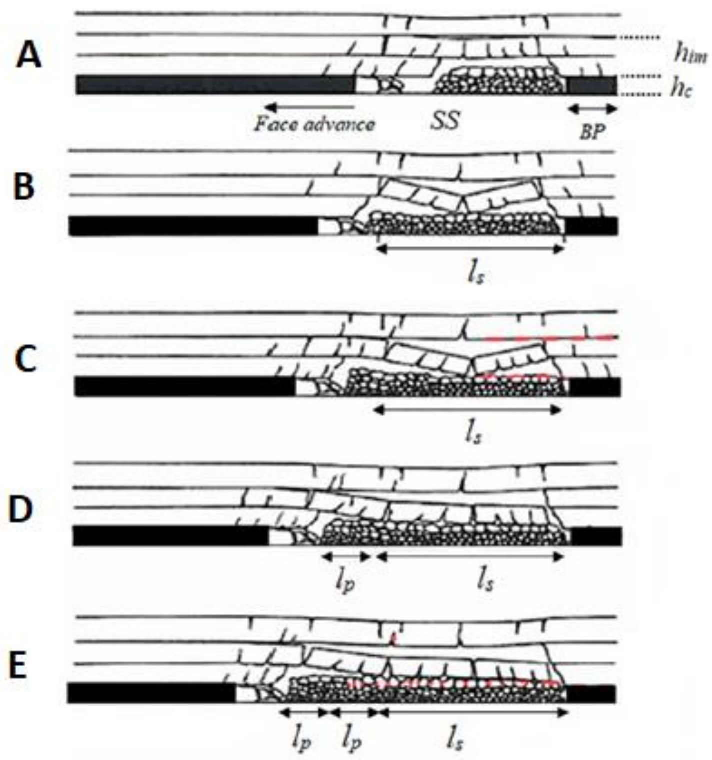
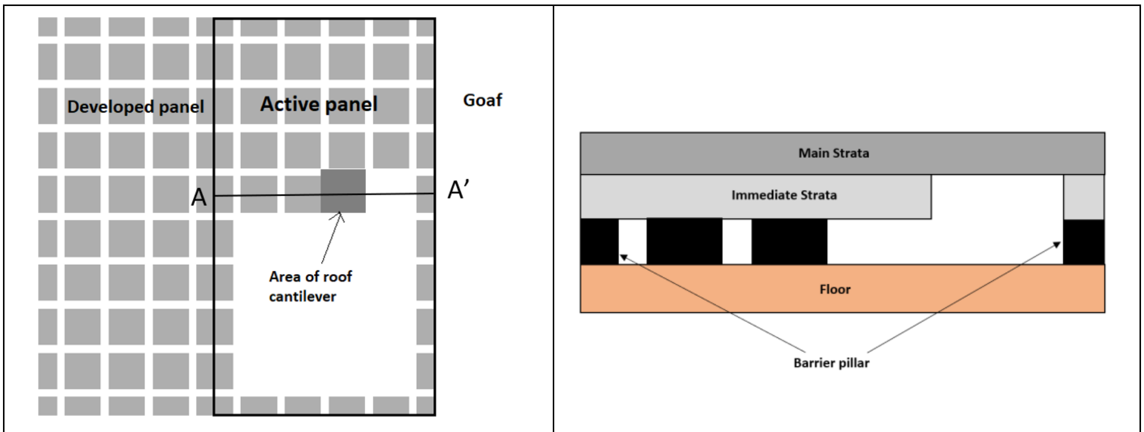


Fig. 2.1 Main and periodic distances in the caving process (Mohammadi et al. 2019)



Plan view	Sectional view at AA'

Fig. 2.2 Typical layout of the bord and pillar panel

2.2.2. *Roof assessment techniques*

The prediction of the behavior of the strata helps in designing the underground structures accordingly to achieve a successful depillaring operation. The unpredictable roof failures result in the loss of men and machinery and affect the mine's ongoing production. Researchers have attempted to access the nature of the strata by developing various theories and models. The proper selection of classification system (mainly *RMR*, *RQD*, *GSI*, and Cavability Index) is essential for the accurate characterization of the strata. The system categorizes the rock into different groups by assigning numerical values to each rock type.

Many researchers attempt to understand the caving behavior of overlying strata for longwall panels (Mohammadi et al., 2019; Wang et al., 2018; Singh, 2015). The coal mass roof rating (*CMRR*) system has been adopted in *US* coal field to access the behavior of the roof strata (Mark and Molinda, 2005; Wang Y et al., 2018). An extensive review has been carried out by GSP Singh (2015) to assess caving behavior using various approaches. Sheorey (1984) has analyzed twelve cases of Indian coalfields, particularly longwall panels, for establishing the relationship between ultimate face advancement (i.e., stable span) vis-à-vis average *RQD* of the overlying strata. The most popular terminology is the cavability index for the assessment of caving behavior (Singh, 2015). Cavability of the rock is the ease of the overlying strata's failure to release the strata pressure. Varieties of models and theories have been developed in the past years using empirical and numerical techniques to determine the cavability of the rock mass. The theoretical models predicting roof failure and periodic caving span are generally based on the plate-beam theory (Obert and Duvall 1967) and the bending moment approach (Majumdar 1986). *CMRI* has developed an empirical relation to categorizing the overlying strata's caving behavior considering Indian geo-mining conditions (Eq. 2.1). It defined as the ‘Cavability Index’ (*I*).

$$I = \frac{\sigma\, l^n\, t^{0.5}}{5} \tag{2.1}$$

Where σ is the uniaxial compressive strength in kg/cm^2, l is the average length of core in cm, t is the thickness of strong bed in m, n is 1.2 for uniformly massive rock, and n is 1 for all other cases. The overlying strata of the coal mine is categorized into five different roof types, as mentioned in Table 2.1. The Cavability index in Indian coalfields has been observed in the range of 2000 to 10000 (Singh et al. 2016).

Table 2.1 Cavability index vs. caving behavior of strata

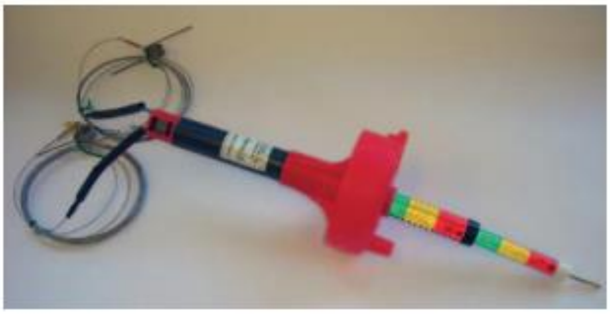
Roof category	**Cavability index**	**Caving nature**
I	$I \leq 2000$	Easily cavable roof
II	2000 < I <5000	Moderately cavable roof
III	5000<$I \leq$ 10000	Roof cavable with difficulty
IV	10,000 <$I \leq$ 14000	Cavable with substantial difficulty
V	I >14000	Cavable with extreme difficulty

The quantification and categorization of the overlying strata help in adopting required support elements for safe mine workings. *RMR* system is mostly used in Indian coal mines to determine the support requirements for the galleries. In mechanized depillaring operations, local stability is the major issue influencing the mine workings' safety and productivity. The local stability can be attained if the remnant pillar (ribs/snooks) sustain the strata load during excavation and fails as the mining gets progressed maintaining a safe distance between the roof's failure edge and the face. The synchronization of the supports with the characteristics of the roof strata is a challenging task. Numbers of researchers have attempted to depict the roof's behavior under different mining conditions (Singh and Singh 2009, Singh and Singh 2010, Singh 2015, Banerjee et al. 2016). Cavability Index is mostly used in Indian coal mines to depict the nature of the overlying strata. The hard overlying strata with a high Cavability Index imply more load on the pillars than the soft strata with a low Cavability Index.

2.2.3. Strata monitoring instruments

Strata Instrumentation also plays a vital role in assessing strata behavior during the coal's final extraction. Strata instruments are commonly used in the depillaring panel of bord and pillar mining systems to ensure safe mining operation. Strata instrumentation proves to be a helpful technique in determining the induced stress and the deformation in the structures nearby the workings area (Smart et al. 1978, Yu et al. 1993, Singh et al. 2004). Strata instruments help in reducing the fatality rate but also provide an uninterrupted production from the mines. The stability of the roof in the depillaring panel can be accessed easily nowadays with Strata instruments. Fig. 2.3 shows the images of various strata monitoring instruments used in a depillaring panel of bord and pillar system (Bigby D, et al., 2010).

Roof bolt extensometer (*RBE*), rotary tell–tale (*RTT*), dual height tell–tale (*DHTT*), and auto – warning tell-tale (*AWTT*) are the commonly used instruments in the depillaring panel to depict the stability of the strata. Tell-tale is the simplest mechanical device which consists of a strata movement indicator positioned in the mouth of a drilled hole and attached to an anchor installed up to the hole (Yerpude et al., 2014). The instrument indicates the dilation of the roof during the depillaring operation. *AWTT* is a crucial instrument generally used in the mechanized depillaring panel. The alarming feature of *AWTT* makes it popular in mechanized depillaring panels as high extraction height (about 4.5 m) and arduous mining conditions may cause a human error while recording the readings. The instrument starts to blink and create a siren sound if the roof convergence exceeds its warning limit.



a. Dual height tell-tale

b. Rotary tell-tale

c. Auto-warning tell-tale

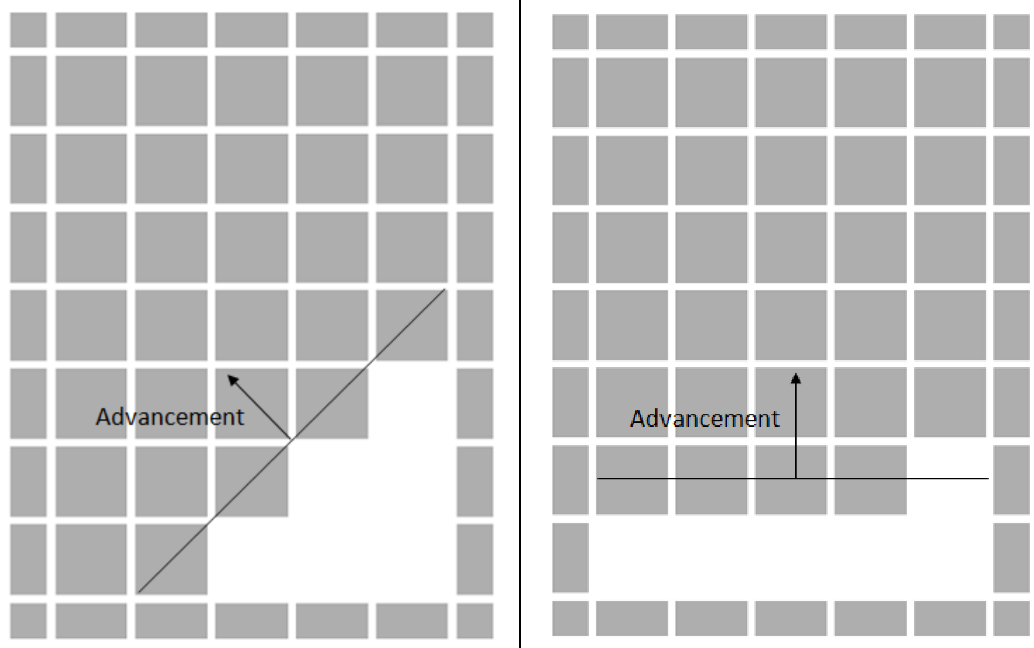
d. Remote reading four-wire extensometer

Fig. 2.3. Strata monitoring instruments

2.3. Pillar extraction schemes

A panel system of working is adopted while extracting coal from underground. The bord and pillar panel generally consists of five or six headings. The length of the panel is decided considering the rate of extraction and the incubation period. Galleries are driven during the development phase, leaving pillars that are extracted during depillaring operation. Fig. 2.4 shows the extraction schemes adopted during the depillaring operation. The conventional depillaring operation adopts drill and blast techniques for coal extraction and generally adopts a diagonal line of extraction (fig. 2.4a). Splitting and stoking pattern of extraction with a slicing angle of about 90° were adopted in conventional depillaring operations. Whereas mechanized depillaring operation using *CM* generally adopts a straight line of extraction considering the machine's maneuverability (fig. 2.4b). The slicing angle of the machine (*CM*) during the final extraction of coal was about 60° - 70°, considering the machine's maneuverability.

A variety of extraction patterns were adopted during mechanized depillaring operations for different pillar dimensions considering the cut-out distance of the machine (Mark and Zelanko, 2001; Singh R., et al., 2016; Chawla S., et al., 2017). Pillars of larger size (more than about 28 m) are generally preferred while working with *CM*, and the split and fender pattern is the most suited extraction pattern during mechanized depillaring operation.



a) Diagonal line of extraction (Conventional depillaring)	b) Straight line of extraction (Mechanized depillaring)

Fig. 2.4 Extraction schemes adopted during depillaring operation

The pillars in an already developed panel are designed as per Indian *CMR*, 2017. As discussed earlier, adopting *CM* technology in such panels requires a widening of the galleries, which results in a reduction of the pillar size (corner to corner). Adopting a split and fender pattern is not feasible for smaller pillars, and such pillars are extracted by taking slices from the dip and rise galleries. Modified Navid and fish-bone are the commonly used extraction pattern adopted for smaller pillars of an already developed panel. A detailed discussion about various extraction patterns adopted during mechanized depillaring has been presented in the subsequent sub-sections.

2.3.1. Modified Navid

Modified Navid pattern of pillar extraction is adopted for pillars of small dimensions, i.e., in general, 17 m (corner to corner) or less. This method involves slicing the pillar from the sides. The slicing operation begins by taking consecutive slices (fig. 2.5) of about 3.5 m each from one side of the working pillar, leaving a small in-bye rib at the corner. Slicing of the immediate nearby pillar is also taken in-between the slicing of the working pillar. Fig. 2.5 shows the typical extraction scheme by the Modified Navid method.

Fig.2.5. Modified Navid pattern of pillar extraction

The first three slices are taken out from one side of the pillar and the next two slices from the other, as seen in Fig. 2.5. After taking the 4th slice, the next slice (slice 4a) is taken out from the immediate next pillar. The final slice (slice 5) is taken out from the pillar, leaving a sufficient-sized snook, as shown in Fig. 2.5. The slicing sequence in the modified Navid method is followed as slice1- slice 2-slice 3- slice 4- slice 4a-slice 5.

2.3.2. Fish-bone

The fish-bone pattern of extraction is adopted for smaller pillars having a dimension in the range of about 17 m - 20 m (corner to corner). Slices have to be taken from three sides of the pillar, leaving ribs at the corners. Consecutive slices of about 3.5

have to be taken out from three sides of the pillar in this pattern. Two pillars have been sliced together in this pattern. Fig. 2.6 shows the typical slicing scheme adopted during the fish-bone extraction pattern. Slice 1a and slice 2a have been taken out from the pillar during the extraction of previous pillar. The fish-bone pattern's slicing sequence is followed as slice 1 – slice 1a’ – slice 2 – slice 2a’ –slice 3 – slice 4. Snook of sufficient size is required while taking the last slice from the pillar. The width of the last slice (i.e., slice 4) can be varied depending on the working condition.

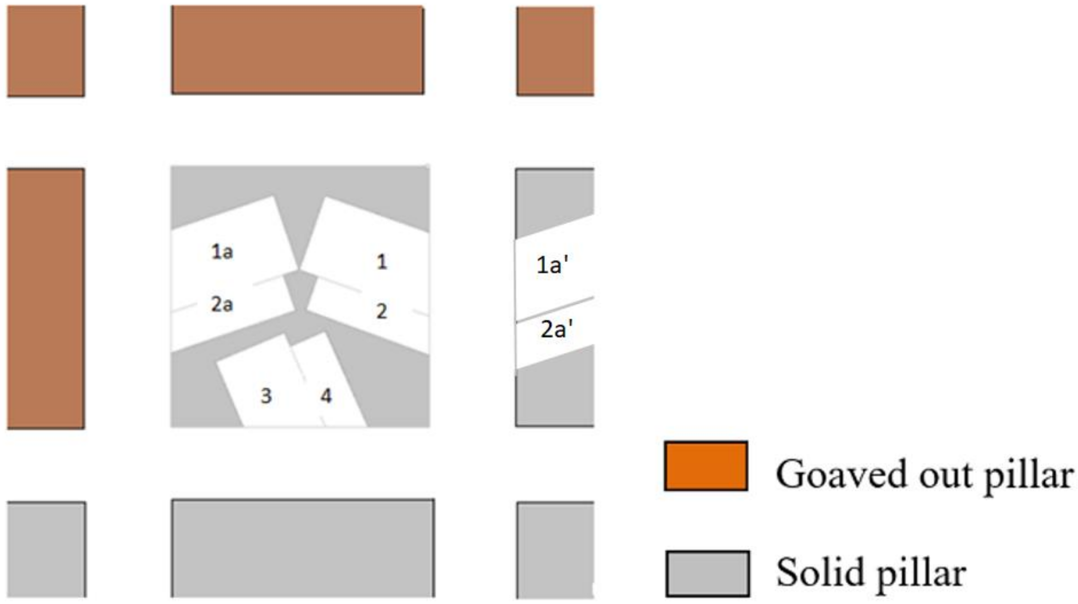


Fig.2.6. Fish-bone pattern of pillar extraction

2.3.3. Split and fender

Split and fender is the most commonly used pattern of pillar extraction during mechanized depillaring operations. This method is generally preferred for pillars of sufficiently large size, i.e., about more than 20.0 m (corner to corner) such that the fender width matches with the machine's cut-out distance. The pillar is split into fenders, and slices are taken out from the fenders one after the other. The width of the split in this method is generally about 6.0 m. Slices are taken out from the fenders at an angle of about 70º during the final coal extraction. Ribs/snooks are left during the slicing operation to provide temporary support to the immediate strata. The first rib, left before taking the first slice, is termed as 'in-bye rib,' whereas the fender's last rib is known as 'out-bye rib' or 'snook.' The average width of the in-bye and out-bye ribs generally varies in the range of 4 m - 6 m. The snook's width mainly depends on the pillar size and the strata conditions and generally varies from 5 m - 7 m. During the slicing operation, ribs of about 3.0 m are left in between two or three consecutive slices. The width of the last slice is generally varied as per the required size of the snook. Pillar size in the range of about 20 m - 30 m (corner to corner) is generally extracted using split and fender pattern. Fig. 2.7 shows a typical extraction scheme in the split and fender pattern. The slicing sequence in this method is Slice 1 – Slice 2 – Slice 3 – Slice 4 – Slice 5 (fig. 2.7). After the fifth slice (Slice 5), another slice can be taken from the last fender considering the working conditions. Under difficult mining conditions, 'Slice 5' will be the last, and a snook of sufficiently large size is left for safe mine workings.

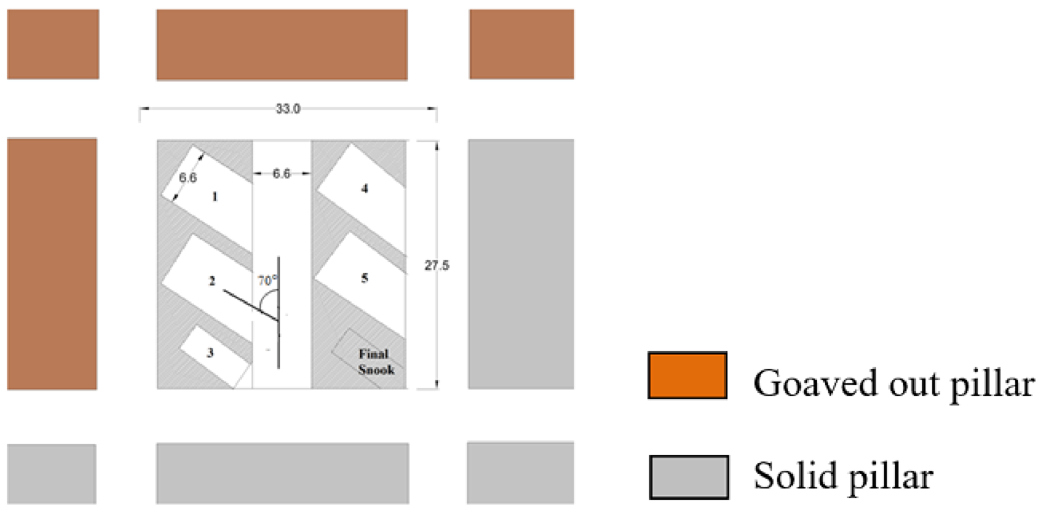


Fig.2.7. Split and fender pattern of pillar extraction

2.3.4. One-third split and fender

One–third split and fender pattern of extraction is one of the variants of split and fender pattern and is generally adopted for pillar size in the range of about 30 m - 35 m (corner to corner). Only one split is drive in this method dividing the pillar into two unequal parts such that the width of one fender is twice that of the other. The smaller fender is formed towards the goaf side, whereas the larger fender is towards the solid pillars. The final extraction is commenced by taking slices from both sides of the split consecutively (i.e., one from the small fender and the other from the larger fender). Fig. 2.8 shows the typical extraction scheme in one-third split and fender pattern. The slicing sequence in the pattern is Slice 1 through Slice 22. A rib of about 3 m is generally left after taking three to four consecutive slices. The larger fender's remaining solid portion is further sliced through the main gallery (Slice 14 and 15, as shown in Fig. 2.8).

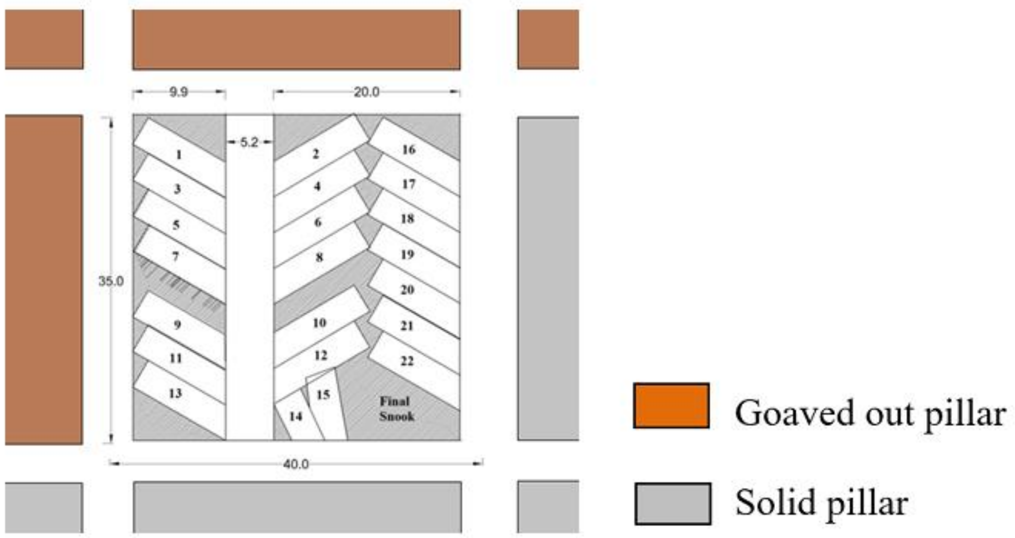


Fig.2.8. One – third split and fender pattern of pillar extraction

2.3.5. Double split and fender

The double split and fender pattern is another variant of the split and fender method in which two splits are driven in the pillar. This pattern is generally adopted if the pillar's size is in the range of about 35 m - 48 m (corner to corner) so that the machine (*CM*) capacity can be utilized more wisely. The pillar is split into three fenders by driving two splits of about 6.0 m. The slicing of the fenders has generally been carried out at an angle of about 70º. Fig. 2.9 shows the typical extraction scheme in the double split and fender pattern of extraction. The slicing sequence in this method is: 'Slice 1' through 'Slice 17,' as shown in Fig. 2.9. Consecutive slices are generally being taken out from the fender before leaving the rib. The width of the final slice from the fender can be varied considering the working conditions such that a sufficient-sized snook can be left out for temporary support.

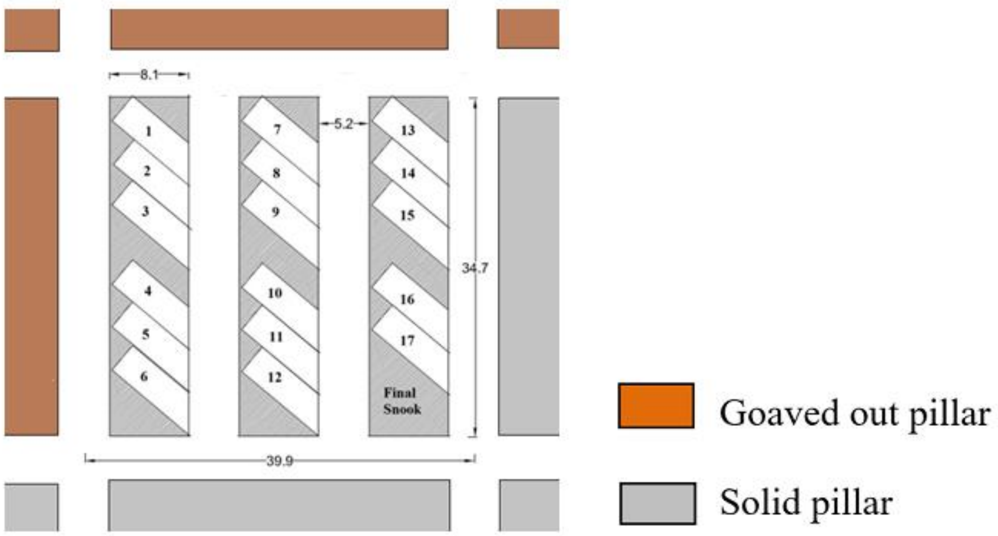


Fig.2.9. Double split and fender pattern of pillar extraction

2.4.Panel designing techniques

The underground mining operation adopting a bord and pillar mining system has been performed in two phases, i.e., development and depillaring. The development phase involves driving the galleries in the panel and forming pillars, whereas the depillaring phase involves the extraction of the pillars in a sequential manner, leaving remnant pillar (ribs/snook) for temporary support. A bord and pillar panel needs to be designed in such a manner that it provides stable mining conditions during development and depillaring. Intact pillars and remnant pillars are the critical elements of a bord and pillar panel during the depillaring operation. The safety and productivity of a mechanized depillaring panel mainly depend on the design of the pillars and remnant pillar. An optimum panel design provides global as well as local stability during the mining operation. The design of the pillars (including barriers) mainly governs the global stability of the depillaring panel. The panel size (mainly its width) also plays an important role in providing safe mining conditions, as a large-sized panel with small pillars may result in the sudden collapse of the strata. On the other hand, remnant pillar is equally important in achieving safe mining goals and play a major role in governing the local stability in the panel during the final coal extraction. The optimum size of the remnant pillars is desired for safe and productive depillaring operation as large-sized remnant pillars delay the caving process, whereas smaller-sized remnant pillar result in the overriding of the pillars in the working area. Numbers of tools and techniques have been developed in the past years to design the intact pillars and remnant pillars in a wiser way to achieve safe and productive mining operations. The techniques adopted to design the intact pillars and remnant pillars were discussed in the subsequent sub-sections.

2.4.1. Pillar design techniques

Pillars are the key elements of a bord and pillar panel as their stability depicts the success of the mining operation. Numbers of researchers have attempted to design the pillars for an underground mining system. The factor of safety (*FOS*) is the basic design approach adopted by the researchers is to determine the stability of the pillars. *FOS* is the ratio of the strength of the pillar and the stress generated on it due to mining activity. The stability of pillars can be accessed easily by determining their *FOS*. A pillar is considered to be stable if its strength is greater than the load or its *FOS* is above one. Likewise, a pillar/remnant is unstable if the load exceeds its strength or its *FOS* reduces below one. Understanding both the strength of the pillar and induced stress behavior is essential for designing a bord and pillar panel.

The strength of the coal pillar has always been an area of grey research in coal mining history. It is the most critical parameter in designing the pillars in underground coal mines. Researchers mostly adopted empirical, analytical, and numerical techniques to determine the pillar/remnant status. The coal mass's laboratory testing is generally not preferred to determine its strength as the coal sample preparation is complex, and the testing requires ample time. Also, laboratory test results are far different from the field due to geological discontinuities in the field. The laboratory tests are generally used to develop theoretical relations for the pillar strength. Over the years, numbers of empirical relations have been developed to determine the coal pillar's strength (Bunting and Douglas 1911, Holland and Gaddy 1957, Holland 1964, Obert and Duvall 1967, Salamon and Munro, 1967, Bieniawski 1968, Sheorey 1992, Jaiswal and Shrivastva 2009). There are many pillar strength formulae developed for various coal fields in the world. Mark – Bieniawski developed a pillar strength function for *US* coal fields (Mark C., 2000). It is also applicable for rectangular sized pillars. A general agreement among researchers is that coal pillar strength increases with pillar width-to-height ratio and can be expressed by the following two general types of expressions: linear and power.

$$\text{Linear,} S_p = S_{cube}\left(A + B\,\frac{w}{h}\right) \qquad (2.2)$$

$$\text{Power, } S_p = S_{cube}\,\frac{w^{\alpha}}{h^{\beta}} \qquad (2.3)$$

Where, Sp is pillar strength, w is the width of the pillar, h is the height of the pillar, S_{cube} is the strength of cubical pillar, and α, β, A, B are constants. Several representative formulae are:

a) Bunschinger (1876) : $S_p = S_{cube}\left(0.778 + 0.222\,\frac{W}{H}\right)$ (2.4)

b) Bunting (1911) : $S_p = 1000\,(0.70 + 0.30\,\frac{W}{H})$ (2.5)

c) Holland and Gaddy (1956) : $S_p = K\,\frac{\sqrt{W}}{H}$ (2.6)

d) Holland (1964) : $S_p = S_{cube}\sqrt{\frac{W}{H}}$ (2.7)

e) Salamon and Munro (1967) : $S_p = 7.176\,\frac{W^{0.46}}{H^{0.66}}$ (2.8)

f) Bieniawski (1968) : $S_p = S_{cube}\,(0.64 + 0.36\,\frac{W}{H})$ (2.9)

Sheorey has also developed an empirical relation (Eq. 2.10) determining the pillar strength from back analysis of the failed and stables cases of pillars of Indian coal mines (Sheorey 1992).

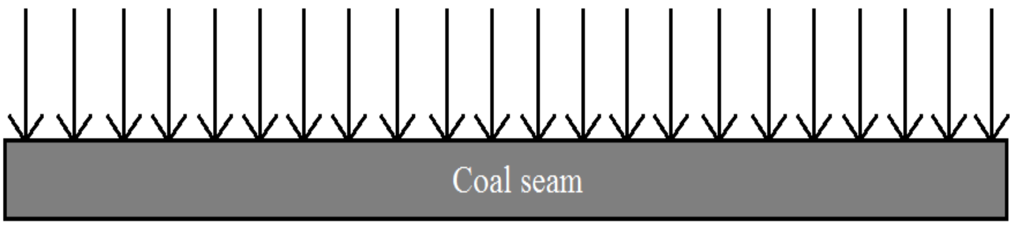
$$Pillar\ strength = 0.27\ x\ UCS\ x\ h^{-0.36} + \left(\frac{D}{250} + 1\right)\left(\frac{w}{h} - 1\right) \qquad (2.10)$$

Numerical techniques are widely used nowadays to determine the strength of the pillar. Numerical methods are capable of simulating complex geological conditions and possess fair computational time. The researchers' only challenge in using numerical methods is to determine the constitutive material properties for coal. Back analysis considering the empirical relations developed for coal pillar or experience from the field is generally used to validate the numerical models. Jaiswal has also developed an empirical equation for pillar strength using numerical techniques (Eq. 2.11) considering failed and stables cases of pillars of Indian coal mines (Jaiswal and Shrivastva 2009).

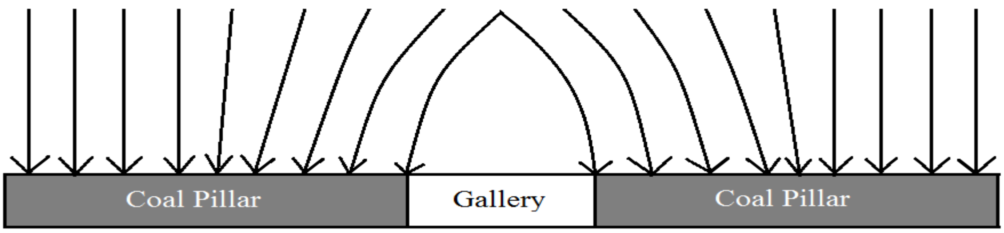
$$Pillar\ strength = \frac{\sigma_c^{0.66}}{2.39}[0.36(w/h) + 0.64] \quad (2.11)$$

A general agreement among researchers is that coal pillar strength increases with pillar width - to - height ratio (*w/h*). Researchers have suggested that the size and shape mainly influence the strength of the coal pillars. Width – to – height ratio (*w/h*) of the pillar is the important parameter in determining the pillar's strength. Almost all the empirical relations developed so far depict the strength of the pillar in terms of *w/h*. Mark classifies the pillars into three different groups based on their *FOS*, i.e., slender pillar (w/h < 3), intermediate pillar (4 < w/h < 8) and squat pillars (w/h > 10) (Mark 2000). The squat pillar is considered to be non – destructive pillars as they show strain hardening behavior during extreme loading conditions. Slender pillars are considered least stable because of their lower safety factor and are designed for short-term stability requirements.

The stress on the pillars redistributes during the mining operation. Fig. 2.10 shows the typical layout of the vertical stress before mining and during the development phase. The load imposed on coal pillars is mainly developed due to the weight of the overlying strata. The actual weight of the strata is challenging to determine due to its complex nature. Tributary area theory is the first attempt to evaluate the overburden load on the pillars. The theory states that the amount of load on the coal pillars is equal to the load imposed on the intact portion of coal before excavation. The field application of tributary area theory reveals an overestimation, but it provides a reasonable estimation of load on the pillars and is widely used in underground coal mines. The load on the pillars during the development stage is generally estimated using the tributary area theory.



a) Typical layout of the vertical stress before mining



b) Typical layout of vertical stress during development

Fig. 2.10 Typical layout of vertical stress

During the depillaring operation, pillars are extracted, which further redistributes the strata load on the nearby solid pillars. The tributary area theory does not work in determining the strata load during the depillaring operation. The pillars nearby goaf face high-stress values as the load of the extracted span was imposed on the solid pillars. The caving phenomena play a major role in resuming the stress equilibrium in a depillaring panel. The failure of the strata occurs in two phases, i.e., local fall (failure of the immediate strata) and main fall (failure of the main strata). Further, the overlying strata's failure is always not reached up to the surface at the time of the main fall. Thus, the load of the other non-damaged overlying strata imposes its weight on the solid coal. The influence of the goaf on the solid coal or pillars depends on the square root of depth, which is also defined by load transfer distance (*LTD*). A detailed discussion on this concept can be found elsewhere (Larson and Whyatt 2012).

Advancement in technology provides several analytical and numerical techniques to determine the overlying strata' actual load during depillaring operation. Numerical simulation techniques require in-situ stresses as an input parameter. The vertical stress (σ_v) and the horizontal stress (σ_h) can be determined using Eq. 2.12 and Eq. 13, respectively. (Sheorey, 1994).

$$\sigma_v = 0.025H \qquad (2.12)$$

Where σ_v is the vertical stress, and H is the depth of cover

$$\sigma_h = \frac{v}{1-v}\sigma_v + \frac{\beta EG}{1-v}(H + 1000) \qquad (2.13)$$

Where σ_h is the horizontal stress, v is the Poisson's ratio, β is the coefficient of thermal expansion, E is the modulus of elasticity, G is the geothermal gradient. Feeding the values of these parameters in Eq. 5, i.e., v = 0.25, β = 3 x 10^{-5}/ºC, E = 2000 MPa, G = 0.03 ºC/m, the generalized horizontal stress formula (Eq. 4.3) can be represented as:

$$\sigma_h = 2.4 + 0.01H\ (MPa) \qquad (2.14)$$

The strata load on the pillars can also be estimated using strata instruments (stress cells and load cells). The numerical method is one of the most suitable techniques for simulating a depillaring panel with advancing stages for assessing the induced stresses on pillars. Researchers have adopted a numerical simulation technique to determine induced stress on the pillars during the depillaring stages (Singh et al., 2016; Jaiswal et al., 2004; Jena et al., 2019). Singh et al. (2011) conduct a detailed field investigation to estimate the influence of goaf in terms of induced stress on the pillars based on instrumentation for Indian coalfields. An empirical expression for maximum induced stress value vis-à-vis cavability index and depth has been proposed based on the analysis (Singh et al. 2011).

2.4.2. Remnant pillar design techniques

Remnant pillars (ribs/snooks) are important natural support elements formed during the final extraction of coal. Slices are taken out from the pillar, leaving ribs/snooks for temporary support during the final coal extraction. Remnant pillars (ribs/snooks) are the coal pillar portion left after the slicing operation. The resultant size of the remnant pillar reduces with the advancement in the slicing operation. The last rib near the junction left after taking the pillar's final slice is termed as snook. A rhomboidal-shaped snook is generally formed during mechanized depillaring operations. The snook size is larger than other ribs, as it plays a vital role in controlling the goaf encroachment. The strata load redistributes with the advancement in depillaring operation. Snook bears an excessive load while attempting the last slice from the working pillar as it is the closest natural support at the face against goaf. Cogs and props provide additional support to the strata at the goaf edge during the depillaring by conventional means (drill and blast). However, roof bolts are the only supporting element during mechanized depillaring (using *CM*). The remnant pillar (ribs/snooks) stability plays a vital role in the absence of props and cogs during the mechanized depillaring. The remnant pillars (ribs/snooks) are generally designed to support the overhang until the men and machine (*CM*) return to a safe distance after slicing. The design of the remnant pillar is an essential aspect of safe mechanized depillaring operation and plays an important role in maintaining local stability in the working area.

Few researchers have attempted to determine the stability of the remnant pillar (ribs/snooks) using analytical (Mark and Zelanko 2001, Van-der-Merwe 2005) and numerical techniques (Singh et al. 2016, Chawla et al. 2017). Mark (2001) has suggested the snook's load-bearing capacity using the Mark-Bieniawski strength function based on the *US* coalfields, considering the snook's residual strength as 40% of the peak strength (Mark and Zelanko 2001). Van-der-Merwe has developed analytical solutions based on beam theory to determine the snook load (Van-der-Merwe 2005). Van-der-Merwe uses the pillar strength equation developed from South African coalfields' experience to determine the strength of the snook (Van-der-Merwe 2005). Singh stated that the moderate roof strata provide more load to the snook than weak or strong strata (Singh et al. 2016). Numerical techniques have been used to assess the stability of the snook under different roof conditions and cover depths (Singh et al., 2016). Researchers believe that the strata generally behaves as a beam or cantilever during the depillaring operation. The load imposed on the rib/snook is mainly governed by the weight of the beam/cantilever formed by the immediate strata (Chawla et al., 2017). The ribs/snook load can be determined by knowing the thickness and exposure area of the immediate strata. The author has also attempted to extend Van-der-Merwe's theory using numerical simulations (Chawla et al., 2017).

2.5.*Concluding remarks*

The bord and pillar system is the most used method of underground coal mining in India, in which coal extraction has been commenced in two phases, i.e., development and depillaring. The depillaring operation results in caving of the overlying strata to restore the stress equilibrium. The behavior of the strata during depillaring has been accessed in this chapter. Several issues have been raised during mechanized depillaring operations using *CM*. The mechanized depillaring panel's design plays a vital role in governing the strata issues and providing safe and productive mining operations. A variety of extraction patterns have been observed during mechanized depillaring using *CM*. Fish–bone, and split and fender are the commonly practiced patterns of pillar extraction. Mechanized depillaring has been practiced in both the already developed panels as well as in the virgin panels. The stability of the pillars and remnant pillar (ribs/snooks) is of vital importance in mechanized depillaring operation. The researchers' design approaches concerning the stability of the intact pillars and remnant pillars have been analyzed in the study.