"Assessment of Roof Fall Risk During Retreat Mining in Room and Pillar Coal Mines"

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ABSTRACT:-

One of the most challenging safety problems in room and pillar coal mines is roof fall phenomena during retreat mining. Roof fall not only causes fatal and non-fatal injuries on miners, stoppages in mining operations and equipment breakdowns, but also results in inefficient recovery of ore reserves. As a result, development of a methodology for risk assessment of roof fall has a remarkable role on safety of retreat mining. In this paper, at first all effective parameters on roof fall during retreat mining are identified and then the role of each parameter on roof fall occurrence is explained. Afterwards, a practical methodology is developed for assessment and control of roof fall risk using semi-quantitative techniques. Finally, this methodology is applied in main panel of Bagdeva Underground Coal Mine, located in the South-eastern of India at Korba, and various possible scenarios of retreat mining and corresponding risks are evaluated.

Keywords: - Underground coal mines Room and pillar Retreat mining Roof fall Risk assessment Semi-quantitative method

1. INTRODUCTION

Potential roof falls in underground coal mines are one of the most significant hazards for miners. Roof falls can threaten miners, damage equipment, disrupt ventilation, and block critical emergency escape routes. The hazardous nature of roof fall can be illustrated from the statistics of mine accidents. The US mine accident statistics indicates that during the ten year period, from 1996 to 2005, 7738 miners were injured from roof falls in underground coal, metal, non-metal and stone mines [1]. Coal mines showed the highest rate, that is 1.75 roof fall injuries per 200,000 h underground work. Fatal injury trends from 1996 to 2005 were equally troubling. Coal mining has the highest number that is 82 out of 100 roof fall fatalities (0.021 fatalities per 100,000 miners). The Mine Safety and Health Administration (MSHA) of the US in 2006 reported seven fatalities, 278 non-fatal-days-lost (NFDL) injuries, and 152 no-days-lost (NDL) injuries because of roof falls in US underground coal mines [2]. Recently, extensive research has been conducted to control and assess roof fall risk in coal mines. Several geotechnical variables are known to influence roof stability. These include geology, mine opening geometry, horizontal and vertical stressregime, abutment load, and support. Using statistical analysis of roof fall database from 37 coal mines in US, Molinda et al. [3] found the relationships among the roof fall rate and coal mine roof rating (CMRR), primary roof support (PRSUP), intersection span and depth of cover. van der Merve et al. [4] investigated roof falls in South African coal mines in details and determined their causes. In their point of view, dominant causes were poor design of support systems, poor performance of support elements, bad mining, unknown nature of the stress regime and weak roof rock.

The main reason of roof fall in coal mine is weak and defective roof. Molinda [5] explained the role of geological deficiencies on occurrence of roof falls. Deb [6], using an extensive database of roof performance from US coal mines and fuzzy reasoning techniques, determined the relationships between coal mine roof rating (CMRR), primary roof support (PRSUP) and intersection diagonal span with roof fall rate. Duzgun and Einstein [7] proposed a risk and decision analysis methodology for the assessment and management of roof fall risk in underground coal mines. In this study, they computed the probability of roof fall risk using statistical analysis of available roof fall data from mines in the Appalachian region, in the US, and consequence of roof fall risk using relative cost criterion. Duzgun [8] proposed a risk assessment and management methodology for roof fall hazard in underground mines of the Zonguldak coal region, in Turkey. She computed the probability of roof fall by fitting a distribution function to the annual roof fall, while the consequence of roof fall is quantified based on a cost model. Palei and Das [9] collected geotechnical data from fourteen roof fall incidents in an under- ground coal mine and conducted sensitivity analysis to examine the effects of the contributing parameters on support safety factor and the probability of roof fall. Shahriar and Bakhtavar [10] collected roof fall data from five coal regions, in Iran, to assess and manage the roof fall risk in these regions using a method that previously was applied to landslide risk assessment by Einstein [11]. Maiti and Khanzode [12] introduced a relative risk model for roof and side fall accidents using loglinear analysis. They devel- oped their models based on data obtained from roof and side fall fatal accidents in 292 Indian underground coal mines. Using collecting the roof fall data from five bord and pillar mines in India, Palei and Das [13] predicted the severities of roof fall accidents based on some major contributing parameters using the binary logistic regression model. Ghasemi and Ataei [14] developed a fuzzy model for predicting roof fall rate in coal mines based on Mamdani algorithm using the US roof fall database.

2. RETREAT MINING

In underground coal mining, room and pillar is one of the oldest methods used for the extraction of flat and tabular coal seams. In this method, a series of rooms are driven in the solid coal using continuous miner and generally Shuttle cars and pillars are formed in the development panels. Pillars are left behind to support the roof and to prevent the collapse. To increase the utilization of coal resources during the retreat, the pillars are removed in a later operation (known as retreat mining or pillar recovery). Retreat mining is one of the most hazardous activities because it creates an inherently unstable situation. The process of retreat mining removes the main support for overburden and allows the ground to cave. As a result, the pillar line is an extremely dynamic and highly stressed environment. In other words, the roof at the pillar line is subjected to severe stresses and deformations. Retreat mining accounted for about 10% of all US underground coal production, yet it has historically been asso- ciated with more than 25% of all roof and rib fall fatalities between 1986 and 1996 [15]. Furthermore, similar statistics are observed in coal mining of Australia and South Africa [16]. During the 14 years period, 1995–2008 in US, there was a total of 112 ground fall (roof and rib) fatalities in bituminous underground coal mines [17]. In Fig. 1, the fatalities are classified by type of the ground fall hazard and as can be seen in the figure 21% of total fatalities have occurred during the retreat mining. These statistics and reviews emphasize the need for continu- ing efforts to reduce roof fall fatalities and injuries. Lind [18] investigated seven full and partial pillar recovery operations in New South Wales, Australia, and described the certain factors which result in safe and economical retreat mining. Deep cover retreat mining (overburden in excess of 750 ft) is an important emerging issue which led to roof/rib fall fatalities and injuries in underground coal mines. Chase et al. [19] and Mark [20] outlined proper design guidelines for successful retreat mining in deep mines. Mark et al. [15] introduced risk factors associated with retreat mining for reducing the risk of roof falls. They provided a risk factor checklist that can evaluate the overall level of roof fall risk and possible ways to reduce the roof fall. Similar studies are carried out for reducing roof fall accidents during retreat mining by Mark et al. [21], Mark and Zelanko [22], Feddock and Ma [23]. By inputting certain physical, risk and economic factors, Lind [16] developed a design methodology and planning tool called A-PEP (Analysis of Pillar Extraction Potential) which is a user-friendly, intelligent tool enabling assessment of pillar extraction potential in South Africa. Iannacchione and Mark [24] identified potential unwanted events during retreat mining at two coal mines in southern West Virginia using major hazard risk assessment (MHRA) technique. The top unwanted events were examined individually using structured risk analysis tools. The output of the process includes a list of priority of controlling measures for monitoring and auditing, and a second list of potential new controls. Ghasemi et al. [25] introduced a new method to assess the overall risk of pillar recovery operation in pre-developed room and pillar mines. The proposed method involves calculating the PR-Risk (Pillar Recovery-Risk) indicator based on which the decision can be made about the safe implementation of pillar recovery operation. Ghasemi and Shahriar [26] presented a new method for designing the coal pillars in room and pillar mines in order to enhance the safety of retreat mining and increase the recovery of coal reserves. In this method the abutment loads due to retreat mining are estimated using empirical equations. As a result it can be said that roof controlling is the most challenging safety problem during retreat mining. One of the measures for roof control is sufficient awareness of effective parameters on roof fall. Roof fall depends on a variety of para- meters that each of these parameters may have detrimental effects on miners in form of injury, disability or fatality as well as mining company due to downtimes, interruptions in the mining operations, equipment breakdowns, etc. In this paper, at first based on expert judgment acquired from extensive retreat mining experience and examination of related literature the major contributing parameters on roof fall during retreat mining are introduced and the role of each one is described. Then, a semi-quantitative methodology to assess the roof fall risk is proposed.

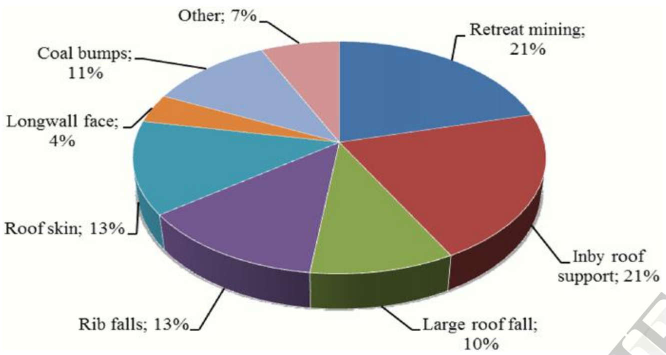

Fig.1. Classification of ground fall fatalities

3. CONTRIBUTING PARAMETERS ON ROOF FALL

Based on performed investigations and past experiences acquired from extensive retreat mining case histories and a review of relevant literature, the major contributing parameters on roof fall during retreat mining can be divided into three categories (as shown in Fig.2):

Geological parameters: these parameters are related to coalfield geological conditions and features of coal seam and its wall. This category of parameters according to Fig. 2 includes six parameters.

Design parameters: this category of parameters is related to the design of extraction panel, pillars and support system of roof. This category includes five parameters (as shown in Fig. 2).

Operational parameters: this category of parameters is related to implementation conditions of retreat mining and according to Fig. 2 includes four parameters.

In the following, each of these parameters and their influence on roof fall are described.

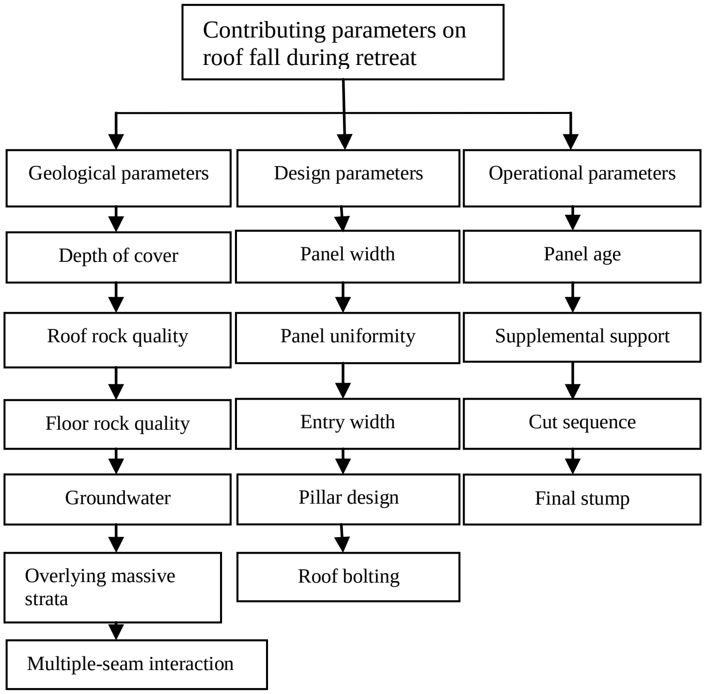

Fig.2 Major contributing parameters on roof fall during retreat mining

3.1. Geological Parameters

3.1.1. Depth of cover In US coal mines, more than one-third of the retreat mining fatalities have occurred in deep cover. Increasing the depth leads to increase of virgins tress levels in the rock mass, both vertically and horizontally. So, achieving to sufficient stability is harder at high depth and special precautions are required to ensure ground stability. Of course, the effect of surface on shallow depth panels is an important issue. Because in shallow depths (lessthan40m), the surface effect can result in over burden failure in brittle and unpredictable fashion [27].

Proper design of barrier pillar is critical for successful mining at deep cover [19,20]. Barrier pillar is used to isolate active panels from adjacent gobs, as a stress control technique. Using advance- and-relieve mining also can lead to improvement of conditions in operations subjected to high horizontal stresses [28]. This mining method is an effective way to minimize the stress damage and to prevent roof falls caused by high horizontal stresses both on development and on retreat stages. Finally, appropriate cut sequences are required for safe recovery of larger pillars under deep cover.

3.1.2. Roof rock quality

Quality of roof rock has an important role in occurrence of roof fall. Incident reports with in retreat mining in the US showed that the weak roof was the main reason in more than one-third of the fatal incidents [15]. Various methods have been presented for classification and evaluation of roof in coal mines, but one of the most applicable of them is coal mine roof rating(CMRR) [29]. CMRR was developed by Molinda and Mark [30] and similar to Bieniawski's RMR has a single rating between 0and100.When the CMRR value is approaching 0 the roof is weaker, while its value approaching100shows that the roof is stronger. One of the important advantages of this classification method is the con-side ration of natural causes of roof fall such as strength of roof rock, bedding and other discontinuities .Based on CMRR value, the probability of roof fall risk during retreat mining can be divided into five categories: Extreme, when CMRR is less than 45;High: when CMRR is between 45 and 55; Moderate: when CMRR is between 55 and 65; Low: when CMRR is between 65 and 85; and Negligible, when CMRR is morethan85.

During retreat mining in the pillar line, abutment loads can influence weak roofs more than strong roofs. Therefore the probability of roof fall is more. In these conditions using a higher level of roof bolting and leaving a final stump (last lift) in order to support the roof temporarily can be effective for reducing the roof fall risk.

3.1.3. Floor Rock Quality

Floor, pillar and roof treat as a system in room and pillar mines. Therefore floor stability plays an important role in the safety and operation of underground coal mines, both in main- taining the access of equipment transportation and in providing a foundation for the floor–pillar–roof system [31].When the floor rock does not have suitable quality, pillars penetrate in to the floor and this can lead to roof convergence and ultimately its failure. In this study,the proposed method by Ghasemi etal. [25] is used in order to evaluate the floor rock quality . This method calculates the stability factor of floor rock (SFf) based on estimations of the maximum load applied on pillar and the ultimate load-bearing capacity of the floor rock during retreat mining. Maximum load applied on the pillar with in retreat mining is estimated using the ARMPS computer program [32] and ultimate bearing capacity of the floor rock under a rectangular pillar is calculated using equations provided by Brady and Brown [33]. Floor rock quality is divided into three categories based on stability factor: Weak: when SFf is less than1; Intermediate: when SFf is between1and2; Strong: when SFf is more than2.

In coal mines with weak floor rock, penetration of pillar into floor is more likely. Pillar penetration can lead to floor heave, failure of floor strata and ultimately roof fall. Proper mine design including proper panel, entry and pillar dimensions are the most effective ways to control and prevent floor heave [34].

3.1.4. Groundwater

Presence of groundwater resources and strata containing water above the extracting panel is one of the effective para- meters on roof instability. Retreat mining results in overburden failure and creation of joints and fractures in it. Water above the panel flows down from these joints and fractures and can cause roof instability especially in pillar line. Depending on the amount of observed water in pillar line, the probability of roof fall is different. If the roof is dry and no water can be seen, the roof fall is not probable; if the roof is wet, the probability of roof fall is low; if dripping occurs, the probability is high and if the flow of water from roof is steady, the probability is extreme.

3.1.5. Overlying massive strata

Safe retreat mining does not mean preventing roof collapse, it means ensuring that it only occurs after the miners have completed their work and have left the area. So, roof collapse should occur uniformly and constantly at a proper distance from the pillar line. One of the most important influencing parameters on roof capability is the existence of massive strata such as sill over the panel [16]. Massive strata can cause intense roof fall during retreat mining because these strata tend to be hang up in large spans, but after achieving a critical span, they break violently. Based on researches done by Anderson [35], the nature of immediate roof strata (up to 20 m over the coal seam) has an important role in capability and creation of gob. Therefore, if the massive strata are in this range, the probability of roof fall is high. In these situations, partial pillar extraction with proper cut sequence is effective in order to prevent violent roof fall.

3.1.6. Multiple-seam interaction

In many of coalfields, coal seams are formed close to each other and as series separated by rock strata (inter burden). The mining of two adjacent seams is called multiple-seam mining and the ground control problems caused by this mining method are called multiple-seam interaction [34]. Ground instability is usually the greatest hazard due to multiple-seam interaction. Interactions may be classified into four categories depending on the mining method, mining sequence, and thickness of the inter burden. The four types of interactions are [36]: undermining, over mining, dynamic interactions, and ultra-close mining.

The effects of multiple-seam interactions can include roof falls, rib spelling, and floor heave, which can seriously disrupt mining operations and threaten the safety of miners. Therefore, identification of potential multiple-seam interaction areas seems essential in planning stage and retreat mining should be prevented seriously in these areas. Inter burden thickness is the most critical factor in determining the potential for multiple-seam interaction. Wide researches have been conducted about the relationship between inter burden thickness and multiple-seam interaction and different consequences have been presented [37–39]. Inter- burden thickness can be considered as a preliminary criterion for estimation of multiple-seam interaction .If thickness of extracting coal seam is h and inter burden thickness is ti, the intensity of interaction is: Extreme: when ti is lessthan4h; High: when ti is between 4h and 10h; Moderate: when ti is between10h and 24h; Low: when ti is between24h and 60h; and Negligible: when ti is more than60h.

In addition of inter burden thickness, other factors such as depth of cover, inter burden geology, immediate roof geology, direction of mining and type of remanent structure influence the intensity of interaction [36]. Thus, in order to predict the intensity of multiple-seam interaction accurately two software programs, the La Model program [40] and the analysis of multiple seam stability (AMSS) program [41], can be used in development and retreat stages.

3.2. Design parameters

3.2.1. Panel width

Panel width affects abutment loads distribution and over- burden caving mechanism during retreat mining. Based on empirical equations for calculating abutment loads, in a specific depth, the increase of panel width leads to an increase in front abutment load applied on pillars adjacent to the pillar line [26]. Increase of load can result in roof in stability .Moreover , with increase of panel width ,the height of tensile zone developed in the over burden increases ,which can cause violent failure and eventually full caving of overburden [42]. As can be seen in Fig. 3, based on width to depth ratio panels are divided in to three categories: sub-critical($P/H < \tan \beta$), Critical($P/H = \tan \beta$), and Super-critical ($P/H > \tan \beta$), where P is the panel width, H is the panel depth and b is the abutment angle. According to Fig. 3, super-critical panels have more width in comparison with two other categories. Therefore the probability of extensive roof fall is more. In these conditions ,partial pillar extraction can prevent unpredictable and uncontrollable roof fall.

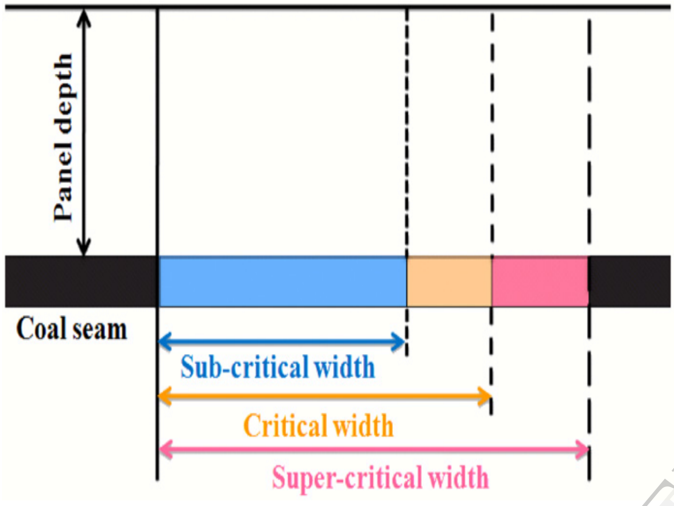

Fig.3. Different types of panels

3.2.2. Panel uniformity

Panel shape and panel's pillars shape and size are important in panel uniformity [25]. Because irregular panel shapes make pillar lines uneven during retreat mining and this causes unpredictable an uncontrollable roof falls. Moreover, panel development con- sisting uniformly sized pillars is recommended strongly, because non-uniform and unequal sized pillars cause non-uniform stress distribution and therefore decrease the roof stability.

3.2.3. Entry width

Between 1997 and 2008, 29 coal miners died from roof fall and coal outbursts while utilizing retreat mining method [43]. Many of these accidents occurred in intersections. Researchers have shown that intersections are 8 to 10 times more likely to collapse than the equivalent length of entry or crosscut. Because rock load applied on roof in intersections is proportional to the cube of the span, unlike of entries and crosscuts [44]. One of the most important methods of decreasing the roof instability at intersec- tions is that entries creating an intersection should be mined to the minimum possible width, in order to make the operation of extraction safe and the haulage equipment possible. Regarding the equipment which are used in room and pillar mines nowa- days (continuous miner, shuttle car and LHD), the proper width of entries is about 4.5 to 5 m and also based on researches done by Jeffrey [45] at width more than 7 m, roof fall and support problems are probable.

3.2.4. Pillar design

As mentioned before, in room and pillar mines roof, pillar and floor treat as a system. It means that in stability of each element leads to in stability of other elements. For example, pillar in stability during retreat mining can lead to roof in stability and finally roof fall. Therefore, proper pillar design has a significant role in roof stability. Analysis of retreat mining pillar stability (ARMPS) program is an effective means for pillar design and prediction of pillar stability during retreat mining. ARMPS was developed by Mark and Chase in 1997 [32]. They evaluated more than 250 case histories of retreat mining across the US in order to verify this program and finally suitable pillar stability factor (ARMPS SF) was presented which is shown in Table 1 [19]. As can be seen, stability factor depends on depth of cover and roof quality (CMRR). In this study, at first pillar stability factor in a specific mine is calculated using ARMPS program. Subsequently the suitability or unsuit- ability of pillar design can be determined using Table 1.

Table 1

Suitable safety factor for stability of the pillars during retreat mining [19]

Depth of cover (H)	Weak and intermediate Roof (CMRRr65)	Strong roof (CMRR465)
H≤200 m	≥1.5	≥1.4
200<H≤400 m	1.5-[(H_200)/333]	1.4-[(H_200)/333]
400<H≤600 m	0.9	0.8

3.2.5. Roof bolting

The purpose of roof bolting is to assist the rock to become self- supporting. Accidents investigation in US coal mines revealed that roof bolt systems failures have been the major factor in one-quarter of recent retreat mining roof fall fatalities because roof bolts are usually the only overhead protection for miners during retreat mining [22]. Experimentally, installation of one roof bolt in one square meters of roof (bolt density=1) in coal mine entries seems to be safe but this value is not adequate at intersection because inter sections are subjected to abutment loads during retreat mining, and therefore require extra roof bolting. Increasing the volume of roof bolt support in many cases, especially in intersections, can be the simplest way to reduce the risk of roof fall. Based on bolt density, the probability of roof all risk at intersections is divides in to three categories: high, when bolt density islessthan1; moderate, when bolt density is between 1 and1.5; and low, when bolt density is more than1.5.

Unfortunately, there is no widely accepted method for design- ing roof fall patterns for retreat mining, but the analysis of roof bolt system (ARBS) method can be a good starting point [46]. ARBS method can make preliminary estimations of the required bolt length, capacity, and pattern using the depth of cover, the roof quality (CMRR), and the intersection span.

3.3. Operational parameter

3.3.1. Panel age

Panel age is a vital parameter in extracting its pillars because as time passes, the roof of mine becomes weaker (time depending rock behavior). Supplemental bolting is often required, particularly in intersections, to prepare old panels for retreat mining. If the panel age is less than one year, no additional support is needed and the probability of roof fall is low. But in older panels, the probability of roof fall increases.

3.3.2. Supplemental support

Supplemental roof support is necessary in retreat mining to increase the safety and minimize the risk of injury from roof falls. Timber posts and mobile roof supports (MRSs) provide supplemental support for retreat mining. Nowadays, using MRS is recommended strongly because using timber posts as pillar line supports has many disadvantages and the most important is that timber posts are passive supports and roof convergence would be small [47,48]. Statistics in US coal mines showed that a miner on a timber panel is exposed to fatality 1.7 times more than a miner protected by MRSs [22].

In comparison with timber posts, MRSs reduce the risk for miners because of reduction in miner exposure to roof fall at the pillar line and elimination of material handling. They have high load-bearing capacity and can maintain load on a much greater range of displacement. They increase production because they make pillar line mechanized and allow fluency of mining through greater cutting time. Furthermore, Maleki and Owens [49] indicated that MRSs influence the roof strata up to 18m. On the other hand, Anderson [35] showed that the nature of the immediate 20m roof strata dictates the caving behavior of over burden, this indicates that MRSs are a successful means for controlling the roof strata during retreat mining and ensuring that caving occurs in controlled manner.

Of course, MRSs have some disadvantage that the main of them are initial costs, the necessity of their recovery if they are trapped by ground fall, and operating range that is limited to seams thicker than approximately 1 m [15].

3.3.3. Cut sequence

Mines employ a wide variety of cut sequences to recover pillars and most of them can be divided into three categories: (a) Left– right (also called Christmas tree or twinning) in which cuts are taken on both sides of the entry and it does not require place changes and bolting; (b) Outside lift in which cuts are taken on just one side and similar to left–right, it does not place changes and bolting; (c) Cut sequences that require cuts to be bolted. These methods are usually used when the pillars are so large that they must be split before they are fully recovered. Split-and-fender and pocket-and-wing are two common types of these methods.

In US coal mines, almost two-thirds of the retreat mining tonnage are obtained using some types of left–right sequences. Outside lift sequences are used for most the remaining productions. Only few of mines employ split-and-fender or other sequences that require roof bolting in the cuts [22]. Mark et al. [21] evaluated the influence of the cut sequences on ground stability using the boundary element numerical model. They compared four common cut sequences (left–right, outside lift, split-and-fender, and pocket-and-wing) based on actual plans used by mines in southern West Virginia. Results show that outside lift is the most stable method and after that left–right is the best one and two other methods almost seem unstable. In view of rock mechanics, the comparison between two common cut sequences, that is left–right and outside lift, shows that in left–right more risky conditions is expected [15]. Analysis of the fatalities statistics confirms this fact too.

The basic advantage of outside lift sequence is that operators always have a solid pillar at their back. Today only the left–right and the outside lift methods are still used. In general, outside lift is used when the width of pillars is 10 m or less, and left–right methods are used when the pillars are too wide to extract completely from one side.

3.3.4. Final stump

The final stump (also known as last lift, push out or stook)is a critical element in roof control during retreat mining, because it protects the active intersection. The final stump is the corner of the pillar at the intersection usually with wedge shaped area which is formed in situ and therefore provides continuous resistance to the roof and floor displacement. Also, it is much stiffer support system than either timber post or MRS and there- fore provides a greater resistance against displacement [18,50]. Fig. 4 indicates the schematic illustration of the final stump that L_1 and L_2 are cut-to-corner distances and θ_1 and θ_2 are cut angels.

In retreat mining, the roof above the intersection should remain stable until after the pillars have been extracted. Leaving a final stump with proper size can reduce the risk of roof fall.

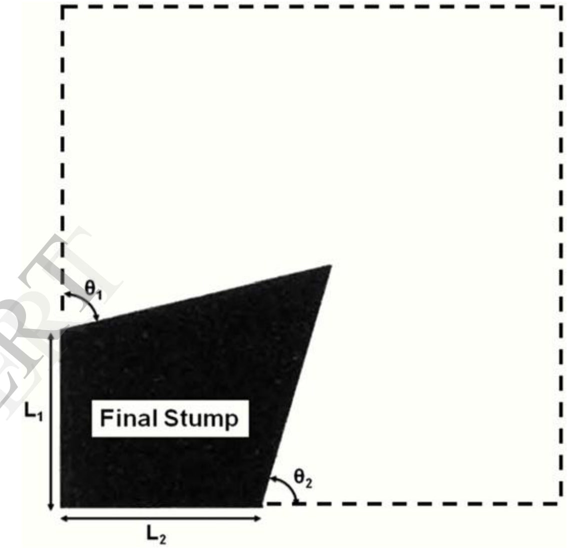

Fig.4. Schematic illustration of the final stump.

Table 2
Proper size of final stump [50].

Seam height (m)	Stump size(m)^a
1.2	2.55
1.8	2.85
2.4	3
3.6	3.15

a Cut-to-corner distance.

The optimum size of the final stump should be large enough to provide effective support to the roof above the intersection, but small enough not to prevent the main roof from caving. The proper sizes of final stumps for a variety of seam heights are presented in Table 2, based on detailed rock mechanic analysis of retreat mining experience [50]. These sizes were obtained as sum -ing that $L_1=L_2$ and $\theta_1=\theta_2=75$ degrees (see Fig. 4).

To ensure that final stumps are properly sized, the cut-to-corner distance should be specified in the roof control plan. Foreman or surveyor can use spray paint to mark the stump dimensions on the rib as a guide to the continuous miner operator.

4. Assessment of Roof Fall Risk

Risk is defined as the chance of occurrence of unwanted events that will have adverse effects on purposes [51,52]. It is measured in terms of probability and consequence. Roof falls during retreat mining continue to be one of the greatest geotechnical risks faced by underground coal miners and cause a lot of loss, injury or fatalities. Therefore, the roof fall risk can be defined as:

$$Rrf=P*C \qquad (1)$$

Where Rrf is the risk of roof fall, P is the probability of roof fall occurrence and C is the consequence of roof fall.

In order to assess and estimate the risk of events such as roof fall risk, quantitative, semi-quantitative or qualitative methods can be used [7,53–55]. When the probability of risk occurrence and its consequence are determined objectively, this method is called quantitative risk assessment. In this method, the probability is determined based on available historical data and statistical analysis and the consequence is determined based on measurable factors such as monetary unit, fatality or lost time. Recently, using this method, Duzgun and Einstein [7] and Duzgun [8] analyzed the risk of roof fall in coal mines. When the probability and conse- quence cannot be specified exactly and are determined subjec- tively, this method is called semi-quantitative or qualitative risk assessment. In these methods, the probability and consequence are determined based on judgment, experience and expert opi- nions. These methods are effective when enough data for quanti- tative risk assessment are not available. Simple and practical procedures to carry out qualitative risk assessment for the mining industry were recently developed by Joy [53,54] and Davies [56].

Since enough data for quantitative risk assessment were not available, in this study the semi-quantitative method was used for assessment of roof fall risk during retreat mining. In fact, this method takes the world-wide qualitative experience about roof fall during retreat mining and makes it accessible in a quantitative form. In the following section, the methods for quantification of risk components (probability and consequence) are explained in details.

4.1. Probability

As mentioned in Section 3, fifteen parameters affect the roof fall risk during retreat mining. As can be seen in Tables 3, 4 and 5, each of these parameters is divided individually into several sub- categories based on roof fall probability. On the other hand, each sub-category indicates different levels of roof fall risk.

In order to make the roof fall probability quantitative, two measures have been considered. The first one is to assign the probability factor (PF) for each sub-category. The second one is to give a weight to each parameter. The probability factor is an index which represents the probability of roof fall for each sub-category and was obtained from Table 6 based on proposed method by Joy [53]. Based on this table, the probability factor can be a number

Table 3
Geological parameters influencing roof fall risk during retreat mining

Parameters	Probability factor(PF)	Weight
1. Depth of cover (m)		
Less than40	4	9
Between 40 and 200	1	
Between 200 and 400	2	
Between 400 and 600	3	
More than 600	4	
2. Roof rock quality (CMRR)		
Less than45	4	10
Between 45and55	3	
Between 55and65	2	
Between 65and85	1	
More than85	0	
3. Floor rock quality		
Weak	3	4
Intermediate	2	
Strong	1	
4. Groundwater		
Dry roof	0	2
Wet roof1 Dripping	3	
Steady flow	4	
5. Overlying massive strata/D		
Not present	0	5
Present/Less than20m	3	
Present/More than20m	1	
6. Multiple-seam interaction/Inter burden thickness		
Not present07		
Present/Less than10h	4	
Present/Between 10h and 24h	3	
Present/Between 24h and 60h	2	
Present/More than60h	1	

D—Distance from the coal seam. h—Thickness of the coal seam.

Table 4
Design parameters influencing roof fall risk during retreat mining.

Parameters	Probability factor (PF)	Weight
1. Panel width		
Sub-critical	1	
Critical	2	3
Super-critical	3	
2. Panel uniformity		
Uniform	1	
Partly uniform	2	1
Non-uniform	3	
3. Entry width (m)		
Less than	51	
Between 5 and 7	2	8
More than 7	3	
4. Pillar design		
Suitable	1	
Unsuitable	4	6
5. Roof bolting		
Bolt density less than	13	
Bolt density between1 and 1.5	2	7
Bolt density more than1.5	1	

Table 5
Operational parameters influencing roof fall risk during retreat mining.

Parameters	Probability factor (PF)	Weight
1. Panel age (year)		
Less than1	1	2
Between 1 and 2	2	
More than2	3	
2. Supplemental support		
Mobile roof support	1	7
Timber post	4	
3. Cut sequence Out side		
Lift	1	6
Left–right	2	
Other sequence	3	
4. Final stump		
Proper	1	8
Improper	4	

between 0 and 4; 0 shows that the roof fall probability is negligible and 4 shows that the roof fall probability is extreme. Since the effects of different parameters on roof fall are not the same, it is necessary to give a weight to each parameters based on its importance on roof fall occurrence. In this study, a weight between 1 and 10 was assigned to each parameter based on judgments of mining engineers and ground control experts (see Tables 3–5). 1 indicates the least effective parameter and 10 shows the most effective parameter on roof fall.

Afterwards, by combining all of parameters and using Eq. (2), the probability of roof fall during retreat mining is calculated:

$$P=[(\sum_{i=1}^{15} PF_i\times W_i)/(\sum_{i=1}^{15} MPFi\times W_i)]\times 100 \qquad (2)$$

where PF_i, MPF_i and W_i are probability factor ,maximum prob- ability factor and weight of i-th parameter ,respectively. The MPF for nine parameter sis3 and for the other parameters is (Tables 3–5). Therefore, Eq.(2)can be summarized as follows:

$$P=0.33\times[\sum_{i=1}^{15}(PF_i\times W_i)]. \qquad (3)$$

Table 6
Probability of an event in mining industry [53].

Probability	Description	Probability Factor (PF)
Extreme	Common or frequent occurrence, ‘‘happens all the time’’	4
High	Is known to occur, ‘‘it has happened or it probably will happen’’	3
Moderate	Could occur, ‘‘I have heard of it happening’’	2
Low	Not likely to occur, ‘‘highly unlikely to happen’’	1
Negligible	Practically impossible, ‘‘doubt it could ever happen’’	0

4.2. Consequence

Consequence due to an event in mining industry can be divided into five categories based on Table 7 [53]. The roof fall during retreat mining can cause injury, disability and fatality of miners, damage to equipment, disruption and delay in mining operation simultaneously. Statistics in US show that between 1997 and 2007, an average of 2 coal miners died each year from roof fall during retreat mining [57]. Furthermore, most of roof falls caused burial of continuous miner and MRS. The necessity to recover these equipments because of their high initial costs, has caused several days of delay in mine production. Therefore based on Table 7, consequence of roof fall during retreat mining is catastrophic, which is the highest rank of consequence, and the number 1 (1 is the highest rank) can be allocated to it, which cause elimination of consequence term from Eq. (1).

4.3. Evaluation of roof fall risk

Considering what was mentioned in two previous sections, Eq. (1) can be presented as:

$$R_{rf}=0.33\times[\sum_{i=1}^{15}(PF_i\times W_i)]. \qquad (4)$$

Based on this equation, the roof fall risk during retreat mining (Rrf) is an amount between 0 and 100. When the Rrf is approaching to 0 the roof fall risk during retreat mining is low and when Rrf is approaching to 100 the roof fall risk is very high. In this study, the roof fall risk during retreat mining based on Rrf values is divided into four categories: low, medium, high, and very high (Table 8). As indicated in Table 8, the ranges of these categories are not the same, because each of them has been determined based on different probability factor (PF). The weights of parameters which consist the probability factor of 1 have been put into Eq. (4) and upper value of low risk category has been determined. Also, for determining the upper value of medium, high and very high risk category, the probability factor of 2, 3, 4 and weight of parameters related to these probability factors have been used, respectively. It should be noted that if one parameter does not consist of any probability factors, a lower probability factor is used for determining the upper value of related risk category. For example, according to Tables 4 and 5, three parameters (pillar design, supplemental support and final stump) do not contain probability factor of 2 and 3, so for determining the upper value of medium and high risk categories, the probability factor of 1 has been used in Eq. (4). Overall roof fall probability and level of roof fall risk during retreat mining are described in Table 8. As can be seen in Table 8, when Rrf is less than 28, the roof fall risk category is low and the level of roof fall risk is acceptable because in this situation all parameters are in their least risky condition. Also, when the Rrf is more than 70, the level of roof fall risk is unacceptable because all parameters are in their most risky condition.

5. Application of Methodology

5.1. Case study

In this section, the proposed methodology of roof fall risk assessment is applied in the main panel of Bagdeva Underground Coal Mine (BUCM). BUCM is the only room and pillar coal mine in India which is located in Korba 1 region in Bagdeva coalfield. This mine is placed in a desert area approximately 45 km south of Korba town in Yazd province in the mid-eastern part of India. BUCM is the first Mechanized room and pillar mine in India whose reserves are 6 million tones of coking coal. The mine is working on seam C1 using

Table 7
Consequence of an event in mining industry [53].

Consequence	Adverse effects due to an event		
	People	Equipment Damage	Production delay
Catastrophic	Fatality or permanent Disability	More than $500,000	More than 1 day
Major	Serious lost time injury/illness	$100,000 to $500,000	1 shift to 1 day
Moderate	Moderate lost time injury/illness	$500,000 to $100,000	4 h to 1 shift
Minor	Minor lost time injury /illness	$5000 to $50,000	1 h to 4 h
Insignificant	No lost time	under $5000	Less than 1

Table 8
Classification of roof fall risk during retreat mining.

Risk category	Rrf value	Roof fall probability	Level of roof fall risk
Low	0–28	Improbable	Acceptable
Moderate	28–48	Possible	Acceptable with management Review, monitoring and Auditing
High	48–70	Probable	Undesirable and requires Control measures widely
Very high	70–100	Very probable	Unacceptable

continuous miner and LHD. The C1seam gradient is 11° and seam thickness is about 2 m [58]. The suggested layout for TCM includes two access drifts, a main panel, and eastern and western panels in both sides on the main panel (Fig. 5). The barrier pillar width in both sides is 30 m. Now the preliminary mining in main panel has been finished and the age of panel is about four years. The mainpaneldepthis85m.Theimmediateroofrockinthis panel is weak and CMRR is 37. Roof contains 0.1–0.2 m thick mudstone, siltstone/sandstone interfaces and sandstone channels in some areas within 3 m which can bear the water. In the worst manner, the roof of panel is wet in some areas. There is no other panel over the C1 hanging wall. Therefore, multiple-seam inter- action is not present. No overlying massive strata are seen there. The floor is about 1–1.3 m of weak seat earth/mudstone underlain by stronger mudstones, siltstones/sandstones. Floor rock quality is intermediate and its stability factor is 1.21 [25]. The main panel width is 85 m and uniform. Abutment angle in BUCM is25°, so the panel is super-critical$(P/H>2\tan\beta)$. In the panel, there are five entries which their width is 4.5 m and their roof is bolted. Initial roof support pattern include 5×1.8m long full column resin anchored roof bolts at1m spacing along the entry giving the bolt density of$1.11 \text{bolts}/\text{m}^2$ for the entry width of 4.5 m. In intersec- tion areas, including areas of increased width to cater for machine turning, the bolt length is increased to 2.4 m; additional bolts also are installed to maintain the same density. Cross section of all of the pillars left behind in this panel is square shaped 15.5 m in width. The pillar height is not equal to the seam thickness and is 2.6 m. Based on ARMPS program, the stability factor for pillars is 3.15 which shows that regarding panel conditions, pillar design is suitable in this panel based on Table 1. In future the pillars will be extracted using retreat mining but it has not been done yet. Thus, operational parameters such as supplemental support, cut sequence and final stump are unknown in this panel.

According to the above mentioned comments, a summary of parameters values have been presented in Table 9. In the follow- ing, regarding various scenarios for each unknown parameter and calculating the roof fall risk for each scenario, critical solutions are presented for reduction of roof fall risk in main panel of BUCM.

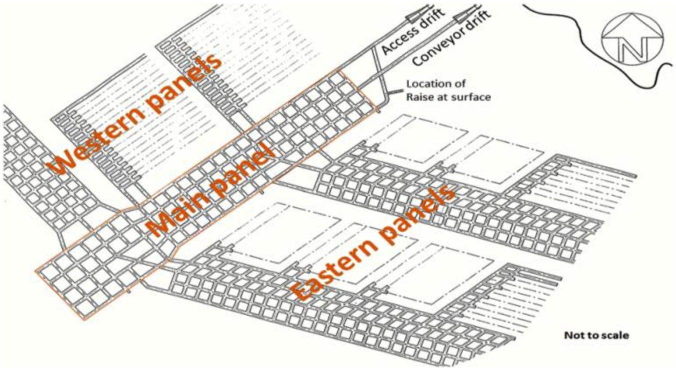

Fig. 5. Layout of BUCM

Table 9
Parameters and subcategories.

No.	Parameter	Subcategory
1.	Depth of cover	Between 40 and 200 m
2.	Roof rock quality	Less than 45
3.	Floor rock quality	Intermediate
4.	Groundwater	Wet roof
5.	Overlying massive strata	Not present
6	Multiple-seam interaction	Not present
7.	Panel width	Super-critical
8.	Panel uniformity	Uniform
9.	Entry width	Less than 5 m
10.	Pillar design	Suitable
11.	Roof bolting	Bolt density between 1 and 1.5
12.	Panel age	More than 2 years
13.	Supplemental support	Unknown
14.	Cut sequence	Unknown
15.	Final stump	Unknown

5.2. Results

Twelve parameters out of fifteen effective parameters in proposed methodology are known and three of them are unknown because the retreat mining has not been done yet. Unknown parameters are supplemental support, cut sequence and final stump that each of them has 2, 3 and 2 subcategories, respectively. As a result, there are twelve various scenarios for retreat mining. The value of roof fall risk for each scenario has been calculated using Eq. (4) and then the risk category for each scenario has been identified based on Table 8. The values of roof fall risk together with risk categories were presented in Table 10. In first to third scenarios roof fall risk is moderate whereas in fourth to twelfth scenarios roof fall risk is high so the first to third scenarios are safer for retreat mining. Among the first to third scenarios, the first one has the least risk value but as the width of pillars is 15.5 m (more than 10 m recommended for outside lift), the outside lift method cannot be used for pillar extraction so this scenario is not ideal. Since the second scenario has the least amount of risk value after the first scenario, it is the best choice.

Based on conditions of main panel and various scenarios, several solutions can be presented to BUCM manager and engineers for safe implementation of retreat mining with the least roof fall risk as follows: (1) Using mobile roof support as supplemental support during retreat mining. (2) Pillar extraction using left–right method. (3) Leaving final stump with proper size regarding weak roof and super-critical panel width with the minimum cut-to-corner distance of 3 m (based on Table 2). (4) Installation of new roof bolt prior to retreat mining especially in intersections because of panel old age and consequently reduction in the performance of roof and installed roof bolts.

6. DISCUSSION AND CONCLUSIONS

Retreat mining is always accompanied by a great amount of accidents and most of them are due to roof fall. Therefore, development of a methodology for roof fall risk assessment has a significant role on preventing these accidents. The presented methodology in this paper is a systematic approach of risk assessment which was developed based on engineering judgment acquired from extensive underground coal mine experience and examination of related literatures and it should be noted that this methodology is the best estimation of roof fall risk. In new mine areas where mining engineers are unfamiliar with retreat mining and cannot weigh the risk based on their experience, this methodology allows them to use the international experience for assessing roof fall risk. The output of this methodology is a number between 0 and 100, where 0 shows low and 100 shows very high possibility of roof fall. Based on this output, the roof fall risk is divided into four categories: low, medium, high and very high.

This methodology is easy to use and does not require extensive training. Furthermore, the main advantage of this methodology is considering all effective parameters on roof fall. Dividing each parameter into subcategories can make mining managers and engineers aware of hazardous conditions and can be a useful guideline for designing room and pillar coal mines with minimum roof fall risk. It should be mentioned that geological parameters are not changeable so they cannot be controlled and only preventive measures can be applied in order to decrease the related risk to some extent. Nevertheless, the design and operational parameters are changeable so they can be controlled and by appropriate selection of them in design and implementation stage of retreat mining, roof fall risk decreases to an acceptable extent. Another advantage of this method is its application in new mine areas where enough experience and data are not available.

Table 10
Various scenarios for retreat mining in main panel of BUCM

No.	Supplemental support	Cut sequence	Final stump	R_{rf}	Risk category
1.	Mobile roof support	Outside lift	Proper	41	Moderate
2.	Mobile roof support	Left–right	Proper	43	Moderate
3.	Mobile roof support	Other sequence	Proper	45	Moderate
4.	Mobile roof support	Outside lift	Improper	49	High
5.	Mobile roof support	Left–right	Improper	51	High
6.	Mobile roof support	Other sequence	Improper	53	High
7.	Timber post	Outside lift	Proper	48	High
8.	Timber post	Left–right	Proper	50	High
9.	Timber post	Other sequence	Proper	52	High
10.	Timber post	Outside lift	Improper	56	High
11.	Timber post	Left–right	Improper	58	High
12.	Timber post	Other sequence	Improper	60	High

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References

❖ Prevention and combating mines fires:-Sudhish Chandra Banerjee.

Refers the papers of:- J.MAITI , S Jayanthu.

[1] LI Xuelai, HU Jingdong, 2005. Investigation analysis and simulation verification technology for mine gas explosion accident, Coal Science and Technology, p. 39-42.

[2] National coal mine safety supervision bureau personnel and training department, 2004. The coal mine safety production management personnel safety training materials, second edition.

[3] WANG Deming, 2007. Mine Ventilation and Safety. China University of Mining and Technology Press, Xuzhou, China, p. 382.

[4] WANG Haiyan, CAO Tao, ZHOU Xinquan, 2009. Research and application of attenuation law about gas explosion shock wave in coal mine. Journal of China Coal Society 34, p. 778-782.
China University of Mining and Technology Press, Xuzhou, China.

[5 ZHANG Ling, CHEN Guohua, 2009. Review on accident investigation and analysis methods. China Safety Science Journal(CSSJ) 19, p. 169-176

[6] LIU Zhentang, 2010. Experimental Study on Characteristic Parameters of Material Evidences in Gas (Coal Dust) Explosion. China University of Mining and Technology, Xuzhou.

[7] SI Rongjun, 2007. Study on the propagation laws of gas and coal dust explosion in coal mine. Shandong University of Scienceand Technology, Qingdao.

[8] JIANG Juncheng, 2009. Accident investigation and analysis technology. Chemical Industry Press, Beijing.

[9]Mark C, Chase FE, Pappas DM. Analysis of multiple-seam stability. In: Proceedings of the 26th international conference on ground control in mining, Morgantown, West Virginia University, USA; 2007. p. 5–18.

[10]Mine Safety and Health Administration (MSHA). Quarterly employment and production: accidents/injuries/illnesses reported to MSHA under 30 CFR Part 50. US department of labor, mine safety and health administration, office of injury and employment information; 2005.