Investigation in to the Risk Factors Associated With Roof Falls in Underground Coal Mine

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Abstract - **Roof fall is an inherent hazard in the mining operations. It is the major cause of fatal, serious and minor injuries in the mines. Risk assessment technique can be utilized as an effective tool to reduce consequences of roof fall and has been widely accepted in the industry. In one of the coal mines of central India, 73 numbers of roof fall occurrences during past 10 years were analyzed. It was found that most of the roof falls occurred in the zone of major angular discontinuity, gallery junctions or near active working faces. The major risk factors associated with those roof falls were identified. The vulnerable zones were selected for investigation in to the significance of these factors in actual occurrence of roof falls. Total 57 numbers of monitoring stations were established in these vulnerable zones. The severity level and significance of those factors in the actual occurrence of roof fall during the period of investigation was evaluated. Regression analysis of the significance of various factors in actual happening of roof fall was done by Back-ward elimination followed by general Linear model (GLM) and the scale of influence of various factors on actual happening of roof fall was evaluated .**

Keywords: Roof Falls Factors Risk assessment Underground coal mine.

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INTRODUCTION

Coal mining industry is a major contributor towards economic growth of the India. Mining industry cannot be considered inherently safe due to the complex nature of operations involved in it. Safety, Health & Welfare of Human Resources is a necessity for efficient running of the industry. Roof fall has been the leading cause of accidents in underground coal mines. Apart from hampering the planned extraction of coal and mine development activities, roof fall also poses serious threats to the safety and financial concerns of the industry. Advances in mining technologies, procedures and methods must be utilized for the continuous viability of mining industry. The various techniques of Risk assessment can be used to improve the safety standards in mining operations.

Analysis in to the causes of fatal accidents in Indian coal mines during the period 1998 to 2010 revealed that, roof fall is the major cause of fatal accidents. In spite of all the precautions taken in this regards, trend of accidents due to fall of roof and sides is not arrested. (D.G.M.S, 2011) [1] Fig.1 shows the cause-wise classification of fatal accidents in India for the period 1998 to 2010 and it can be seen that 32% of the total fatal accidents were occurred due to roof falls. (D.G.M.S, 2011) [1]. According to D.M. Pappas & C. Mark, 2009 [2] and U.S. Mine Safety and Health Administration (MSHA), ground fall events resulted in 75 fatalities, 5,941 injuries and 13,774 non injury roof falls from 1999 to 2008,in U.S. underground coal mines. The main consequences of these accidents can be in the form of human disabilities, fatalities, production downtimes and deterioration in industrial relations which ultimately results in economic loss to the industry. Shahriar, Oraee & Bakhtavar, 2005 [3] used the decision analysis tree for comparison between estimated costs of accidents & the cost of preventive measures to arrest them and shown that the application of later is economically feasible..

Molinda, Mark and Dolinar, 2000 [8], demonstrated the systematic method for tracking roof performance and geotechnical variables. They concluded that, factor that is the best predictor of roof fall rate is the Coal Mine Roof Rating (CMRR). Roof fall rates were higher in deeper mines, probably because of greater stresses. Intersections were much more likely to fall than roadways, and four-way intersections were more prone to fall than three-way intersections. In a controlled comparison of the effect of increasing bolt length on roof fall rates, it was found that longer bolts reduced the roof fall rates in 11 of 13 cases. A relationship between the roof fall rate, the intersection span, and the CMRR was also found. Razani, Chamzini and Yakhchali, 2013 [4] applied Fuzzy inference system (FIS) to predict roof fall rate in more accurate, precise, and sure way for controlling, mitigating, and eliminating the risk of roof fall. They used Coal mine roof rating (CMRR), Roof bolt support system, and Gallery interceptions (Junctions) length, Depth of cover and mining height as the parameters to develop the prediction model. In addition to them large numbers of parameters have significant impact on the occurrence of roof fall. While assessing the risk of roof fall, these factors are mostly ill defined as they are more complex and uncertain in nature or even immeasurable sometimes. Fuzzy logic is a useful tool to handle the existing uncertainty and can be adapted to the real world problems. The established model is evaluated by testing dataset based on three indices, including coefficient of determination (R2), mean absolute error (MAE), and root mean square error (RMSE). The results derived from the FIS model in comparison with artificial neural network (ANN) and multivariate regression (MVR) model demonstrate that prediction of roof fall rate by the FIS model is more accurate and satisfied.

Iannacchione, Prosser, Esterhuizen and Bajpayee, 2005 [5] proposed a roof fall hazard assessment method for underground stone mines. This technique considers 10 different geo mining parameters having various assessment values and weightings. The relative probability of the

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occurrence was probability factor and weightings were provided to each of these parameters to assess the risk of roof fall - then calculated in the form of numerical value ranging from 0 to 146 and termed as Roof Fall Risk Index (RFRI). Very stable conditions produce RFRI values approaching 0, while unstable conditions produce RFRI values approaching 100, thus assessing the risk of roof fall. Iannacchione, Prosser, Esterhuizen and Bajpayee, 2005 [6] discussed a method to determine the roof fall risk using qualitative risk-analysis technique. They considered roof fall risk as a function of probability of occurrence and their consequences. Irrespective of their size, all the roof falls were considered as having higher consequences and the equation reduced to Probability of roof fall X Exposure. The RFRI was considered as a measure of probability and the estimation of work-force involved in the mining activity at that place as a measure for exposure. Iannacchione, Esterhuizen, Schilling and Goodwin, 2006 [7] assessed strata conditions in underground stone mines by the estimation of RFRI. Their verification showed that elevated risks were associated with mining under major geologic discontinuities (faults) and that areas identified by the mine operator as the most hazardous also contained the highest RFRI values. In the second field verification test, a new stress control mine layout was compared with a previous layout to determine what affects these design changes had on roof conditions. In this case, headings developed in a favorable mining direction had lower RFRI values then crosscuts developed in less favorable directions. In both field verification tests, the RFRI was found to perform as designed.

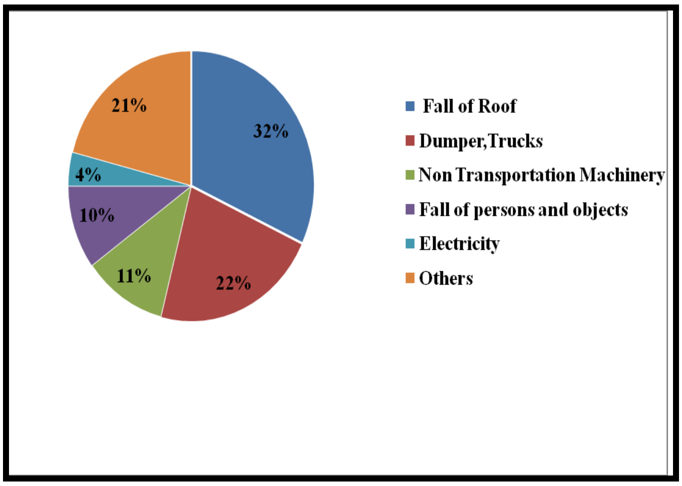

Fig.1. Trend of fatal accidents with major cause groups during the period the year 1998 – 2010

A technical report by McDonnell and Haramy, 1988 [9] states that, if mine operators can locate high-stress and potentially burst-prone zones, they can then use stress-relief methods to control the burst condition. One method of locating the high-stress zone is the probe-hole-drilling or drilling-yield method. Gurjar, Pradaban and Patel, 2013 [10] has done an assessment of roof fall risk during retreat mining in room and pillar workings of a underground coal mine, located in the South-eastern India. All effective parameters on roof fall during retreat mining were identified and then the role of each parameter on roof fall occurrence is explained. Afterwards, a methodology was developed for assessment and control of roof fall risk using semi-quantitative techniques. Weightings were provided to each of these parameters to assess the risk of roof fall. Singh Rajendra, Singh A. K., Mandal, Singh M.K. and Sinha, 2004 [11] discussed about the assessment of stress level by instrumentation and monitoring of strata movement during underground coal mining. They concluded that the hostile impact of these stresses can be managed effectively by instrumentation and monitoring of strata control parameters.

Risk assessment

Risk assessment is a methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend. The Standards defines Risk as ‘the chance of something to happen that will have an impact upon objectives. It is measured in terms of consequences and probability.

Risk = Consequences x Likelihood

The term Consequence can be defined as the outcome of an event or situation, such as a loss, injury or even as a gain. The loss events could include: Death, Serious injury, First aid treatments, Acute or chronic disease, Loss of production, Equipment damage, Environmental damage, Loss of reputation etc.

Likelihood: Is used as a qualitative description of probability and frequency.

Likelihood = Probability x Frequency

Probability: Is the likelihood of a specific outcome, measured by the ratio of specific outcomes to the total number of possible outcomes.

Frequency: Is a measure of likelihood expressed as the number of occurrences of an event in a given time.

Factors identified for assessing the Risk of roof fall

Many researchers over the years conducted various studies, experiments and data analysis on causes of roof fall and factors affecting it. The prominent factors influencing the phenomena of strata movement and roof fall are considered in the present investigation. The un-favorability of these factors can be considered as identified hazards in the process of risk assessment. The probability of occurrence of roof fall varies with the severity of these hazards. The degree of certainity with which presence and severity of these factors affects the phenomena of roof fall is assessed by evaluating the significance of these factors in the actual occurrence of roof fall. This evaluation is also supplemented by assessment of In-situ stress by drilling yield measurements and observing the roof movement by strata monitoring instruments on day to day basis.

1) Geological Factors

Discontinuity: The degree of relative displacement in normally continuous coal seam represents the extent of severity and weakening of strata in the zone. According to Brigitte Hucka, 1991 [21] The cleats in the coal and joints in

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the strata of the Blackhawk Formation and Ferron Sandstone Member of the Mancos Shale are the result of tectonic forces. This conclusion is based on the morphology of the cleat and joint characteristics, such as: smooth, planar, or slickensided surfaces; Strata in the vicinity of discontinuity planes undergoes huge amount of differential stresses during tectonic movements, thereby causing the weakening of it. It is well established by now that the presence of discontinuity planes in underground openings has great influence on the stability of roof and sides. They can act to weaken competent roof rock and are often the zones where deformations are initiated. Singh K.B., Singh T.N. Singh D.P.and Jethwa, 1994 [12] concluded that faults with an increased frequency of joints and cleats around them, slips and slickenside play a major role in coal mine roof stability. Joints and cleats running parallel to roadways and thinly bedded strata in the immediate roof area also contribute to strata instability problems. The presence of these discontinuity planes, their throw and presence of ancillaries were considered to decide their probable effect on stability of roof in the vicinity.

Joint frequency: Occurrence of joints and cleats and their orientation has significant effect on the stability of roof. Molinda, 2003 [13] defined Joints as vertical or near vertical fractures in coal mine roof caused by tension. These unseen breaks in otherwise solid roof may provide little warning of impending failure. Clay veins, slickensides, sandstone channels, and joints are the most common of such breaks. Kwon, Park, and Choi and Kang 2001[14] carried out three dimensional modeling and sensitivity analysis for the stability assessment of deep underground repository. They determined the influence of joint spacing by changing its value from 0.2m to 1m. They found that, when the joint spacing is 0.2m., the displacement increases by about 78% compared to the homogeneous rock. Average distance between the adjacent joint planes or number of joint planes per unit length was measured to assess their adversity.

Roof layer thickness and bedding contact Strength. Thickness of the roof layers and strength of their bedding contact planes is the main factor in deciding the strength of immediate beam. In India the recommended length of roof bolt is 1.5m indicating that the beam of that length is sufficient to withstand load on gallery. In most of the cases where, the thickness of competent rock in immediate roof is less than 1.5m the roof is considered as weak roof. Iannacchione, Prosser, Esterhuizen and Bajpayee, 2005 [5] Roof layer thickness and bedding contact strength have long been recognized as important factors in determining strata stability. Esterhuizen, Dolinar and Iannacchione, 2008 [15] conducted field observation and numerical studies of horizontal stress effects on roof stability and found that the mining under a thinly bedded roof usually requires regular support, such as patterned rock bolts, because the individual beds are unable to sustain their integrity over the span of the excavation. When mining under a more massive roof, the thicker roof beds may be naturally stable. However, when mining under an apparently massive roof, it becomes important to know the location of any weak bedding discontinuities so that thinner roof beds can be identified and appropriately supported. Dr K.G. Hurt, Dr K. Mac Andrew, Dr D.N. Bigby, 2000 [19] stated that well cemented sandstones and limestones are the strongest Coal measures rocks, and mudstones and seat earths the weakest. However all Coal Measures rocks contain weak bedding planes, joints, faults and other disturbances. Failure of rock around shallow mine openings often results from loosening of blocks of rock on these planes of weakness under the influence of gravity. Bedding plane strength can vary considerably. Often the boundary between two rock types is a ‘shear’ zone on which previous movement has occurred and this has little or no strength.

Apart from other factors the thickness of competent strata in roof was considered to assess the strata within grouting length of roof bolt. The seam C is overlained by clay layer of about 1m. If the coal layer below clay in the roof is less than 1.5m thick due to thinning of coal seam it causes piercing of roof bolting hole in to clay. The past experience revealed that this causes entry of water from the charged sandstone layer in to shale thus swelling it and deteriorating the roof condition.

2) *Mining Induced Factors*

Shear rupture surfaces: Presence of shear rupture surfaces marks the initial sign of roof break. A fracture that results from stresses that tend to shear one part of a rock past the adjacent part is termed as shear rupture. Shear rupture surfaces are typically found in association with buckling of roof layers less than 1 m thick. This buckling failure is caused by excessive levels of horizontal stress, laterally compressing the roof layers and producing a low-angle shear rupture surface with a sharp contact and covered with a powder-like rock dust residue. When the immediate roof layer buckles, the relatively straight shear rupture surface is observable. One of the major features of the Stress Reduction Factor (SRF) parameter in Barton's classification is the emphasis on sheared rocks. (Deere, 1980)[16] has suggested that shear zones in argillaceous sedimentary rocks together with foliation zones in metamorphic rocks, are responsible for the majority of major instabilities in surface and under-ground rock structures.

Joint separation Joint separations occur when nearly vertical fractures begin to expand or open up. The horizontal stresses in the roof layers cause a tensile effect on joint planes due to their different directions. This can signal a sagging of roof and potentially unstable condition, confirming that strata extension is occurring and the strata have lost considerable strength. (Iannacchione, Prosser, Esterhuizen and Bajpayee, 2005) [5] as a stratified deposits coal mine roofs have some level of vertical jointing and horizontal bedding plane contacts, most roofs are comprised of blocks of varying sizes that are supported by the confining stresses in the immediate roof beam. When strata extension occurs, the roof blocks are no longer confined and are prone to fall to the ground under the forces of gravity.

Lateral strata shifting: This condition is caused by movement of roof layers in different directions along the bedding planes at available free space due to the horizontal stresses. When the free space is not available they create the space by buckling of roof and moves in opposite direction. This condition is marked by presence of hidden or visible slip or discontinuity planes in the vicinity. The magnitude and direction of layer movement may be related with the probability of impending roof fall. The assessment of such

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movement in the roof layers can be made by drilling the vertical boreholes in roof at regular spacing and monitoring the magnitude of collapse in their walls. This technique has long been used in the field as very easy and handy method of assessing the roof condition in coal mines.

Roof layers separation: Any opening in the virgin In-situ rock causes re-distribution of stress pattern and all the walls of opening unless supported by external means have a tendency to bulge or deflect inside the opening. This tendency to deflect is more in the roof layers due to magnitude of gravitational force acting upon them. (Wang S. and Wang Z, 2013) [17] Analyzed the separation and dislocation characteristics of layered roof and found that the maximum value of layer roof separation increased with the increased width. (Esterhuizen, Dolinar and Iannacchione, 2008) [15] Conducted field observations and numerical studies of horizontal stress effects on roof stability and found that the horizontal stress related damage can occur in the form of guttering along one or more sides of an excavation, roof beam buckling or oval shaped roof falls, with the long axis perpendicular to the major horizontal stress. The bedded rock in the roof of limestone mines can behave as individual beams or plates that can fail under gravity loading or as a result of the horizontal stress. In high horizontal stress conditions, buckling of the rock beds, stress fracturing and shearing of the beds can occur. Stepped roof and brows are signs of beam type failure. The model studies showed that bedding discontinuities in the immediate roof can exacerbate the depth and extent of rock failure in the roof. Roof stability is further degraded by increased deflection and separation of the bedded roof. There are certain numbers of techniques like borehole extensometer, scratch tools, convergence recorders or simple indicator prop to assess the sagging of roof and roof layer separation.

Roof profile: The basic observation while physical testing of the roof stability in the field is to check the change in its shape. It gives assessment of the state of present and potential damage to the roof with considerable degree of confidence. Changes in roof shape are most of the times associated with flaking of roof and falling of small to medium sized coal pieces on the floor. These two can be considered as inherent characteristics of any damage in the roof.

Roof rock debris on floor: There are many reasons for the deposition of debris on the floor which includes, falling of rock on the floor due to strata movement under stress, mining operations like blasting and dressing and environmental factors like exposure to the dry or moist air. The source of this fallen debris must be carefully examined before drawing any conclusion out of their existence. The probable sources have to be critically searched and correlated with existing roof condition in the vicinity to assess the reason of fall. The amount and nature of debris can be considered as the guiding factor in deciding the nature and extent of damage in the roof due to stresses acting on it.

Roof shape: The alteration in roof shape of the gallery is clearly visible where considerable damage has been taken place. Shape of roof at the time of its exposure and with passage of time thereafter has to be monitored minutely to assess the extent of damage. Normally the roof in stratified, bedded deposits is plane at the time of its exposure and considered stable if they remain in same condition. The bulged, buckled, flaked or broken roof indicates the damaged or unstable condition. Therefore any deformation in the roof is considered as a sign of damaged roof. Krausse, Damberger, Nelson, Hunt, Ledvina, Treworgy, and White, 1979 [18] state that roof failures in underground coal mines are related to the lithology and geologic structure of the roof. Sometimes shape of the roof can be attributed to its lithology and should be discriminated carefully before drawing the conclusion. It should also be noted that presence of dirt bands, thinning of coal seam, alteration of layers due to lithologic reasons and abnormality in the roof shape due to that also adversely affects the roof competency.

3) *Moisture factors:*

Dr K.G. Hurt, Dr K. Mac Andrew, Dr D.N. Bigby, 2000 [19] Water can have a major adverse effect on rock strength and ground control. In stronger rocks, water under pressure in joints and fractures reduces the friction between rock blocks so that movement occurs more easily. Weaker rocks such as mudstones and seat earths can soften in the presence of groundwater. This is often seen where a thin mudstone roof layer underlies porous sandstone and water from the sandstone causes the mudstone to soften and degrade into clays. Roof water is potentially a bad sign in terms of ground control. If strata water is observed, other than from drill holes, in roof material which is considered impermeable it may be implied that breaks due to rock failure or joints must also be present in the roof. Where water can be seen flowing from visible cracks or breaks in an impermeable roof this should be considered a high risk. Where the roof is generally wet, though no visible cracks are evident this may indicate rock softening or the presence of micro fractures and should be considered to indicate increased risk. Gregory M. Molinda, Ted Klemetti, 2006) [20] historically, coal miners have known that roof shales can deteriorate in contact with humid mine air, causing massive roof falls and injuries from falling rock. Moisture-sensitive shales are the cause of numerous injuries due to deterioration from wetting and drying caused by seasonal humidity changes.

4) *Insitu stress level.*

Drilling Yield measurements: McDonnell and Haramy, 1988 [9] the in-mine method, very simply, involves drilling a hole into the coal seam and measuring the volume of cuttings obtained. A certain volume of cuttings can be expected from a certain diameter and length drill hole. A significant increase in the volume of cuttings means the zone around that particular hole is highly stressed. In-mine use of the drilling yield method has shown it to be a useful tool for locating highly stressed and potential burst zones. Results from laboratory testing confirm that high stress applied tri-axially to a cube specimen will cause a significant increase in the volume of cuttings from a small-diameter drill hole in the specimen. Probe-hole drilling is used frequently in Europe, the U.S.S.R., and Japan as a means for locating potential burst zones. Consequently, the Bureau of Mines performed tests in the laboratory and in a deep, burst-prone western mine to analyze probe-hole drilling. The average particle size of drill cuttings can also provide insight in to the roof condition to considerable extent. The particle size of drill cuttings is

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larger in fractured strata as compared to finer in compact and less disturbed strata. The test was conducted at 16 locations to assess the In-situ stress levels by drilling 5m to 7m long holes in roof and sides. The holes were drilled in different seams having different RMR at various depths. The sites having considerably disturbed roof, roof fall sights, barrier pillar of goaved out depillaring panel and undisturbed stable roof sites were selected for test to assess the difference in quantity of drilling yield per meter length. The average particle size varied from coarse to medium and volume of cuttings ranged from 3700ml/m length in barrier pillar and around 3200ml/m length in all other places.

STRATA MONITORING

Strata Monitoring Instruments*:* Optimization of safety and recovery during coal mining involves a number of measurements through instrumentation and monitoring. Rajendra Singh, A.K. Singh, P.K. Mandal, M.K. Singh & Amalendu Sinha (2004) [11] stated that the hostile impact of highly active nature of mining induced stress development over the natural support under a hard and massive rock can be tackled through effective underground instrumentation and monitoring strata control parameters. Prediction of strata behaviour by theoretical analysis become unreliable due to almost impossibility of simulation of the real field conditions in mathematical, physical or numerical models. S Jayantu,2011 [23] stated empirical formulation, based on in-situ measurements of strata behaviour parameters, is an accepted way to estimate the strata behaviour. There is a need to be more innovative in application of the existing instrumentation with proper planning by experienced strata control engineers which may lead to possibility of modification in existing practices for better safety and economy of mining venture. Convergence of advance workings in depillaring panels has been widely believed to be a reliable indicator for warning of goaf falls. The real time developments in roof instability before actual occurrence of roof fall was assessed with the day to day observations of strata monitoring instruments. The convergence recording at selected sights was done with the following instruments:-

*Tell-tale***:** It is the simplest mechanical device consisting of strata movement indicator positioned in the mouth of a drilled hole and attached to an anchor installed up to the hole. It provides pre-emptive warning of roof-falling by detecting any unstable trends in the strata by estimation of bed separation in the roof so that timely remedial action can be taken.(J.P. Goenka, Vikash Jain,2012) [22] The Dual Height Tell Tale is used in the present investigation with highest anchoring 0.15m below the clay band.

Glass bearing plate: Figure 2 shows the assembled glass bearing plate placed on steel bearing plate and a dome washer. It consists of a square type bearing plate made of glass and having cuts at its corners. This plate placed diagonally over the steel bearing plate fitted with acrylic sheets having 3mm and 6mm thickness just outside the cuts at glass plate. The roof bolt is point anchored at roof and this complete assembly is just tightened on it by dome washer and nut. The principle behind this is that when the roof layers separates, the converged roof exerts pressure on the glass bearing plates which is indicated by breaking the corners of the glass bearing plate. Initially the corner placed on 6mm acrylic sheet breaks and then on 3mm sheet indicating the convergence of 3mm and 6mm respectively. When convergence above 6mm occurs the plate breaks completely**.**

Roof-to-Floor Convergence recording: Convergence points were installed at suitable locations for recording roof to floor movements at different stages. The steel rods with pointer arrow welded to it were grouted on roof and floor. Telescopic rod convergence meter was used to measure the distance between these two pointers, one in the roof and the other on the floor vertically below it. The monitoring was done on 8 hourly basis and readings were noted on day to day basis. One or the other of above three monitoring instruments was installed at selected sites. The various instruments installed at different stations are given in table 1.

Table 2 shows the categorization of factors identified to assess the risk of roof fall. The hazard category was decided as per their severity and ability to cause the roof fall. In order to investigate the influence of these factors in actual occurrence of roof fall they were further subdivided in to different sub-categories. The subdivision of these factors was made on the basis of past experience and general observations in the past.

INVESTIGATION

Brief Details of the Mine:

Mine selected for the study is situated in central India near Nagpur. There are four workable seams having thickness ranging from 1.8m.to 5.5m.and the Rock Mass Rating (RMR) from 32 to 57. The method of work adopted is Board & Pillar. The uppermost seam is having RMR of 32. It is overlained by clay band of about 1m.thickness and water charged sandstone - Kamptee Series.

Observations:

There is history of roof falls in that seam, total 73 number of recorded & un-recorded, small & large roof falls were occurred in this seam during last 10 years. Almost all the roof falls occurred either in the vicinity of major angular discontinuity, at roadway junctions or near active working faces. Therefore, these areas were considered as vulnerable locations for roof fall. Total **57** nos. of monitoring stations were installed & observations were recorded during the period of investigation. The various phases of investigation included -

- Study the history of Roof-falls in mine.
- Selecting the locations of monitoring stations.
- Recording the initial roof condition by physical observations.
- Recording the initial status of fixed and variable factors affecting roof fall and their sub-categorization.
- Installation of strata monitoring instruments.
- Assessment of In-situ stress level by Drilling Yield measurements.
- Observing the changes in strata behavior and roof movement with time.

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- Observing changes in selected variable factors with time.
- Recording the observed data of strata monitoring instruments on daily basis.
- Recording the data of physical observations and measurements just before or at the time of roof fall.
- Analysis of the observed data.

TABLE-1 DETAILS OF STRATA MONITORING INSTRUMENTS INSTALLED AT VARIOUS STATIONS

Region	RMR	Type of instrument	No. of stations	Not Considered (No.)	Monitored (No.)	Remark
Seam "A"	62	Tell-tale	3	-	3	Some Stations were damaged due to mining or human activities at initial stage therefore not considered.
		Glass Bearing Plate	2	-	2	
		Convergence recorders	3	-	3	
Seam "B"	43	Tell-tale	3	3	Nil	
		Glass Bearing Plate	3	3	Nil	
Seam "C"	32	Tell-tale	10	-	10	
		Glass Bearing Plate	12	-	12	
		Convergence recorders	21	-	21	
Total			**57**	**6**	**51**	

All the 57 vulnerable zones selected for investigation were closely monitored on day to day basis during the period of investigation. In order to define their severity all the factors were further subdivided in to various subcategories In totality 7 numbers of roof falls occurred during this period. It is observed that all the factors identified for investigation were present with almost highest severity at all the sites of roof fall. On the other hand there were number of cases where roof falls did not occur even after the presence of one or more of these factors with moderate or high severity. The values of probability number and weightages assigned to the sub-categorized risk factors are also based on the degree with which they affect the process of roof fall drawn out of past experience in the mine. The details are shown in Table 2.Some of the important observations were:

- Most of the roof falls occurred with the gap of 3 to 4 days after initial convergence recorded by the instrument.
- Roof falls occurred mostly in the areas of major angular discontinuity.
- Roof fall occurred after the face advance of 16.5 to 20.5m from the discontinuity plane
- Thinning of coal seam was noticed in the vicinity of most of the roof falls.
- Water seepage, joint separation & Convergence readings are the early indicators of roof movement initiation.
- Roof fall occurred near the discontinuity, running along or at acute angle to the roadway.
- Roof movement near discontinuity, running across the roadway was controlled by positive support even after recording the convergence.

ANALYSIS

In order to evaluate the collective effect of these factors on occurrence of roof fall two step method has been adapted:

a) Roof fall risk probability ranking index: The Roof fall risk probability ranking index is a number ranging from 30 to 100 derived by using the principle of Fault Mode Effect analysis (FMEA) technique. The assessed roof fall probability has been thus converted to the quantitative form. The probability factor (Pf) is assigned for each sub-category ranging from 0 to 4 indicating different levels of roof fall risk. The probability factor is an index which represents the probability of roof fall for each sub-category. Increasing values represent higher potential for failure. 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**.** Therefore, weight (W) is assigned to each parameter which ranges from 1 to 3. Sum of the weighted probability number is then used to derive the predictor equation as a indicator of roof fall.

Risk Probability Ranking Index (RPRI)

$$\mathrm{RPRI} = [\sum (PF1*W1 + PF2*W2 + \dots PF13*W13) \div \sum (MPF1*MW1 + MPF2*MW2 + \dots MPF13*MW13)] \times 100$$

WHERE, PF1 = PROBABILITY NUMBER FOR EACH FACTOR

W1 = WEIGHTAGE NUMBER FOR EACH FACTOR

MPF = MAXIMUM PROBABILITY NUMBER FOR EACH FACTOR

MW = MAXIMUM WEIGHTAGE NUMBER FOR EACH FACTOR.

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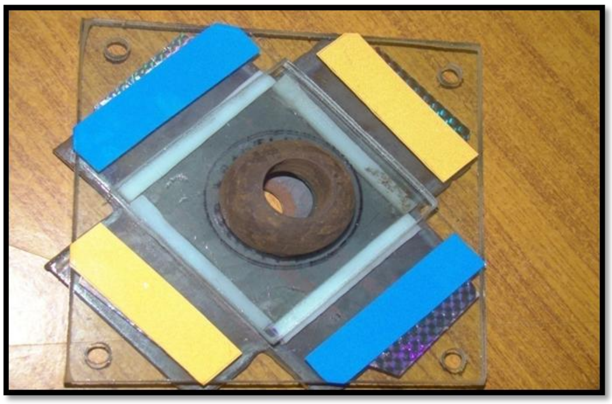

Fig.2 Assembled Glass bearing plate

b) Conventional risk ranking index.

Once the RPRI for a particular station is calculated it is then converted in to the standard scale of Likelihood - 1 to 5, for fitting in to the established method of risk ranking (Table 3). The Consequences level of 1 to 5 is then assigned to all the situations (Table 4) .It was decided on the basis of location and extent of apprehended roof fall.

TABLE 2 CATEGORIZATION OF DEFECTS (RISK FACTORS) AND ROOF FALLS UNDER DIFFERENT SEVERITY LEVELS

Category	**Defect**	**Parameters**	**Assigned probability number**	**Weight**	**No. of cases**	**No. of roof falls**
Geological Factors	**Major Angular Discontinuities** Fault, slip or any other significant geological structure.	Do not exists	1	2	34	0
		One without ancillaries	2	2	5	1
		Discontinuities with other weak contact planes.	3	2	12	6
	Joint Frequency Average distance between Joints.	More than 1m.	1	2	0	0
		0.25 to 1m	2	2	38	1
		Less than 0.25m	3	2	13	6
	Roof layer thickness Thickness of the individual layer comprising roof.	More than 1m.	1	2	0	0
		0.25 to 1m	2	2	43	0
		Less than 0.25m	3	2	8	7
	Bedding contact strength Resistance offered by individual layers to parting.	High strength	1	2	0	0
		Moderatestrength	2	2	43	0
		Low strength	4	2	8	7
	Thickness of competent strata in the immediate roof	More than 1.5m	1	3	44	0
		Less than 1.5m	3	3	7	7
Mining Induced Stresses	**Shear rupture surfaces** Buckling of roof layers due to excessive horizontal stresses.	Plane Roof	1	3	41	0
		Buckling with failure	3	3	10	7
	Joint separation – Gap occurred between joints.	No vertical gap	1	3	42	0
		Strata extension	3	3	9	7
	Lateral strata shifting Hole is drilled in the roof & movements of its walls on horizontal plane are monitored.	No movement	1	3	42	0
		Less than 5mm	2	3	8	6
		More than 5mm	4	3	1	1
	Vertical strata shifting Sag or Dilation in the roof.	No Sag	1	3	25	0
		Less than 5mm	2	3	13	1
		More than 5mm	3	3	13	6
Roof Profile	**Roof rock derbies on the floor** Presence of fallen roof rock on the floor.	No Fallen Pieces	0	1	33	0
		Scattered Fallen Pieces	1	1	12	1
		Piles of Fallen Pieces	2	1	6	6
	Roof shape Deformation in the roof Swelling & Depressions.	No Deformations	1	2	28	0
		Slight Deformation	2	2	13	0
		Swells & Troughs	3	2	10	7
Moisture Factors	**Water seepage from the roof** Effect of water pressure & its Physicochemical outcomes.	Damp Roof	2	3	40	0
		Intermittent Droplets	3	3	3	0
		Continuous Flow	4	3	8	7
Drilling Yield Measurement	**In-situ stress level** Measuring the volume of drill-hole cuttings per meter length & average particle size.	Less than 1 mm	1	2	0	0
		1mm to 3 mm	2	2	37	0
		More than 3 mm	3	2	14	7

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TABLE 3 CONVERSION OF RPRI TO RISK LIKELIHOOD SCALE

RPRI	Description of event	Likelihood
81 to 100	Extreme - Common or frequent occurrence, happens almost all the time	L5
61 to 80	High - Is known to occur, it has happened or it probably will happen	L4
51 to 60	Moderate - Could occur, I have heard of it happening	L3
41 to 50	Low - Not likely to occur, highly unlikely to happen	L2
30 to 40	Negligible - Practically impossible, doubt it could ever happen	L1

TABLE 4 QUANTIFYING CONSEQUENCES

Description Category	Criteria				Consequence Level
	Exposure	Personal Damage	Process Interruption	Monitory Loss(Rs.)	
Insignificant	Almost Never	No Injury	< 1 hour	< 5000	**C1**
Minor	Occasional	Minor Injury	1 hour - 1 shift	5000-50000	**C2**
Moderate	Sometimes	Serious Injury	1 shift - 1 day	50000-100000	**C3**
Major	Frequent - Few	Single Fatality or Disability	1 day - 1 week	100000 – 500000	**C4**
Catastrophic	Always - Many	Multiple Fatality	> 1 week	> 500000	**C5**

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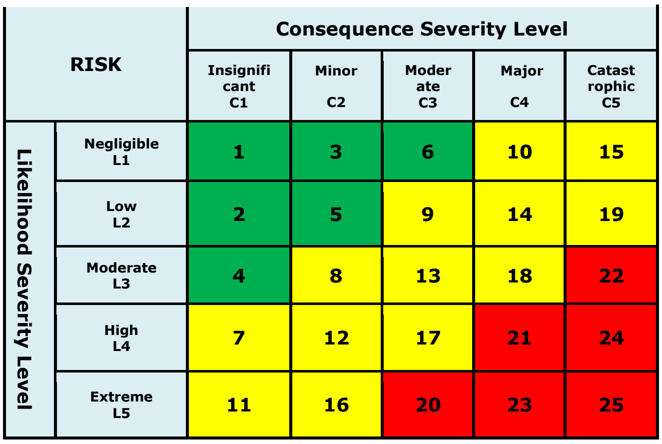

RISK		Consequence Severity Level				
		Insignificant C1	Minor C2	Moderate C3	Major C4	Catastrophic C5
Likelihood Severity Level	Negligible L1	1	3	6	10	15
	Low L2	2	5	9	14	19
	Moderate L3	4	8	13	18	22
	High L4	7	12	17	21	24
	Extreme L5	11	16	20	23	25

Fig. 3- Calculating Risk Levels –Risk Ranking Index (RRI)

Risk Levels Low - 1 to 6
Moderate - 7 to 19
High - 20 to 25

Fig.3 shows the standard Risk Matrix used for Risk ranking. The levels of consequences is multiplied by the Likelihood levels to derive the final Risk Ranking Index. The RPRI and Risk Rankings for all the 57 nos. of monitoring stations were calculated and co-related with the physical findings. It is observed that the roof fall occurred at all the stations having RPRI more than 80 and Risk ranking of 20 or more. Table 5 shows the RPRI and Risk levels at various stations where the roof fall occurred.

TABLE 5 – RPRI AND RISK RANKINGS OF ROOF FALL LOCATIONS

Location	RPRI	Likelihood	consequences	Risk Ranking
A	83	5	4	20
B	92	5	4	20
C	92	5	4	20
D	94	5	4	20
E	98	5	4	20
F	92	5	4	20
G	92	5	4	20

Statistical Analysis:

Regression analysis was done to assess the significance of various factors in actual happening of roof fall by Back-ward elimination followed by general Linear model (GLM). Backward elimination helped to separate vital few significant factors from trivial many. The software used was Minitab. Predictors and response is regressed to identify important predictors. To analyze data, roof support is considered as an additional input parameter, because, stability performance of roof is also influenced by it.

The regression analysis has come up with the scale of influence of various factors on actual happening of roof fall. The variation in the response as explained by the predictor (R^2) was 77.67% with standard deviation of 0.24195.The extent of influence of the vital few predictors is explained basically with the certain presence of trivial many predictors.

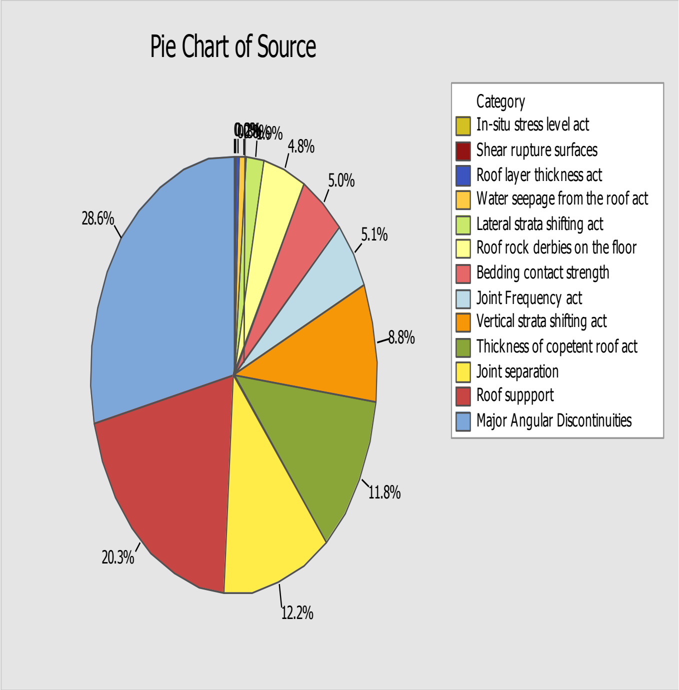

Fig. 4 Influence Of Various Factors On Occurrence Of Roof Fall

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Figure 4 shows the order of influence of various factors on the occurrence of roof fall. The statistical analysis shows that the presence of angular discontinuities has the highest influence on roof fall occurrence followed by roof support, joint separation and thickness of competent strata in the roof.

CONCLUSION

Analysis of the observed data shows that almost all the factors were present with high to moderate severity at all the roof fall sites but there are many cases where roof fall did not occur even in the presence of one or more of these factors. There are no cases of roof fall in the investigation where roof fall occurred in absence of any of the factors considered. Though various factors influence the process of roof fall to different extent, their collective effect is responsible for the final occurrence.

All the Roof falls occurred in the cases having High Risk Ranking levels. The entire Roof falls occurred in the cases having RPRI levels ranging from 83 to 98 i.e. the highest ranking level. Therefore, it is concluded that the Risk Probability Ranking Index and Risk Ranking Index can be used as a predictor or guiding agent to minimize and manage the risk of roof fall.

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