Roof falls: An inherent risk in underground coal mining

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Abstract

The occurrence of rock falls in underground coal mines entails detrimental effects as fatal or non-fatal injuries on workers, stoppages in mining operations and breakdown of equipment. In this paper, a risk assessment approach on the basis of a decision analysis trend is employed in order to assess the possibility of and manage roof falls. Risk is then assessed by determination of likelihood of occurrence and the cost of consequences (outcomes). In this regard, collected real roof fall data from Tabas and Kerman coal regions comprising of several underground coal mines are used. It is concluded that the annual accidents due to the roof falls occurrence in the all investigated mines are so high that it is economically feasible to improve the support systems and to implement a suitable educational program as well as an accurate supervision and other elements of safety management.

Introduction

Mining can be a particularly hazardous profession because of the nature of work carried out. Furthermore, it is generally expected by mining engineers that the total risk involved in working in underground coal mines is substantially higher than that of other types of mines such as construction stones, sand and gravel and metalliferous minerals. Injuries, fatal or non-fatal, could result from the presence of dusts and gases, fires and explosives, slips, falls, interaction with machinery, confined working spaces, repetitive work, vibrations, and many other sources. Accidents and diseases can impose a high cost to the mining operations not only in the direct costs of accidents but also because of the production losses during the stoppage and also the reduction in productivity that follows an accident and of course the potential for liability claims. In the past few years some 760,000 claims have been made (The Times 2009) by former coal mines workers to the judicial system against UK government. These claims, being only for respiratory diseases, have cost the British government GBP 8 Billion (USD 13 Billion). Effective health and safety management begins with its acceptance of the concept as an integral part of total operations in which an organization is involved (Shahriar et al., 2006). Six different areas have been recognised (Oraee 1983), in which efforts must to be spent in order to improve safety in underground coal mines.

The nature of data on injuries is not continuous but discrete and count based. An appropriate model for discrete injuries data, covering several work locations is needed. Modelling of injuries and assessment of the related risks (especially roof falls as geotechnical risks) in mining, has been the subject of some academic research, though much more work is required if it is to cover all types of mining methods and different locations in the mine.

The research conducted by Smith (1984) and Schaller & Savidis (1986), for example would only be useful in particular types of mines since the data are not representative of all mines. It would be preferable to have more generally applicable procedures to manage the risk of roof falls during the course of mining operations.

Injury severity in the U.S. underground bituminous coal mines, during 1975–1981, was assessed relative to mine and miner characteristics using logistic regression (Bennet and Passmore, 1984).

A multiple regression model was used for evaluating factors associated with occupational injury severity in New South Wales underground coal mining industry (Hull et al., 1996). For count based injury data, when the counts are large (>10), a normal distribution can be assumed therefore allowing multiple regression to be used. With over dispersed and annually collected injury data, multiple regression models may not work due to problems such as autocorrelation. A risk and decision analysis methodology was applied to landslide risk assessment (Einstein, 1997).

Risk of occupational injuries among Indian underground coal workers through multinomial logical analysis was assessed (Maiti and Bhattacharya, 1999). Risk indices for these workers were developed by employing various personnel and workplace independent variables using logistic regression analysis (Maiti, 2003).

A research program was also carried out by using collected data from the Mine Safety and Health Administration (MSHA) on underground coal mine production, injuries, safety inspections and other regulatory activities to estimate a sophisticated econometric regression model of the connection between mine inspections and mine safety outcomes (Kniesner and Leeth, 2004).

Kerkering and McWilliams (1981) assessed indices of mine safety data such as the hazard rate, safety, risk and mean time between accidents from the U.S. mining accident data for a 10 year period during 1975–1984. Both fatal and non-fatal injuries combined for one mine operation were analyzed using the Poisson distribution model (cited in Karra, 2005, p.414). Here the focus was on underground bituminous coal only and the logistic regression model is used for modelling a dichotomous dependent variable. Underlining both fatal and non-fatal injuries caused by working accidents during the years of 1997-2005 at the mines and coal washing plant of Kerman coal region in Iran, a risk assessment and statistical analysis was carried out (Shahriar et al., 2006).

A method that used a Beta distribution to model the losses and to compare underground coal mining to underground metal/non-metal mining from 2000 to 2004 was also produced (Coleman and Kerkering, 2007). The first objective of the study was to examine the distributions and summary statistics of all injuries and to compare the safety program effectiveness in mines, for situations where the denominator data were lacking.

Through research related to roof falls that happened in underground stope mining, a risk approach was introduced that allows such designs to be carried out that are compatible with the acceptable risk, defined by the mining company management. The implementation of this approach would overcome the ethical shortcomings of the support design practices (Stacey and Gumede, 2007).

In coal working face, in order to determine safety degree, the number of roof falls and sudden rock drops from the roof are taken into account. Roof falls are found to be the only major problem that can result in geotechnical risks in the investigated coal mines of the regions under consideration. In more general terms, accidents caused by roof falls are the most common geotechnical risk faced by Iranian underground coal mines. These accidents have caused numerous occasions where workers have been affected in the form of injury, disability or fatality. Furthermore, these accidents have caused many stoppages and equipment breakdown in the mining industry.

In this paper, the risk of roof falls in Tabas and Kerman coal regions is assessed and managed using a method that has previously been applied to landslide risk assessment by Einstein (1997).

General description of the coal regions

For the purpose of this study, real data from Tabas and Kerman coal regions are used.

The coal region of Tabas (CRT) comprises of some 30,000 km2 (Fig. 1). The total coal reserves in this region is estimated to be 2.5 Billion tons. The region has been subdivided into four major areas.

Amongst these, Parvadeh, being famous for the high quality of its coal, has a total economically minable reserves of about 400 Million tons.

Coal Field of Kerman (CFK) is another significant coal field located in central Iran (Fig. 1). There are numerous coal seams in the coal field and some active underground mines in the region. On the basis of production rate, there are five important mines in this coal region, the data of which have been used in this research. The probable and proven reserves in this coal field are estimated to be 202 and 107 million tons respectively.

Statistical analysis

In order to determine the main factors that cause the occurrence of accidents and their reasons, a statistical analysis is required. In this section, all incidents occurring in the investigated underground coal mines during a period of 5 years (2003 to 2007) are statistically analyzed.

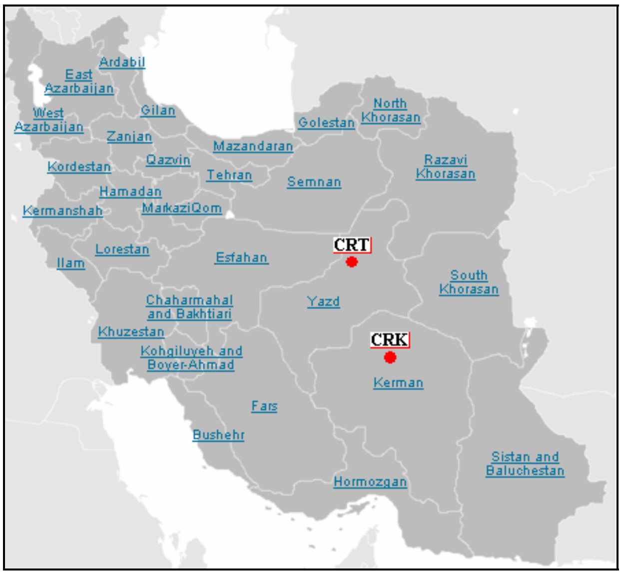

Figure 1: Location of the studied coal regions

The achieved results of frequency and severity coefficients are summarized in Table 1. It is evident that the frequency of total events in the CRT is higher than those for CRK, although the accidents that happened in CRK show higher degree of severity.

Table 1: Frequency and severity coefficients of the investigated coal regions during 2003-2007

Coal region	Frequency coefficient	Severity coefficient
CRT	16.8	1.73
CRK	9.75	2.09

The management in the above coal regions have produced these as the main causes of accidents in all mines of the regions:

- Collision
- Blasting
- Collapse and Caving (is known as a kind of roof fall)
- Roof falls in roadways
- Sudden falls of rocks (is known as a kind of roof fall)
- Encounters with machinery
- Stumbling and falling
- Exposure to high heat
- Exposure to electricity
- Suffocation
- Others

This classification was used as the basis of the established checklist and collection of the essential roof falls data. Among the all the causes in this classification, it is only "collapse and caving" and "sudden falls of rocks" that can be named as accidents that occurred due to roof falls.

Fig. 2 shows the results achieved from statistical analysis of the occurred events in respect to their percentage in the coal regions during 2003 to 2007.

According to the statistical analysis of the events illustrated in Fig. 2, the following results are deduced:

- In the CRT, the maximum number of events occurred in the form of "collisions", "encounters with machinery" and "sudden falls of rocks".
- In the CRK, the maximum number of events is happened in form of the "sudden falls of rocks".

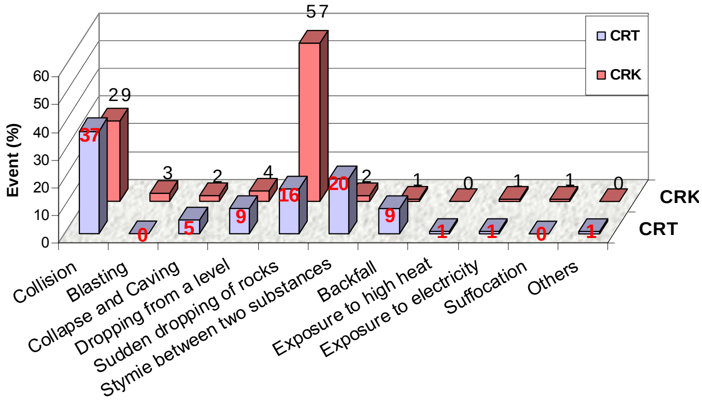

Figure 2: Statistical analysis of events regarding their kinds and percentage during 2003-2007

As it is shown in Fig. 3, most accidents happened due to "collapse and caving" and "sudden falls of rocks" which are both related to roof falls that is the main area of study in this research.

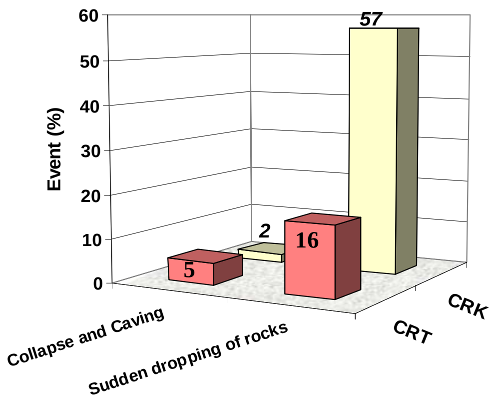

Figure 3: Statistical analysis of two kinds of roof fall events in the coal regions during 2003-2007

As it shown in Fig. 3 the maximum percentage of "collapse and caving" occurred in the CRT and the related mines, whereas "sudden falls of rocks" mostly happened in the underground mines of CRK.

Risk assessment and management

Risk assessment is a systematic examination of any activity, location or work process to identify risks to system success, understand the likelihood and potential consequences (outcomes), the threat to success or hazards and review the current or planned approach to controlling the risk, adding new potential controls where required. Because of the uncertainties associated with the inherent variability of the roof fall phenomenon, it is not possible to predict the roof fall occurrences with an acceptable degree of certainty. Since in a risk assessment process, the first task is to determine the likelihood of roof falls and to ascertain the accuracy of the data. This means that in order to quantify uncertainty values, likelihoods must first be estimated. Identification and ascertaining of the related consequences (outcomes) is the second step of risk assessment process. Here, roof fall risk is introduced as a function of both likelihood and consequence (Eq. 1).

$$R_{RF} = L_{RF} \cdot Con \qquad (1)$$

Where, R_{RF}: Roof fall Risk; L_{RF}: Likelihood of occurrence of a roof fall during a certain period of time; *Con*: the consequences if the roof fall occurs.

Estimation of RF likelihoods

The roof fall likelihood can be estimated by using statistical analysis on the collected data. Since it is difficult to collect adequate data for appraisal of these likelihood values, information gathered from experienced miners, experts and engineers can be effectively used to supplement the statistics of the occurred events . In other words, an experienced miner or engineer by looking at the roof can have some feeling about the possibility roof falls and depending on some indicators, he can actually make a decision.

In this research, through the adequate collected data of roof falls occurred in the underground coal mines of Iran, the likelihoods are assessed. In this manner, two major variables named "Time Intervals between the Roof Falls" (TIRF) and "Number of Roof Falls in each Month" (NRFM) are statistically analysed during 2003 to 2007 in the investigated mines. The results obtained from statistical analysis of TIRF and NRFM variables for the coal regions under investigation are summarized in Tables 2 and 3.

Table 2: Summary results of statistical analysis of the NRFM during 2003-2007

Coal region	Standard deviation	Mean	Minimum	Maximum
CRT	1.167	0.85	0	5
CRK	3.95	3.48	0	10

Table 3: Summary results of statistical analysis of the TIRF (days) during 2003-2007

Coal region	Standard deviation	Mean	Minimum	Maximum
CRT	49.47	32.66	0	264
CRK	10.89	8.1	0	101

In order to evaluate the likelihoods of RF incidents, it is necessary to determine statistical distributions that best fit the data on NRFM and TIRF values. Generally, statistics of accidents tend to follow a Poisson distribution. In other words, the nature of NRFM data fit a kind of Poisson distribution. When NRFM fits to Poisson distribution then Exponential distribution will demonstrate the best fit for TIRF values. Also, in order to achieve the most appropriate distribution, Chi-square test will also be applied to test the goodness of fit.

The likelihood (probability) density function of a Poisson distribution and the likelihood mass function of an Exponential distribution are given in Equations 2 and 3, respectively.

$$P(i) = \frac{e^{-\lambda} \cdot \lambda^{i}}{i!} \qquad i = 0,1,2,... \qquad (2)$$

$$F(i) = \frac{1}{\theta} \cdot e^{-i/\theta} \qquad i = 0,1,2,... \qquad (3)$$

Where, λ= Mean of NRFM; θ= Mean of TIRF.

The histograms of NRFM with respect to relative frequency attained from the statistical data analysis of the coal regions are demonstrated in Figure 4.

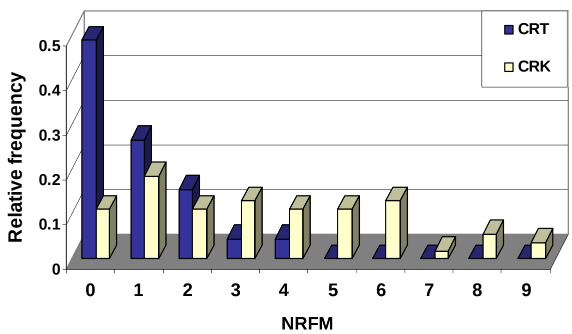

Figure 4: Statistical analysis of NRFM in the coal regions during 2003-2007

The likelihood of having a roof fall in *n* days, *L*, is simply:

$$L = \int_0^n \frac{1}{\theta} \cdot e^{-i/\theta} \cdot dx \Rightarrow L = 1 - e^{-n/\theta} \qquad (4)$$

Fig. 5 reveals graphs of the likelihoods of roof fall occurrences in the considered coal regions during 2003 to 2007. It can be deduced from the graphs of Fig. 5 that on the basis of 95% confidence level, TIRF in the underground mines of CRT and CRK is equal to 98 and 36 days respectively.

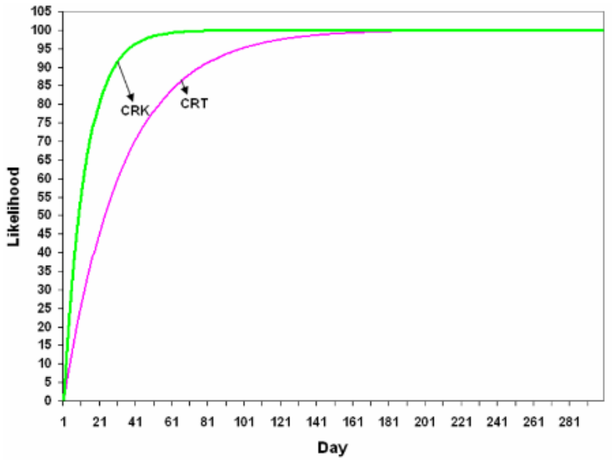

Figure 5: Graphs of the likelihoods of roof fall occurrences in the considered coal regions

Quantification of consequences

The financial burden to a coal mine and hence the reduction in the mine productivity can be substantial (Oraee 1983). In here, the financial outcomes of roof falls accidents have to be identified and quantified in order to assess risk. The outcomes or consequences may differ from each other in different circumstances depending on many factors. For roof falls, the main outcomes can be imposed in the form of injury, disability, fatality, equipment breakdown, stoppage in operation and clean up. Although it is usually impossible to determine the true cost of an accident due to the complexities involved in the evaluation of non-physical outcomes, the cost of each imposed outcome can be estimated by using the relative cost criterion. Among the above mentioned outcomes related to roof fall damages, the major issues that should be taken into consideration for the investigated mines are as below:

- Fatality (f)
- Injury (i).
- Equipment breakdown (eb).

- Stoppage in operation (so).

For the purposes of this research the costs imposed by the "clean up" category are ignored. Furthermore, disability figures have been added to the fatality and injury figures. The total cost of a roof fall (C_t) is defined as the sum of the costs of fatalities C_f, injuries C_i, equipment breakdown C_{eb}, and stoppages in operations C_{so}:

$$C_t = C_f + C_i + C_{eb} + C_{so} \qquad (5)$$

According to the experts' ideas in this field and some quantitative evaluations of the total cost of damages (as consequences) due to roof falls, it is estimated that 20 percent of C_t is due to the fatalities C_f; 40 percent of C_t belongs to injuries C_i, 25 percent of C_t belongs to the equipment breakdown C_{eb} and finally 15 percent of C_t is due to stoppages in operations C_{so}. Therefore, if the cost of fatalities is assumed to be *Y,* then:

$$C_f = Y; \quad C_i = 2Y; \quad C_{eb} = 1.25Y; \quad C_{so} = 0.75Y \qquad (6)$$

It is notable that the entire relative weights in Equation 6 are assumed for the present study and it is possible to modify these constants to fit other circumstances. Having determined the component of total cost of roof fall, the risk in *n* days is formulated as:

$$R_{RF} = C_t \cdot (1 - e^{-n/\theta}) \qquad (7)$$

Decision tree

The evaluation of risk leads to the following two questions:

Is the calculated risk acceptable? If not, what should be done to decrease the risk? The answers to these questions can be determined by a decision analysis approach.

The problem is to decide on whether the present situation, that is to say the mean NRFM is acceptable or not. If it is not acceptable then there is a requirement to improve the support system in order to reduce the safety costs by decreasing the expected NRFM (Oraee 2003). In other words, the decision has to be made between the two actions, being: ‘‘do nothing’’ (status quo), denoted by action a_1 and ‘‘support improvement’’, which is marked as action a_2. The decision tree of the problem is given in Fig. 6. Here *k* denotes number of roof falls per year, $L(k)$ is the likelihood that *k* is equal to 0,1,2 etc.

Assuming that action a_2, that is, support improvement, enhances the roof condition leading to a reduction in C_t by Q%, then cost functions for a_1 and a_2 can be formulated as follows:

$$C_1 = C_t \cdot k, \quad k = 0,1,2,... \tag{8}$$

$$C_2 = (1 - \frac{Q}{100}) \cdot C_t \cdot k + C_m \quad k = 0,1,2,... \tag{9}$$

Where,

C_i= Cost function for the action a_i, i=1,2

k= Number of roof falls

C_t= Total cost of a roof fall

C_m= Cost of support improvement

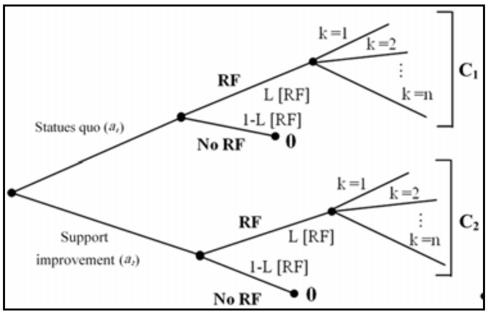

Figure 6: Decision tree for roof fall problem

The expected value (E) of any action can therefore be calculated as:

$$E[a_i] = \sum_{k=0}^{\infty} C_i \cdot L(k) \tag{10}$$

For action a_1, the expected value is:

$$E[a_1] = C_t \cdot \lambda \tag{11}$$

Correspondingly, using Equation 10, the expected value of action a_2 can be calculated as follows:

$$E[a_2] = (1 - \frac{Q}{100}) \cdot C_t \cdot \lambda + C_m \tag{12}$$

Our basic aim is to choose the branch in the decision tree, which has minimum expected value. The expected value of branches of a_1 and a_2 for the mines under investigation here, together with the chosen actions are tabulated in table 4. On the basis of the following assumptions, the relative cost of

a_2 branch can be calculated. It is to be noted that some of the assumptions are made according to local conditions. Different assumptions can therefore be made under different circumstances.

- Employing a proper educational system and accurate supervision and checking all safety considerations leads to 40% reduction in the total cost of roof fall after the employment.
- The employment of educational systems and suitable supervision on safety aspects adds a maximum of 30% to the total cost of roof falls.
- Improving the roof condition and its stability by applying additional supports or the improvement of the present system leads to 20% reduction in the total cost of roof falls.
- The required cost for the improvement of roof condition by improving the support system is 30% more than the total cost of roof falls before the improvement.
- Therefore, if the two above procedures are employed, they lead to a total of 60% reduction in the cost of roof falls. In this regard, the total cost of adopting these procedures and improving the condition is 60% more than the total cost of roof falls.
- Finally, the cost function for the action a_2 becomes:

$$C_2 = 0.4C_t \cdot \lambda + 1.6C_t \tag{13}$$

Table 4: Expected values option actions for the coal regions

Coal region	**NRFM**	**E[a_1]**	**E[a_2]**	**Chosen option**
CRT	0.85	10.2 C_T	5.68 C_T	a_2
CRK	3.48	41.76 C_T	18.3 C_T	a_2

It can easily be seen from table 4 that in the two coal regions chosen here, the expected value of a_2 branch is considerably lower than the expected value of a_1 branch. This means that employment of the above procedures is economically feasible, since the average number of occurred events per year is high.

Conclusion

Roof falls are known to be the major geotechnical cause of accidents in underground coal mines of Iran. The main consequences of these accidents can be in the form of human disabilities, fatalities, production downtimes etc. In this pa per the magnitude of the risk from the roof falls were first determined. The costs of these outcomes have also been estimated. In order to reduce the probability of occurrence of such accidents in the areas where the risk levels are excessive, appropriate actions are suggested. The success rate of each action is then evaluated by the use of decision analysis. It is concluded from the calculation and the analysis provided based on expected values of the effectiveness of the remedial actions prescribed, that in these coal fields, the expected value of a_2 branch is considerably lower than that for a_1 branch. This means that, the application of the modifications suggested in the study (employing a proper educational system, accurate supervision on safety considerations and support improvements) is economically feasible.

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