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Assesing a risk of roof fall in the development mine workings in the process of longwall coal mining in terms of Ukrainian mines

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Abstract

Purpose is the analysis of the available approaches used to determine risks of injures of miners and the development of a new method to assess risks of roof fall in the development mine workings, which maintain long stopes of coal mines.

Methods. The paper applies a complex approach involving: analysis and generalization of previously carried out research of injuries of miners in the process of underground mineral extraction; analysis of methods to assess risks inclusive of injury risks; methods of mathematical statistics while processing risk information; planning of experiments while constructing questionnaires and expert groups; methods of expert estimations while developing proper technique of risk assessment; and cluster analysis while processing the examination results.

Findings. It has been determined that the majority of coal mining countries consider the "roof fall" factor as one of the most dangerous ones. Insufficient reliability of support systems is the key reason of injury of miners as a result of roof falls. Methodology of roof fall and injury of miners has been developed basing upon a probability analysis as well as upon the use of a method of expert estimations. Adequate consistency of the expert estimations has been proved by statistical methods, and the cluster analysis elements. Classification of risk levels, corresponding to inrush probability and taking into consideration the importance of each factor, has been proposed. Analysis of the proposed methodology to assess injury risk as a result of roof fall has made it possible to determine that irrespective of the inrush hazard, extra anchoring helps reduce a level of such an inrush probability down to 8.9% (when weight variation is 1 to 4). Hence, anchoring is the viable tool to reduce injury level of miners.

Originality. The basic factors, effecting injury risk of miners as a result of rock inrushes, have been identified. Importance of the factors has been defined. Regularities of changes in risk of rock failure and its inrush from a roof of the development mine working in the process of longwall coal mining, depending upon the abovementioned factors, have been obtained. Roof rock rigidity, condition of the main support, and anchoring are key ones among the factors.

Practical implications. The obtained results may be applied to assess roof fall risk in the development mine workings, which maintain long stopes of coal mines. The necessity to take extra steps aimed at the improved labour safety and basic contents of the measures is based upon the aforesaid.

Keywords: *injuries risk, rock inrush, development mine workings, longwall, anchoring*

1. Introduction

Despite the powerful vector of progress of renewable energy sources, coal, which share in the world electricity generation is 27%, is considered by the International Energy Agency [1] as a competitive participant of market of energy carriers up to the year of 2040 owing to its persistent demand. China (3.8 bln tons), the USA (900 mln tons), India (600 mln tons), Australia (478 mln tons), and Indonesia (421 mln tons) are worldwide leaders in coal production. The industry is rather profitable in TOP-10 countries of coal mining. Innovation investment in the extracting sector is quite high inclusive of investment in the projects intended to improve safety level. However, in spite of annual increase in labour safety at the industry, mining is still one of the most risky industrial sectors. The fact has been mentioned by the scientists from China [2], the USA [3], [4], India [5], Australia [6], Indonesia [7], SAR [8], Iran [9], Turkey [10], and Poland [11].

Underground enterprises are more dangerous than those engaged in open-pit mining. Indeed, even in the USA where labour safety indicators are rather high, Case Fatality Rate (CFR) per 100000 full-day workers is 24.9%. In the context of ore mining and non-metal mining, the figure is 15.8% [12]. Studies by Coleman [13] demonstrate that probability of lost time injuries (10 days and longer) is by 48.5% higher for coal mines to compare with ore mines and non-metal mines. Similar tendency is considered worldwide which can be explained by specific features of the working

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environment of coal extraction. Complex mining and geological conditions; high concentration of mechanical and electrical facilities; and the restricted working space are responsible for the potential hazard due to a number of specific factors which are not typical for other enterprises.

The situation is complicated due to managerial and organization errors; labour grade of employees being out of keeping with the work performed by them; violations of Safety Rules as well as description of mining; and insufficient professional experience [14]. However, the listed factors are casual by their nature rather than systematic ones; thus, it is possible to consider them as exclusions since their regular effect is a part of a statistic error. Minimization of their impact is achieved through training, labour discipline, and personally oriented motivation decisions made by the authorities. Hence, the analysis may ignore their effect.

According to the statistics of the Fund of Social Insurance of Ukraine in 2017 "…a miner, a transport driver, and a shaftman joined the list of the most hazardous professions as for the level of industrial injuries. Extraction industry (underground mining and open-pit mining) is the most hazardous production since. In this context, share of the occupational incidents is 18.9%..." [15]. It should be noted that the indices of fatal injuries at mining enterprises in the countries with the developed extraction industry are among the highest ones as compared to other industrial sectors [16], [17]. It is obvious that the incidents rates differ country to country since they depend upon mechanization level, risk of mining environment, and reliability of facilities. Legislative regulations and governmental safety strategy are of great importance.

Purpose of the research is to analyze and identify the most hazardous factors as well as the factors of injury of miners in the underground mine workings, and to develop methods for assessment of the injury risks for preventive planning of measures aimed at the improvement of labour safety.

2. The overview of research

In Ukraine, the basic indices, according to which a level of industrial injuries is analyzed, are as follows:

– incident frequency factor is:

$$k_f = \left(\frac{N_{r.i.}}{W}\right) \cdot 100, \quad (1)$$

where:

$N_{r.i.}$ – the number of the recorded incident (when lost time injuries are more than a day);

W – average number of manual workers on the strength;

– incident frequency factor of fatal injuries is:

$$k_{ff} = \left(\frac{N_{f.i.}}{W}\right) \cdot 1000, \quad (2)$$

where:

$N_{f.i.}$ – the number of the recorded fatal incidents;

– factor (index) of fatal injuries is:

$$I_f = \frac{N_{r.i.}}{N_{f.i.}}; \quad (3)$$

– factor of injury severity is:

$$K_{i.s.} = \frac{O}{N_{r.i.}}, \quad (4)$$

where:

O – the total lost time injuries in terms of each incidents ignoring fatal ones;

– injury factor per a mln tons is:

$$K_{i.s.} = \frac{N_{r.i.}}{A_p}, \quad (5)$$

where:

A_p – annual coal production, mln tons.

According to the data of the generalized report of a supervision office as for the labour safety in coal industry, 25 cases of fatal injuries took place in Ukrainian mines during 2017. In the context of coal industry, total coefficient of fatal injuries was 1.07 per a mln ton of the extracted coal. Total number of incidents in mines, subordinated to the Ministry of Energy and Coal of Ukraine, was 417; total number of incidents in the industry was 787. Hence, the factor of fatal injuries in mines, subordinated to the Ministry of Energy and Coal of Ukraine, is 0.059. In 2017, incident rate was 7.8574 in the context of coal industry (total number of the industry employees is 100160). Fatal injury factor is 0.2496. In this context, ten fatal injuries happened in longwalls; ten fatal injuries happened in the extended mine workings.

As for the incident factors, differentiation of injuries in coal mines is indicative of the following: rock failure; transportation and hoist; machines and mechanisms; gas explosions and dust explosions; and falls in people and falling objects are the most dangerous factors. It is quite obvious that ratio of injury factors should vary in different mines, and in different countries since injury level and degree of its severity at a certain enterprise depend upon mining and geological conditions, mechanization level, support being in use as well as mistakes by miners and authorities. For instance, in nongassy mines, which are safe from the viewpoint of gas/dust explosions, accident rate is zero one when accident rate from the viewpoint of fall in people/falling objects depends primarily upon personal care as well as physical and psychological state of miners. The abovementioned should be involved in the analysis. Such worldwide coal mining countries as China and the USA demonstrated cases in point for the last decade (Table. 1). Fatal incidents in PRC dropped drastically in the last 15 years: from 2002 to 2017, the number of fatal injuries decreased from 7000 down to 375 a year [18]. In 2017, the amount of fatal injuries per a mln of tons of the mined coal was 0.16 in PRC, and 0.0168 in the USA.

Consequently, mining and geological conditions impact directly and indirectly three of four the most importance factors of fatal injury in PRC while impacting the only one in the USA. In this context, such a factor as roof inrushes is among the first four accidental factors.

In Ukraine, statistics of fatal injury for the period of 2000-2012 [19] defined the first five dangerous factors, i.e.: roof inrushes – 18.3%; transportation and hoist – 17.9%; gas/dust explosions – 14.2%; operation of machines and mechanisms – 7.4%; and falls in people – 6.9%. According to the data of the generalized report of a supervision office as for the labour safety in coal industry, rock failure resulted in 9% of fatalities ranking fourth after gas explosions (36%), cardiovascular diseases (23%), and electrical shocks (13%).

Table 1. Injury comparison in underground mining in the context of China and the USA

Factor	Country / source of the information	Percentage of fatal injury
Explosions, fires	PRC [18]	43.0
Roof inrushes		33.0
Transport operations		9.0
Flooding		8.0
Transport operations	The USA [13]	29.3
Machines and mechanisms		15.0
Falls in people		14.4
Roof inrushes		10.8

While analyzing injuries in the TOP-10 countries, we can see that despite different ratios of the rates, roof inrushes are among the most dangerous factors for the majority of the coal mining countries. For instance, 32.7% of total fatalities in India are connected with roof failure [20].

In Australia, 18% of lost time injuries (more than 10 days) depend upon falling objects inclusive of rock falls [21]. Unfortunately, no report involves separation of share of the 18%. Injury statistics in Indonesia is not available due to the imperfection of mining legislation of the country as well as a great number of small, illegal mines. In the Republic of South Africa, probability of incidents, resulted from the operation of machines and mechanisms, is 1.22%; roof failure results in 21.7% of incidents [22]. According to [23] research, 22% of the fatalities in Iran is a result of roof inrushes.

Analysis of the obtained results and their generalization make it possible to separate three conceptually different reasons of injuries in mining. The activities providing safety of miners and their health within a human-machine-environment system may be implemented in terms of a scheme in Table 2. The authors believe that such a factor as an environment is the most important one. Inrushes, explosions, and gasdynamic manifestations are critical; in spite of the implementation of monitoring and controlling systems, they are the reason of a prevailing injury share in coal mines annually. In this connection, decrease in injury level resulting from the reasons will help improve significantly the rates of labour protection in terms of the industry.

The world practices apply following rates of industrial injuries: fatal injury frequency rate (FIFR); lost time injury frequency rate (LTIFR); and lost time injury severity rate (LTISR). Hence, it is sometimes rather a difficult task to compare injury rates in different countries.

Table 2. Basic tendencies to provide safety and health for miners of a coal mine

	Environment		Human		Machine
Tendency	Protection from the industrial accidents which source is natural one (i.e. sudden inrushes, gasdynamic manifestations etc.)	Gas protection; dust protection	Personal safety; compliance with the requirements of labour protection standards	Health and hygiene measures	Protection against the accidents and failures
Ways to provide safety in terms of the tendencies	Monitoring of the environment; measures for accident prevention	Monitoring of the aerologic state of mines	Organization of safety training	Occupational disease prevention	Scheduled maintenance of the equipment
	Control over the environmental parameters; warning on the violation of safety parameters	Control over the gas/dust content; the current information transfer; and power cut within the dangerous areas	Control over skills; systems of periodic assessment of the skills connected with the work authorization	Development of the means of individual protection and their implementation	Control over the equipment performance and depreciation
	Measures to normalize environmental conditions; control over their quality	Implementation of the measures for degasification, gas outlet, dust control etc.	Popularization of safe working methods; testing for risk proneness; improvement of personal responsibility	Early professional treatment	Implementation of the modern equipment, systems, and networks
	Emergency rescue service	Quality monitoring of measures	Implementation of training systems and systems of skill improvement	Popularization of a healthy life	Early replacement of the units, parts, and networks

Progress of the available methods for industrial injury analysis follows the four tendencies: technical, statistical, examining, and probabilistic. Statistical method provides the most reliable analysis.

The analysis method relies upon the statistical data concerning accidents (in Ukraine, they are protocols on H-1 form and investigation results). The generalized assessment of labour safety degree in a mine or in the industry is the analysis result.

In accordance with the statistical method assessing the occupational risks, the factor of the occupational risk of a miner injury, got at the place of production, is:

$$\upsilon = \frac{N_{o.a.}}{W}, \text{ 1/workers/year,} \tag{6}$$

where:

$N_{o.a.}$ – annual number of occupational accidents;

W – annual number of workers at risk.

Statistical uncertainty is characterized by the error:

$$\delta = \frac{Z_y}{\upsilon W}, \tag{7}$$

where:

Z_γ – a quantile of normal distribution of γ level.

In terms of formula 7, for a year of 2017, injury risk factor for employees of mines, subordinated to the Ministry of Energy and Coal of Ukraine, was $\upsilon = 4.16 \cdot 10^{-3}$, 1/workers/year. In 2017, fatal injury risk factor was $\upsilon = 1.99 \cdot 10^{-4}$, 1/workers/year.

According to the accountability in forms #1 of fuel and energy complex, average percentage of workers of mining sites is 12-14%; in 2017, two fatalities happened in the extended mine workings adjoining longwalls. Hence, fatality factor, as a result of rock failure in the extended mine workings, is $\upsilon = 1.42 \cdot 10^{-4}$, 1/workers/year.

According to ISO 31010 [24], all the methods, applied to analyze a risk, can be qualitative, semiquantitative, and quantitative. Qualitative methods make it possible to determine the risk level as “high”, “average”, and “low”. On the basis of the proposed numerical scales, semiquantitative methods help determined the risk level in terms of some formula. Quantitative methods rely upon practical values of the risk level in terms of particular units. The methods, mentioned in the above standard, involve brainstorming, structural or semistructural enquiries, Delphi technique, a list of advancement questions, PHA, HAZOP, HACCP, general assessment of the environmental risk, SWIFT, analysis of scenarios, analysis of impact of activities, analysis of sources, analysis of a fault tree, analysis of an event tree, analysis of the causes and effects, LORA, decision tree, general assessment of human reliability, bow tie, maintenance on the basis of reliability, analysis of stray schemes, Monte Carlo method, hazard and operability study, Markov method, Bayesian statistics and Bayesian network, F-N curves, risk factors, consequence-likelihood matrix, and MCDA.

Analysis of risks and their control are connected with hazard identification, identification of possible health and life damages as well as their likelihood, and availability of the adequate statistical information to calculate the required risk factor. Direct methods to assess the risks rely upon the approaches [25], [26]. Following techniques are the most popular ones:

1) British Standard BS-8800;
2) risk assessment method on the basis of “likelihood-loss” matrix;
3) method to construct assessment graph;
4) methodology of the National Institute for Occupational Safety and Health (NIOSH) in Ukraine;
5) method of verbal functions.

Mostly, risk assessment is applied in the form of the factor:

$$R = \sum_{i=1}^{N} P_i \cdot S_i \,, \tag{8}$$

where:

P_i – implementation probability of each i^{th} risk likelihood;

S – consequence severity of the i^{th} risk likelihood implementation.

Subjectivity is the basic weakness of the method since the expert assessment of risk level is characterized by a certain dispersion basing upon personal practice of each of the experts.

In terms of NIOSH methodology [26], risk analysis relies upon actual state of technical risk of equipment, buildings (structures) as well as conforming to the current norms, rules, and labour safety instructions by the employees. The risk is assessed using the dependence:

$$P = k_{re} \cdot k_{rb} \left(7800 - k_o + S_{ps} + 0.1\right) \cdot 9 \cdot 10^{-7} \,, \tag{9}$$

where:

k_{re} – a coefficient of technical risk of equipment;

k_{rb} – a coefficient of technical risk of buildings (structures);

7800 – the required empirical maximum score in terms of which injury risk is minimal;

k_o – a coefficient of organizational safety;

S_{ps} – the total of penalty scores assessed according to a scoring scale.

The majority of input parameters in formula 9 are analytical ones; thus, the subjectivity share has been minimized depending mainly upon the penalty score scale use.

However, neither of the mentioned method is focused on the risk assessment of an injury resulting from the rock inrush. The authors believe that the approach, proposed in [27], [28], is the most adequate one.

According to the research, any risk is determined as a likelihood of the adverse events (i.e. inrush) factoring into the unfavourable result (i.e. injury). It is calculated on the formula being comparable with 8.

Hence, it is necessary to improve the current system of risk assessment, which will help increase labour safety level in the context of mining industry. Such an assessment should be object-oriented.

3. Results and discussion

Since methodologies to assess injury of mines as a result of inrushes are not available and the current abovementioned methods of risk assessment cannot be used directly to the effect, a shot has been taken to design an algorithm, and to develop author’s assessment methodology on its basis. The approaches, used by [27], [28], have been adopted as the prototypes.

Thus, risk is understood as a likelihood of rock failure as a result of roof fall resulting in the injury of miners. Generally, it can be calculated on formula 10 being a special case (8):

$$R_o = \sum_{i=1}^{N} P_o \cdot S_o \,, \tag{10}$$

where:

P_o – rock failure likelihood;

S_o – is consequence severity of the rock failure.

Apply a probabilistic approach to assess qualitatively the failure likelihood P_o. Stage one determines the basic factors affecting roof inrushes. Failure likelihood is identified separately for each factor. To do that, each of the factors obtains the importance level (B) on the basis of the expert estimation method. The importance varies from 1 (i.e. minimum affect) to 10 (maximum affect). Each factor is graduated from 0 to 4 (i.e. characterization of failure likelihood coefficient for each i^{th} P_{bi} factor). If $P_{bi} = 0$ then the failure likelihood is close to zero; if $P_{bi} = 4$ then the likelihood is maximal.

Hence, it is possible to represent roof inrush likelihood as:

$$P_o = \frac{\sum_{i=1}^{N} P_{bi} \cdot B_i}{\sum_{i=1}^{N} P_{bi\max} \cdot B_i} \cdot 100\% \,, \tag{11}$$

where:

P_{bi}, $P_{bi\max}$, B_i – failure likelihood coefficient for the i^{th} factor; maximum likelihood coefficient; and importance of the i^{th} factor respectively.

According to [29], roof fall severity consequences (S_o), used by (11), should be equal to 1 (i.e. the highest rank) since roof fall may result in injuries, disability, fatality in miners; equipment damages; and interruptions as well as delays during mining. Certain share of inrushes factors into the equipment damages resulting in the interruptions as well as delays in the enterprise performance due to the necessity of the equipment maintenance, restoration systems, and resumption of normal mine activities.

To carry out the expert estimation, the three groups of factors have been proposed as the factors affecting inrush formation: geological factors, design factors, and processing ones. Geological factors cover: operating depth; roof stability; floor stability; water content; availability of guiding seams; and effect of contiguous seams in the process of their undermining. Design factors involve: panel length; length homogeneity (i.e. geological disturbances, variations in physical and mechanical characteristics etc.); mine working width; and conditions of the basic support during all the supporting stages. Processing factors include: supporting period of a mine working; extra supporting; and roof anchoring.

Scientists and academics of the leading branch institutes and Higher Educational Institutions of Ukraine (Candidates of Sciences and Doctors of Sciences) engaged in the problems of stability of mine workings, inrush control, and its prevention participated as experts as well as representatives of engineering mine service; supervisors; representatives of labour safety service whose work experience in the field is not less than 10 years; and employees of design mining offices.

Kendall's concordance coefficient has been assumed as a degree of coherence if the connected ranks are available:

$$W = \frac{12d^2}{m^2\left(n^3 - n\right) - m\sum_{i=1}^{L_i}\left(t_i^3 - t_i\right)}, \qquad (12)$$

where:

d^2 – a total of the squared differences of the ranks (i.e. deviations from the mean one);

m – the number of experts in a group;

n – the number of factors;

L_i – the number of links in estimations of i^{th} expert;

t_i – the number of elements in i^{th} link of i^{th} expert.

Since ranks with the similar rank number (i.e. the linked ones) are available in estimations by all the experts, the ranks have been re-structured with no variations in the expert opinion.

In the order of increasing, analysis of importance of the factors is as follows: $x_7 = 108$; $x_3 = 127$; $x_5 = 152.5$; $x_8 = 186.5$; $x_9 = 213.5$; $x_6 = 227$; $x_1 = 229$; $x_4 = 232$; $x_{11} = 239$; $x_{12} = 242.5$; $x_{10} = 296$; $x_{13} = 297.5$ and $x_2 = 361.5$.

In terms of 6, a degree of coherence of the experts is:

$$W = \frac{12 \cdot 59651.5}{32^2\left(13^3 - 13\right) - 32 \cdot 270} = 0.34.$$

It has been identified that $W = 0.34$, i.e. a degree of coherence of the expert opinion is insufficient.

Pearson's concordance coefficient has been calculated to assess concordance coefficient importance:

$$\chi^2 = \frac{12d^2}{mn\left(n+1\right) + \frac{1}{n-1}\sum_{i=1}^{L_i}\left(t_i^3 - t_i\right)}.$$

The calculated $\chi^2 = 128.88$ excesses a tabular one if number of freedom degree is 12 when importance level is $\alpha = 0.05$ (2.02607); thus, the obtained results make sense and $W = 0.34$ is not a random value. Hence, the findings can be used for further research.

Consequently, while prescribing minimum assessment level (1) on x_7 factor (rank total is 108) and maximum one (10) on x_2 (rank total is 361.5), we have following increasing estimations: $x_7 = 1$; $x_3 = 1.7$; $x_5 = 2.6$; $x_8 = 3.8$; $x_9 = 4.7$; $x_6 = 5.2$; $x_1 = 5.3$; $x_4 = 5.4$; $x_{11} = 5.6$; $x_{12} = 5.8$; $x_{10} = 7.7$; $x_{13} = 7.7$ and $x_2 = 10$.

Expert opinions differed greatly in the context of the research. Figure 1 demonstrates the summary factor-clustered graph.

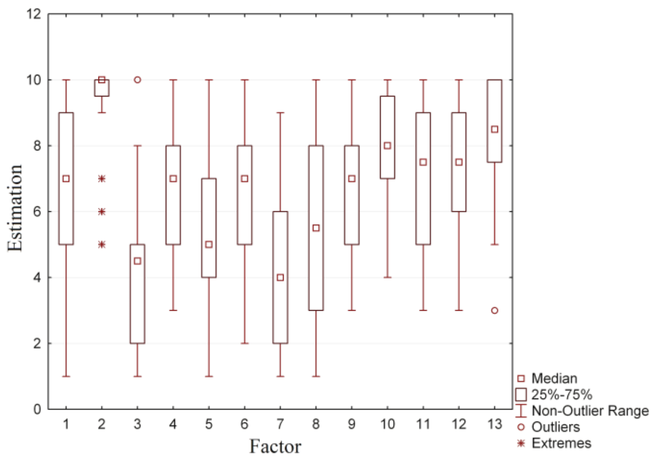

Figure 1. Factor-clustered graph of the expert estimations

The analysis shows that the expert opinions concerning the effect of such factors as x_2 (i.e. rock stability), x_{13} (i.e. anchoring), and x_{10} (i.e. condition of a basic support) turned out to be the most coherent ones. Such estimations as x_8 (i.e. panel homogeneity), and x_7 (i.e. panel length) demonstrated the least concordance. Estimation range concerning such factors as x_5 (i.e. availability of accompanying seams), x_1 (i.e. mining depth), and x_8 (i.e. panel homogeneity) was the widest one. Probably, the abovementioned is based upon both the objective reasons and subjective ones. Personal practices, specific labour conditions, and different problems, solved by the experts in the process of their professional activities, result in the averaged estimations or, rather, in drastically different ones. Cluster analysis has been applied to analyze the obtained expert estimations. Figure 2 demonstrates the tree-like clusterization of the experts.

The Figure explains that such experts as 13, 23, 25, 29, 31, and 32 form separate clusters; i.e. their opinions are not in the agreement with others. Further, it is possible to identify two large separate clusters of the experts intersecting each other. While using a method of K-averages, divide all the experts into two clusters (Fig. 3). analysis of the clusterization results demonstrates that expert group one (Cluster 1) is characterized by more oppositional estimations in terms of almost the whole range; in this context, expert group two (Cluster 2) has a tendency to assess in the upper third of the range.

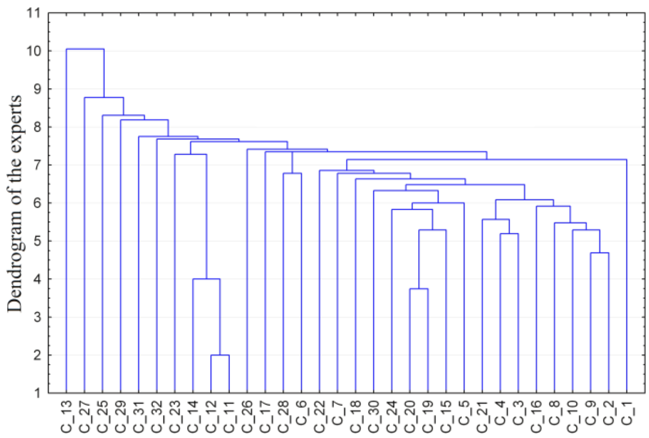

Figure 2. Dendrogram of the experts

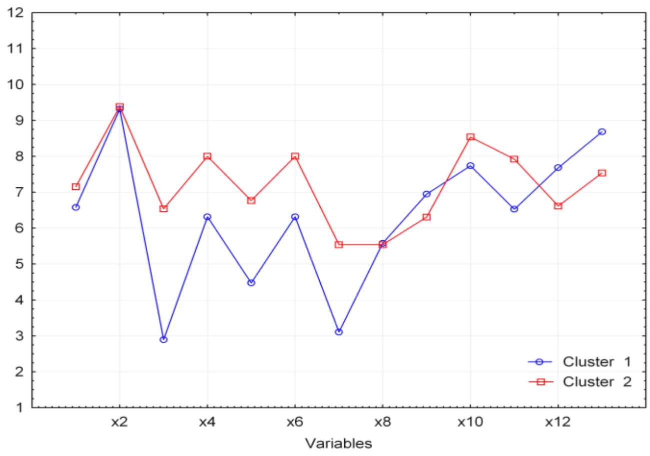

Figure 3. Coordinate graph of the centres of the clusters

Basically, there are no law estimations and average score is higher. To some extent, the fact can explain poor coherence level of the expert estimations. However, analysis of interrelations of the scores, similar assessment dynamics on the factors is obvious although with different absolute values.

Hence, within $x_1 - x_7$ range of the factors, graphs are similar; within $x_7 - x_{11}$, and $x_{12} - x_{13}$ ranges, increases and decreases almost coincide. The only opposite dynamics is observed between $x_{11} - x_{12}$ factors. Consequently, expert opinions are rather coherent as for the mutual importance of the factors. If Cluster 2 experts use factor estimations within the whole range of the scores rather than in the upper third of the range, then numerical coherence would be higher.

Since anchoring effect upon inrushes is of intense interest in the context of the research, differences in expert opinions as for x_{13} factor (i.e. anchoring) have been estimated (Fig. 4). Score difference range is 30%; in this context, expert 13, whose opinion differs from others (Fig. 2), underestimated the factor.

Consequently, the analysis of expert opinions means that the results may be helpful to further analysis.

Diagram in Figure 5 represents the importance of each factor in terms of the processed expert estimations. It is essential that x_2 and x_{13} factors take almost 25% of the total amount. Other factors are shown in proportion to their increase, i.e. x_7 to x_{10}. Dimensions of the sectors help evaluate importance percentage of each of the factors in opposition to inrushes.

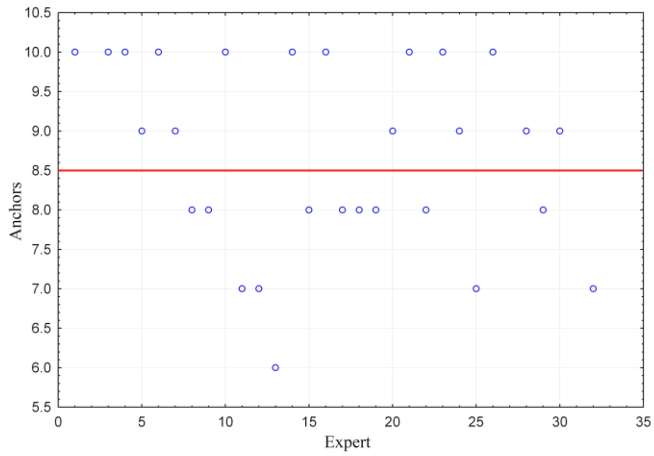

Figure 4. Expert opinion on x_{13} factor (anchoring) as for the median

Results of the expert opinions, represented in (11) formula, make it possible to estimate contribution share of each of the factors to the inrush formation as well as each factor group (i.e. geological parameters, design parameters, and processing ones) both on the whole and at a certain enterprise. Such estimation under specific conditions should involve the importance of each factor.

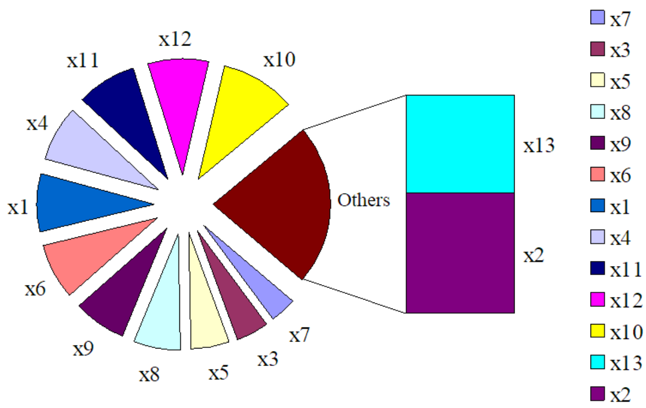

Figure 5. Diagram of share distribution of expert opinions in terms of the factors

Introduce the importance range for each factor (Table 3). In terms of the importance characteristic, "0" value means that negative effect of the factor is not available. "4" value means maximum negative effect of inrush formation.

According to the technique, maximum risk is 258.8 scores; minimum risk is 41.6 ones. On the basis of dependence (11), roof fall risk is 16 to 100%. Thus, it has been proposed to implement four-score system to estimate inrush risk in terms of the levels: "low" level (16.0-36.9); "average" level (37.0-57.9); "high" level (58.0-8.9); and "critical" one (79.0-100.0) (Table 4). The ranges are divided proportionally since there is no any statistical information for ranging.

According to the inrush likelihood levels, probability of inrush formation is characterized by means of following indices: "very low"; "possible"; "expectable"; and "very expectable".

Depending upon the inrush likelihood, risk level is "acceptable"; "acceptable in case of supervision and repetitive monitoring"; "nonacceptable without regular control measures"; and "nonacceptable". The latter should involve extra measures to reduce inrush likelihood.

Table 3. Importance of each factor

Factor, measurement unit	Importance				
	0	1	2	3	4
Mining depth (x_1), m	–	40 to 200	200 to 400	400 to 600	Less than 40, more than 600
Roof stability (x_2), category by DonSRCI	B5	B4	B3	B2	B1
Floor stability (x_3), category by DonSRCI	S3	S2	S1		
Water content (x_4)	Dry roof	Wet roof	Soft drop	Intensive drop	Constant flow
Accompanying seams (availability) (x_5)	No	At > 20 m distance	At 15-20 m distance	At 10-15 m distance	At < 10 m distance
Effect of contiguous seams (during mining) (x_6)	No	At > 20 m distance	At 15-20 m distance	At 10-15 m distance	At < 10 m distance
Panel length (x_7), m	–	< 500 m	500-1000 m	1000-1500 m	> 1500 m
Panel homogeneity (x_8)	–	Conditionally homogenous	Partially homogenous	Nonhomo-genous	
Mine working width (x_9), m	–	< 4 m	4.0-5.5 m	5.5-7.0 m	> 7.0 m
Condition of the basic support (i.e. pillars) (x_{10})	–	Satisfactory			Unsatisfactory
Supporting period (x_{11}), years	–	< 1 year	1-2 years	2-3 years	> 3 years
Extra support (x_{12})	–	Satisfactory	< 50% under unsatisfacto-ry condition	< 50% under unsatisfactory condition	No
Roof anchoring (x_{13})	–	Energy absorbing anchors	Two-level anchoring systems	Rigid anchors	No bolts

Table 4. Qualification of the inrush risk levels

Inrush risk	Inrush likelihood level, P_0, %	Inrush probability	Injury risk resulting from inrush
Low	16.0-36.9	Very low	Acceptable
Average	37.0-57.9	Possible	Acceptable in case of supervision and repetitive monitoring
High	58.0-78.9	Expectable	Nonacceptable without regular control measures
Critical	79.0-100.0	Very expectable	Nonacceptable

4. Conclusions

Analysis of the injury structure in the TOP-10 coal mining countries confirms that despite different ratios of the injury reasons, roof inrush is among the most hazardous factors for the majority of coal extraction states. Poor reliability of support systems in mine workings is the basic reason of the injuries of miners.

Lack of a system, aimed at the analysis of injuries of miners resulting from rock inrushes, stipulated topicality of the technique development. The methodology has been evolved on the basis of a probability approach with the use of a technique of expert estimation. The applied techniques of mathematical statistics proved the expediency of the expert survey. A system to assess inrush risk as well as adequate injury risk has been proposed.

Analysis of the technique, assessing injury risk resulting from roof inrushes, has made it possible to understand that despite the injury risk, anchoring helps decrease inrush probability down to 8.9% (if importance variation is 1 to 4). consequently, anchoring is the effective tool reducing injury risk.

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Оцінка ризику обвалення покрівлі в підготовчих виробках при вийманні вугілля лавами на прикладі шахт України

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Мета. Дослідження існуючих підходів, що використовуються для встановлення ризиків травмування гірників, і розробка нового методу оцінки ризику обвалення покрівлі в підготовчих виробках, що обслуговують довгі очисні вибої вугільних шахт.

Методика. У роботі використано комплексний підхід, що включає аналіз і узагальнення раніше виконаних досліджень травматизму гірників при підземному видобуванні корисних копалин; аналіз методів оцінки ризиків, в тому числі ризиків травмування; методи математичної статистики при обробці інформації з травматизму; планування експериментів при розробці опитувальних листів і експертних груп; метод експертних оцінок при розробці власної методики оцінки ризиків; кластерний аналіз при обробці результатів експертизи.

Результати. Встановлено, що фактор "вивали з покрівлі" в більшості вугледобувних країн світу є одним з найбільш небезпечних. Основними причинами травмування гірників від вивалів є недостатня надійність систем кріплення. Розроблена методика оцінки ризику обвалення порід і травмування гірників, яка ґрунтується на ймовірнісному аналізі і використанні методу експертних оцінок. Достатня узгодженість оцінок експертів доведена статистичними методами і елементами кластерного аналізу. Запропоновано класифікацію рівнів ризиків відповідно до імовірності вивалоутворення з урахуванням ваги кожного фактора. Аналіз запропонованої методики оцінки ризику травмування від вивалів з покрівлі дозволив встановити, що незалежно від небезпеки вивалів додаткове кріплення анкерними болтами дозволяє знизити рівень імовірності вивалу до 8.9% (при зміні ваги від 1 до 4). Тобто анкерне кріплення є дієвим інструментом зниження рівня травматизму гірників.

Наукова новизна. Виділені основні фактори, що впливають на ризик травмування гірників від вивалів порід і встановлена їх вага. Отримано закономірності змінення ризику руйнування і вивалу порід з покрівлі підготовчої виробки при вийманні вугілля лавами, від зазначених факторів, основними з яких є стійкість порід покрівлі, стан основного кріплення і анкерне кріплення.

Практична значимість. Отримані результати можуть використовуватися для оцінки ризику обвалення покрівлі в підготовчих виробках, що обслуговують довгі очисні вибої вугільних шахт. На основі чого встановлюється необхідність проведення додаткових заходів з підвищення безпеки робіт і основний зміст цих заходів.

Ключові слова: *травматизм, ризик, вивал порід, підготовчі виробки, лава, анкерне кріплення*

Оценка риска обрушения кровли в подготовительных выработках при выемке угля лавами на примере шахт Украины

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Цель. Исследование существующих подходов, используемых для установления рисков травмирования горняков, и разработка нового метода оценки риска обрушения кровли в подготовительных выработках, обслуживающих длинные очистные забои угольных шахт.

Методика. В работе использован комплексный подход, включающий анализ и обобщение ранее выполненных исследований травматизма горняков при подземной добыче полезных ископаемых; анализ методов оценки рисков, в том числе рисков травмирования; методы математической статистики при обработке информации по травматизму; планирование экспериментов при разработке опросных листов и экспертных групп; метод экспертных оценок при разработке собственной методики оценки рисков; кластерный анализ при обработке результатов экспертизы.

Результаты. Установлено, что фактор “вывалы с кровли” в большинстве угледобывающих стран мира является одним из самых опасных. Основными причинами травмирования горняков от вывалов является недостаточная надежность систем крепления. Разработана методика оценки риска обрушения пород и травмирования горняков, основанная на вероятностном анализе и использовании метода экспертных оценок. Достаточная согласованность оценок экспертов доказана статистическими методами и элементами кластерного анализа. Предложена классификация уровней рисков в соответствии с вероятностью вывалообразования с учетом веса каждого фактора. Анализ предложенной методики оценки риска травмирования от вывалов с кровли позволил установить, что независимо от опасности вывалов дополнительное анкерное крепление позволяет снизить уровень вероятности вывала до 8.9% (при изменении веса от 1 до 4). То есть анкерная крепь является действенным инструментом снижения уровня травматизма горняков.

Научная новизна. Выделены основные факторы, влияющие на риск травмирования горняков от вывалов пород, и установлен их вес. Получены закономерности изменения риска разрушения и вывала пород с кровли подготовительной выработки при выемке угля лавами, от указанных факторов, основными из которых являются устойчивость пород кровли, состояние основного крепления и анкерная крепь.

Практическая значимость. Полученные результаты могут использоваться для оценки риска обрушения кровли в подготовительных выработках, обслуживающих длинные очистные забои угольных шахт. На основе чего устанавливается необходимость проведения дополнительных мероприятий по повышению безопасности работ и основное содержание этих мероприятий.

Ключевые слова: *травматизм, риск, вывал пород, подготовительные выработки, лава, анкерная крепь*

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