ASSESSMENT OF THE INDIVIDUAL RISK OF FATAL INJURY TO COAL MINE WORKERS DURING COLLAPSES

Purpose. To develop an effective model for assessing occupational risk due to rock caving in the country’s coal mines.

Methodology. A mathematical model based on the maximum-likelihood method is presented, which makes it possible to assess the probability of a rockfall. The use of Bayes theorem for assessing the individual risk of fatal injuries of coal mine workers is justified. The complex method for effective control of mountain pressure is illustrated by application of the developed methodology of computer modeling of geomechanical processes, instrumental and geophysical methods for protection and maintenance of mine workings at development of a coal seam of the Barentsburg field.

Findings. The work demonstrates the relationship between the key statistical indicator that affects the accident rate and the value of professional risk. A key statistical indicator, the value of which is determined using the multifunctional systems of safety, is substantiated.

Originality. The development efficiency of the multifunctional safety system installation in coal mines to monitor the condition of the rock mass is analyzed.

Practical value. The model developed by the authors will make it possible to determine the predicted value of the individual risk of fatal injury to personnel during rock collapse more accurately compared to the existing methods.

Keywords: coal mines, fatal injuries, mountain pressure, Bayes theorem, geomechanical process

Introduction. According to the Federal Service for Ecological, Technological and Atomic Inspection, falls of rock mass are the second most common cause of fatal injury in coal mines. For the period of 2006–2017 for this reason, 103 fatal accidents occurred in the coal mines of Russia, which is 14% of the total number of fatal injury (Fig. 1) [1].

Approximately 65–66% of the total number of accidents caused by the rock mass falls on the highwall mining (faces). The faces of the advance workings and during the existing advance workings are the causes for 22–23 and 12–15% of accidents, respectively [2, 3].

Risk assessment is a widely used process in the mining industry. The assessment of the level of bifactorial hazard is carried out on the basis of the individual risk indicator R — the expected frequency of death of a person as a result of exposure to the injury-risk factor under study, which is necessary to prevent the main hazards [4].

The average value of the observed individual risk of fatality caused by rockfall in 2017 is $1.9 \cdot 10^{-4}$ year$^{-1}$. In individual coal mines, the observed individual risk of fatality reached $3 \cdot 10^{-4}$ year$^{-1}$ (Krasnohorskaia mining, 2014), $3 \cdot 10^{-4}$ year$^{-1}$ (Ziminka mining, 2012), $4 \cdot 10^{-4}$ year$^{-1}$ (Kiselevskaia mining, 2011), $4 \cdot 10^{-4}$ year$^{-1}$ (Severnaia mining, 2016) [Parkhanski, 2016] [5].

According to the authors, the conditions of professional activity should be considered safe if the individual risk index $R$ for personnel falls below the average value $R_0$, which took place by type of professional activity, and dangerous if it exceeds this threshold. Risk reduction at coal enterprises depends on a scientifically based forecast and taking into account the response of the mining and geological environment to dangerous geomechanical and geodynamic manifestations due to technogenic factors, and on adherence to technological and production discipline. Cases of injury in existing advance workings occur mainly when dislocating the lining [1].

Methods. In accordance with the methodology described in the order of Rostechnadzor No. 339 “Instructions for predicting dynamic phenomena and monitoring the rock mass during mining of coal deposits”, the probability of a dangerous geodynamic phenomenon for specific geological and geodynamic conditions is determined by the yield of drill cuttings (l/m) [5].

The installation of a multifunctional safety system (MFSS) in coal mines is gradually becoming a widespread practice. To monitor the state of the rock mass, a system of geophysical observations is used as the main component of the MFSS [6, 7]. The system is designed for operational detection and monitoring of the development zones of dangerous geodynamic phenomena during underground coal mining. The system provides registration and selection of seismic waves of the reflected type with different polarization and the use of pulsed type sources (sledgehammer, hydraulic pickoff) and rotors of roadheading machines of various models [7].

The source of the pulse type ensures a reliable range of “visibility” of the mass up to 100 meters, and the rotor of the machine — up to several hundred meters. The system for recording elastic waves involves the arbitrary placement of three-component (3C) geophones in the bottom of the mine and its walls (from 3 to 10 geophones) and an arbitrary position of the source of elastic vibrations. The system of operational process-
The number of cases of fatal injury due to rockfall in coal mines, in the period of 2006—2017 [1]

Fig. 1. The number of cases of fatal injury due to rockfall in coal mines, in the period of 2006—2017 [1]

The structure of the mathematical model for determining the individual risk of fatalities of coal mines due to rockfall

As indicated above, the value of the integrated criterion, including the magnitude of the overburden gradient and the magnitude of seismic energy, is used as a key statistical indicator. The values of this quantity received from the MFSS are used in a mathematical model based on the maximum likelihood criterion to assess the probability of rock mass collapse.

To determine the individual risk of fatal injury to coal mine workers, it is necessary to process statistical data, for which their high quality is a prerequisite [10, 11]. For calculations, the following indicators are required: the number of fatal accidents in coal mines, the number of workers employed at mining sites, the number of fatal injuries caused by rock mass collapse.

The calculation of individual risk of fatal injury to workers in coal mines due to rock mass collapse is based on the Bayesian theorem. A decision is made on the admissibility of the risk calculated. The obtained value is compared with the average individual risk in the professional field of activity (2.5 · 10⁻⁴ years⁻¹).

The mathematical model for assessing the probability of rock mass collapse according to the maximum likelihood criterion has the following form:

\[ R = \begin{cases} R_{\text{adm}}, & \text{if } L(P) \geq 1 \\ R_{\text{inadm}}, & \text{if } L(P) < 1 \end{cases} \]

where \( R_{\text{adm}} \) is admissible risk; \( R_{\text{inadm}} \) is inadmissible risk; \( L(P) \) is the ratio of the likelihood of the values of the integrated criterion, taking the value above and below the threshold. The critical value of the integrated criterion for a coal deposit is determined with consideration of mining and geological conditions in accordance with the procedure described in [6]. Wells for determination of the yield of drilling cuttings are drilled through the most durable coal bank. Next, a nomogram is compiled to establish the threshold value of the integrated criterion. The likelihood coefficient of the integrated criterion \( L_i \) values is calculated using the following formula:

\[ L_i = \frac{N_{\text{adm}}}{N_{\text{inadm}}} \left( \frac{N_{\text{gen}}}{N_{\text{gen}}} \right)^q \]

where \( N_{\text{adm}} \) is the number of values of the integrated criterion below the threshold value for the measurement interval obtained from the MFSS; \( N_{\text{inadm}} \) is the number of values of the integrated criterion higher than the threshold value for the measurement interval obtained from the MFSS; \( N_{\text{gen}} \) is the total number of values for the measurement interval received from the MFSS.

Distribution density for \( f_{\text{inadm}} \):

\[ f_{\text{inadm}} = \frac{q_i}{\sum q_i} \]
where \( q \) is the number of excesses of the threshold value of the integrated criterion for the measurement interval received from the MFSS; \( \sum q \) is the number of values of the quantities of the integrated criterion for the averaging interval received from MFSS.

By analogy, for \( R_{adm} \)

\[
f_{adm}^i = \frac{z_i}{\sum z_i}
\]

where \( z_i \) is the number of values of the integrated criterion, not exceeding the threshold for the measurement interval, received from the MFSS; \( \sum z_i \) is the number of values of the quantities of the integrated criterion for the averaging interval received from MFSS.

Probability of decision \( R = R_{adm} \) when \( R = R_{adm} \) is true, is as follows

\[
\beta = \frac{1}{b} f(L | R_{adm}) dL = \sum_{j=1}^{n} f_{adm}^i \cdot L_i.
\]

Accordingly, for the reliability of the \( R_{adm} \) decisions, we obtain a simple expression that determines the risk of rock mass collapse

\[
R_{adm} = 1 - \beta.
\]

The assessment of the individual risk of fatal injuries of coal mine workers is based on the Bayesian theorem, the formula is as follows

\[
R_{ind} = \frac{AR_{adm}}{B},
\]

where \( A \) – the proportion of workers who received fatal injuries as a result of rock mass collapse (of the total number of workers who were present at the work site); \( R_{adm} \) – probability of rock mass collapse; \( B \) – the share of fatal injuries of workers in coal mines conditioned upon rock mass collapses; \( R_{adm} \) – the probability that the worker will be fatally injured in the event of a rock mass collapse.

It is proposed to calculate the proportion of workers who received fatal injuries because of the collapse of rock mass \( A \) while present in the mining site from statistical data. For 2013–2017, 23 fatal accidents caused by rock mass collapses occurred in Russian coal mines. The average annual number of fatal injuries is 4.6. In the periods preceding the collapse of the rock mass, 2,556 workers were present at the sites [1]. Accordingly, the value of \( A \) is calculated as the ratio of the average annual number of fatal injuries to the total number of workers employed in these areas

\[
A = \frac{4.6}{2556} = 0.0018.
\]

The probability of rock mass collapse is calculated according to the criterion of maximum likelihood and is presented above.

The proportion of fatal injuries to workers in coal mines because of rock mass collapses is determined by processing statistical data. According to Rostekhnadzor, for 2013–2017, 23 fatal accidents caused by rock collapses occurred in Russian coal mines. A total of 183 fatal accidents were registered in this period [1]. Thus, the value of \( B \) will be calculated as the ratio of fatal accidents due to rock mass collapse to the total number of fatal injuries over a given period. This value will have a quantity of 0.126.

\[
B = \frac{23}{183} = 0.126.
\]

Results. Based on the data arrays received from the MFSS, at the mining enterprises corresponding to the trouble-free operation mode, the mathematical model was tested. The averaging interval of 32 hours consists of 4 measurement intervals. Each measurement interval includes 8 measurements of the integrated criterion.

According to the data obtained, for the averaging interval, no excesses of the threshold values of the integrated criterion were detected. Consequently, the probability of rock collapse is zero. Accordingly, the value of individual risk also equals zero

\[
R = \begin{cases} 
R_{adm}, & \text{if } L(P) \geq 1; \\
R_{adm}, & \text{if } L(P) < 1. 
\end{cases}
\]

\[
L_1 = L_2 = L_3 = L_4 = 1; \quad f_{adm}^1 = f_{adm}^3 = f_{adm}^4 = 0; \quad f_{adm}^2 = \frac{8}{32} = \frac{1}{4}.
\]

\[
\beta = \sum_{i=1}^{n} f_{adm}^i \cdot L_i = \frac{1}{4} + \frac{1}{4} + \frac{1}{4} + \frac{1}{4} = 1;
\]

\[
R_{adm} = 1 - \beta = 1 - 1 = 0; \quad R_{ind} = \frac{AR_{adm}}{B} = \frac{0.0018 \cdot 0}{0.126} = 0.
\]

The situation preceding the accident at the coal mine was simulated. In this case, the averaging interval also includes 4 measurement intervals. The threshold value of the integrated criterion for these mining and geological conditions is 8 liters of drill cuttings yield (Table 1).

In all measurement intervals, the values of the integrated criterion that exceed the threshold, quantitatively exceed the values of the integrated criterion below the threshold value (Table 2)

\[
L_1 = L_2 = \frac{N_{adm}/N_{gen}}{N_{adm}/N_{gen}} = \frac{3/8}{5/8} = \frac{3}{5}; \quad L_2 = L_4 = \frac{N_{adm}/N_{gen}}{N_{adm}/N_{gen}} = \frac{2/8}{6/8} = \frac{1}{3};
\]

\[Table 1\]

<table>
<thead>
<tr>
<th>Measurement interval</th>
<th>Integrated criteria values, l/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 6 9 9 7 9 10 9</td>
</tr>
<tr>
<td>2</td>
<td>10 9 9 7 7 10 9 6</td>
</tr>
<tr>
<td>3</td>
<td>7 10 11 11 10 10 9 7</td>
</tr>
<tr>
<td>4</td>
<td>7 11 10 11 11 11 11 10</td>
</tr>
</tbody>
</table>

\[Table 2\]

<table>
<thead>
<tr>
<th>Values/Measurement intervals</th>
<th>Tolerable (below the threshold)</th>
<th>Unacceptable (above threshold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
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Proceeding from the fact that the value of admissible individual risk is $R = 2.5 \cdot 10^{-6} \text{ years}^{-1}$, the obtained value of individual risk is inadmissibly high. In the course of the study, using the example of experimental data, a correlation was established between the value of the individual risk of fatal injury to workers in coal mines and the integrated criterion. Based on the calculations, a linear relationship was established between the individual risk of fatal injury to workers and the integrated criterion value on the example of experimental data (Fig. 4), which is described by the following equation

$$R_{ind} = \frac{1}{1 - \frac{\beta}{1 - 0.39}} = 0.61;$$

$$\beta = \sum_{i=1}^{n} f_{iind} \cdot L_{i} = \frac{3}{32} + \frac{3}{32} + \frac{3}{32} + \frac{1}{16} + \frac{1}{16} + \frac{1}{16} + \frac{3}{100} = 0.39;$$

$$R_{ind} = \frac{AR_{ind}}{B} = \frac{0.0018 - 0.61}{0.126} = -0.0087 = 87 \cdot 10^{-4}. $$

The dependences of the individual risk of fatal injury to coal mine workers caused by rock mass collapse were compared with the value of the integrated criterion using two operating modes of a mining enterprise as an example, one of which corresponded to an emergency operation, and the other — to an accident-free operation with a threshold value of the integrated criterion of 8 liters of yield of drill cuttings per linear meter of the well, determined in accordance with [5] (Fig. 5).

Also, using the example of experimental data, a relationship was established between the individual risk of fatal injuries to coal mine workers and the percentage of workers who received fatal injuries because of rock mass collapse (Fig. 6), described by the following equation

$$R_{ind} = 4.84 + 0.0001. $$

In accordance with the frequency of rock caving in Russian coal mines, it is proposed to introduce the following ranges of individual risk (Table 3).

A value of $1 \cdot 10^{-6}$, corresponding to the frequency of rock caving less than 1 time in 10 years, is the maximum acceptable level of individual risk of death at production site in accordance with the international practice. For example, in the Netherlands, a value of $1 \cdot 10^{-6}$ was adopted in accordance with the recommendation of the National Health Council [11]. This value characterizes the extremely low probability of fatal injuries among workers caused by rock mass collapse.

$2.5 \cdot 10^{-4}$ is the average value of the permissible risk in the professional field of activity in Russia. On average, rock caving in the country’s coal mines occurs from 1 time per year to 1 time per month. Proceeding from the fact that the state of labor protection of workers at enterprises in this industry is still unsatisfactory, the value of individual risk for this range exceeds this value.

To predict the response of the geological environment to dangerous geomechanical and geodynamic manifestations, it is advisable to use an integrated approach [12], including a methodology for computer modeling of geo-processes in technogenic structures based on a more complete reflection of the important real features of the geological environment, its deformation and destruction, geophysical monitoring, full-scale and laboratory studies [13, 14].

Over the current decade, this methodology serves as the basis of forecast calculations of changes in the stress-strain state of the rock mass during mining operations in the seam liable to rock-bumps of the Barentsburg coal deposit (Spitsbergen Island) [12].

### Table 3

<table>
<thead>
<tr>
<th>The frequency of rockfall in coal mines</th>
<th>Quantitative risk value</th>
<th>Qualitative risk indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less often than 1 time in 10 years (possible under exceptional circumstances)</td>
<td>$&lt;1 \cdot 10^{-6}$</td>
<td>Minor risk</td>
</tr>
<tr>
<td>From 1 time in 10 years to 1 time per year</td>
<td>$1 \cdot 10^{-6} - 2.5 \cdot 10^{-4}$</td>
<td>Tolerable risk</td>
</tr>
<tr>
<td>From 1 time per year to 1 time per month</td>
<td>$&gt;2.5 \cdot 10^{-4}$</td>
<td>Unacceptable risk</td>
</tr>
</tbody>
</table>

**Fig. 4.** The relationship between the individual risk value of fatal injury to workers and the integrated criterion value on the example of experimental data

**Fig. 5.** The dependence of the value of individual risk on the integrated criterion value under different operating conditions of the mining enterprise

**Fig. 6.** The dependence of the value of individual risk on the proportion of workers who received fatal injuries as a result of fall of rock mass on the example of experimental data
An example of the joint use of geophysical methods for continuous monitoring and computer simulation of changes in the stress-strain state of a rock mass is illustrated in [15, 16] for the case of the mine. The results of the change in form-changing stresses in the rocks of the immediate mine roof of the declining area before and after flooding are given in [12].

Based on the studies, the project for the processing of dried coal was supplemented with regard to the prognosis and proactive measures on prevention of dynamic phenomena, which appeared to be an effective means of preventing rock mass collapse in order to reduce the risk of injury to workers.

**Conclusions.** Despite the emerging trend towards a decrease in the number of fatalities in coal mines as a result of rockfall, their number remains extremely high. Therefore, there is a need to create an effective model for assessing occupational risk due to rockfall in the country’s coal mines. Since the role of the MSS in ensuring industrial safety at enterprises, conducting underground coal mining is increasing, in the developed model it is necessary to take into account the data coming from these systems.

This model, developed taking into account the identified dependencies, allows one to determine the predicted values of the individual risk of fatality to personnel during rockfall taking into account these data. Establishing the dependencies between the value of the individual risk of fatalities of coal mine workers and the rock pressure value allows us to determine a safe value. An integrated approach in predicting the response of the mining and geological environment to technogenic manifestations, including computer modeling of geomechanical processes in a rock mass, instrumental measurements of rock pressure manifestations in advance workings and a face, geophysical methods for monitoring the stress-strain state allows us to predict potentially dangerous zones in a coal seam. Timely and prompt recording of the increase in stress concentration caused by the zone of high rock pressure allows one to effectively implement measures to protect against rock bumps and rockfall, which reduces occupational risks for miners.

**References.**

Оцінка індивідуального ризику смертельного травмування робітників угольних шахт при обрушениях

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Ціль. Створення ефективної моделі оцінки професійного ризику, обумовленого обрушеннями горних порід на угольних шахтах країни.

Методика. Представлена математична модель, основана на методі максимального правдоподібності, яка дозволяє оцінити вероятність камнепаду. Використання теореми Байеса для оцінки індивідуального ризику смертельних травм робітників угольної шахти оправдано. Комплексний метод ефективного контролю горного тиску ілюструється прикладами реалізації в розробці угольного пласту Баренцбургського родовища.

Результати. В роботі показана взаємозв'язок між ключевим статистичним показником, що впливає на рівень аварійності, і величиною ризику смертельних травм робітників. Обґрунтовано ключовий статистичний показник, значення якого розраховується з допомогою многофункціональної системи безпеки.

Наукова новизна. Складається на аналізі ефективності установки многофункціональних систем безпеки на угольних шахтах для контролю стану горного масиву.

Практична значимість. Розробка авторами моделі дозволить більш точно, за порівнянням з сучасними методами, визначити прогнозне значення індивідуального ризику смертельного травмування персоналу при обрушеннях пород.

Ключові слова: угольні шахти, смертельні травми, горного давління, теорема Байеса, геомеханічний процес

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