

M. L. Rudakov,
orcid.org/0000-0001-7428-5318,
E. N. Rabota,
orcid.org/0000-0002-7037-1056,
K. A. Kolvakh,
orcid.org/0000-0003-0145-9465

Saint Petersburg Mining University, Saint Petersburg, Russian Federation, e-mail: rudakov_ml@nuos.pro

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 $1.9 \cdot 10^{-4} \text{ year}^{-1}$. In individual coal mines, the observed individual risk of fatality reached $3 \cdot 10^{-4} \text{ year}^{-1}$ (Krasnohorskaia mining, 2014), $3 \cdot 10^{-4} \text{ year}^{-1}$ (Ziminka mining, 2012), $4 \cdot 10^{-4} \text{ year}^{-1}$ (Kiselevskaia mining, 2011), $4 \cdot 10^{-4} \text{ year}^{-1}$ (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_a , which took place by type of professional activity, and dangerous if it exceeds this threshold. Risk reduction at coal enterprises de-

pends 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 Rostekhnadzor 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 geogasdynamic 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-

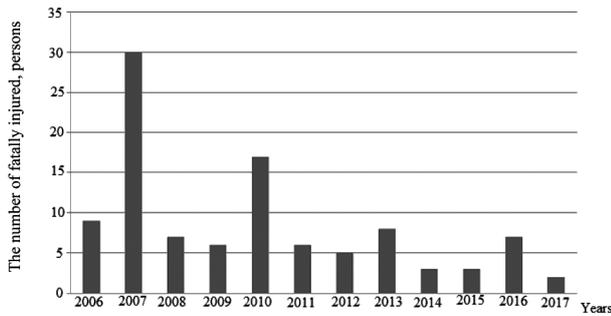


Fig. 1. The number of cases of fatal injury due to rockfall in coal mines, in the period of 2006–2017 [1]

ing of the results of the geophysical observation system allows obtaining the value of the integrated criterion, expressed in liters of drill cutting yield, based on the established interrelation of this criterion with the values of the overburden gradient and seismic energy [7].

For this system, the following key statistical indicators are formulated: statistical indicators of exceeding the established limits for the safe operation of a hazardous production facility (HPF); prerequisites for exceeding the safe operation limit; statistical indicators of the effectiveness of barriers to industrial safety violations [8, 9].

The state of industrial safety is assessed according to data from the geophysical observation system with consideration of events classification (Fig. 2).

Class C4 is formed by events that manifest themselves in such a change in parameters that, when developed, can potentially lead to the prerequisites for incidents. Class C3 is formed by events that are formally defined as a clear prerequisite for an industrial safety incident. Class C2 is formed by events that formally characterize the increased risk of industrial safety. Class C1 is formed by events that formally characterize the considerable risk of an accident that exceeds the level of acceptable accident risk established at the facility [8].

In the calculations, the most significant are the statistical indicators of exceeding the established limits for the safe operation of a hazardous production facility, including:

- the number of events of classes C2–C1 for the period t ;
- the frequency of events of classes C2–C1 for the period t ;
- the total duration of the events of classes C2–C1 for the period t (with consideration of the level of the event);
- the normalized duration of events of classes C2–C1 for a period t ;
- relative indicator of exceeding the safe operation limit: dynamics of the normalized duration of events of classes C2–C1 [8].

The structure of the mathematical model for assessing occupational hazard is presented in Fig. 3.

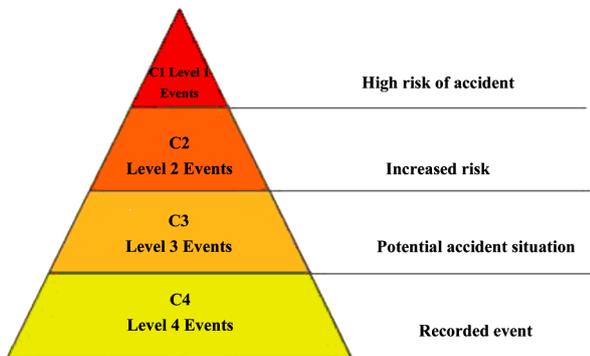


Fig. 2. The pyramid of recorded events during the operation of a hazardous production facility [8]

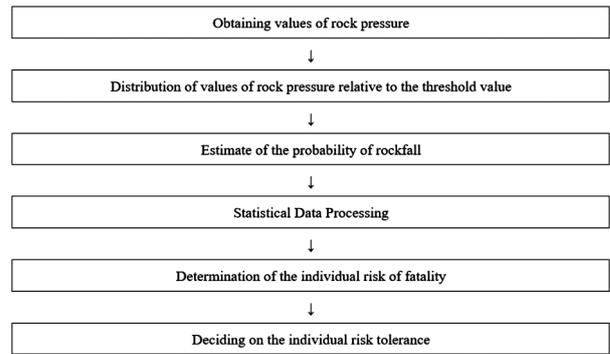


Fig. 3. The structure of the mathematical model for determining the individual risk of fatalities of coal mines due to rockfall

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 ($2.5 \cdot 10^{-4} \text{ years}^{-1}$).

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

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

where R_{adm} is admissible risk; R_{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

$$L_i = \frac{N_{adm} / N_{gen}}{N_{inadm} / N_{gen}}$$

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

Distribution density for R_{inadm}

$$f_i^{inadm} = \frac{q_i}{\sum q_i}$$

where q_i is the number of excesses of the threshold value of the integrated criterion for the measurement interval received from the MFSS; $\sum q_i$ is the number of values of the quantities of the integrated criterion for the averaging interval received from MFSS.

By analogy, for R_{adm}

$$f_i^{adm} = \frac{z_i}{\sum z_i},$$

where z_i is the number of values of the integrated criterion, not exceeding the threshold for the measurement interval, received from 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 $R = R_{inadm}$, when $R = R_{adm}$ is true, is as follows

$$\beta = \int_0^1 f(L | R_{adm}) dL = \sum_{i=1}^n f_i^{adm} \cdot L_i.$$

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

$$R_{inadm} = 1 - \beta.$$

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

$$R_{ind} = \frac{AR_{inadm}}{B},$$

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_{inadm} – probability of rock mass collapse; B – the share of fatal injuries of workers in coal mines conditioned upon rock mass collapses; R_{ind} – 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

$$A = \frac{4.6}{2.556} = 0.0018.$$

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 av-

eraging 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

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

$$L_1 = L_2 = L_3 = L_4 = 1;$$

$$f_1^{inadm} = f_2^{inadm} = f_3^{inadm} = f_4^{inadm} = 0;$$

$$f_1^{adm} = \frac{z_i}{\sum z_i} = \frac{8}{32} = \frac{1}{4};$$

$$f_1^{adm} = f_2^{adm} = f_3^{adm} = f_4^{adm};$$

$$\beta = \sum_{i=1}^n f_i^{adm} \cdot L_i = \frac{1}{4} \cdot 1 + \frac{1}{4} \cdot 1 + \frac{1}{4} \cdot 1 + \frac{1}{4} \cdot 1 = 1;$$

$$R_{inadm} = 1 - \beta = 1 - 1 = 0;$$

$$R_{ind} = \frac{AR_{inadm}}{B} = \frac{0.0018 \cdot 0}{0.126} = 0.$$

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)

$$L_1 = L_2 = \frac{N_{adm}/N_{gen}}{N_{inadm}/N_{gen}} = \frac{3/8}{5/8} = \frac{3}{5};$$

$$L_3 = L_4 = \frac{N_{adm}/N_{gen}}{N_{inadm}/N_{gen}} = \frac{2/8}{6/8} = \frac{1}{3};$$

Table 1

Integrated criterion values distributed over measurement intervals

Measurement interval	Integrated criteria values, l/m							
1	5	6	9	9	7	9	10	9
2	10	9	9	7	7	10	9	6
3	7	10	11	11	10	10	9	7
4	7	7	11	10	11	11	11	10

Table 2

Distribution of integrated criterion values relative to the threshold

Values/Measurement intervals	Tolerable (below the threshold)	Unacceptable (above threshold)
1	3	5
2	3	5
3	2	6
4	2	6

$$f_1^{inadm} = f_2^{inadm} = \frac{q_i}{\Sigma q_i} = \frac{5}{32};$$

$$f_3^{inadm} = f_4^{inadm} = \frac{q_i}{\Sigma q_i} = \frac{6}{32};$$

$$f_1^{adm} = f_2^{adm} = \frac{z_i}{\Sigma z_i} = \frac{3}{32};$$

$$f_3^{adm} = f_4^{adm} = \frac{z_i}{\Sigma z_i} = \frac{1}{16};$$

$$\beta = \sum_{i=1}^n f_i^{adm} \cdot L_i = \frac{3}{32} \cdot \frac{3}{5} + \frac{3}{32} \cdot \frac{3}{5} + \frac{1}{16} \cdot \frac{1}{3} + \frac{1}{16} \cdot \frac{1}{3} = \frac{74}{150} = 0.39;$$

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

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

Proceeding from the fact that the value of admissible individual risk is $R = 2.5 \cdot 10^{-4}$ 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 two indicators (Fig. 4), which is described by the following equation

$$R_{ind} = 0.0018P - 0.109.$$

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).

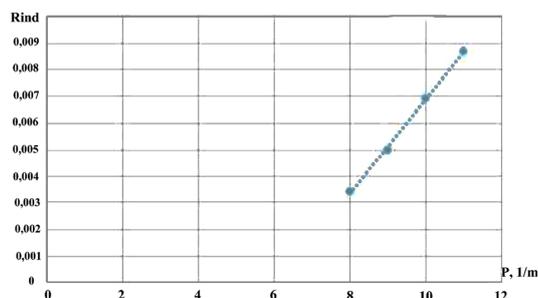


Fig. 4. The relationship between the individual risk value of fatal injury to workers and the integrated criterion value on the example of experimental data

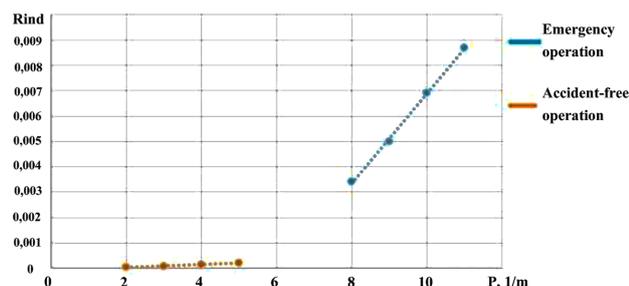


Fig. 5. The dependence of the value of individual risk on the integrated criterion value under different operating conditions of the mining enterprise

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

$$R_{ind} = 4.8A + 0.0001.$$

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 geotechnogenic 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].

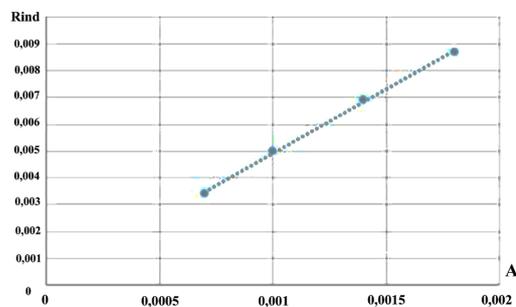


Fig. 6. The dependence of the value of individual risk on the proportion of workers who received fatal injuries as a result of fall of rock mass on the example of experimental data

Table 3

Quantitative risk values in accordance with the frequency of rockfall

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

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 liquidation of the flooding of the emergency section of mine No. 1–5 of the Barentsburg mine. The results of the nature of the change in form-changing stresses in the rocks of the immediate mine roof of the declining lava before and after flooding are given in [12].

Based on the studies, the project for the processing of dried lava 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.

1. Report of the Federal Service for Ecological, Technological and Nuclear Supervision "State of industrial safety at hazardous production facilities of the coal industry" (2019). Retrieved from <http://docs.cntd.ru/document/560448587>.
2. Kabanov, E. I., Korshunov, G. I., Kazanin, O. I., Rudakov, M. L., & Nedosekin, A. O. (2017). Development of a methodology for assessing the risks of accidents in coal mines, taking into account specific mining and geological conditions. *Mountain News and Analysis Bulletin*, 4, 374–383.
3. The concept of acceptable risk (2019). Retrieved from http://ohrana-bgd.ru/bgdobsh/bgdobsh1_39.html.
4. Parkhanski, U. (2016). Risk of injury to workers in coal mines and its hysteresis. *Notes of the Mining Institute*, 222, 869–876. <https://doi.org/10.18454/PMI.2016.6.869>.
5. Rostekhnadzor Order No. 339 "On the Approval of Federal Norms and Rules in the Field of Industrial Safety "Instruction for predicting dynamic phenomena and monitoring the massifs of rocks during mining of coal deposits"" (2016). Retrieved from <https://legalacts.ru/doc/prikaz-rostekhnadzora-ot-15082016-n-339-ob-utverzhenii-federalnykh/>.
6. Iphar, M., & Cukurluoz, A. K. (2018). Fuzzy risk assessment for mechanized underground coal mines in Turkey. *International Journal of Occupational Safety and Ergonomics*, 3, 110–158. <https://doi.org/10.1080/10803548.2018.1426804>.
7. Babenko, A. G. (2016). Quantitative evaluation of the current risk of exploitation coal mine. *News of Higher Educational Institutions*, 4, 24–35.
8. ISO 31000:2018, Risk management – Guidelines (2018). Retrieved from <https://www.iso.org/iso-31000-risk-management.html>.

9. Kumar, R., & Ghosh, A. K. (2017). Mines systems safety improvement using an integrated event tree and fault tree analysis. *Journal of the Institution of Engineers (India): Series D*, 98, 101–108. <https://doi.org/10.1007/s40033-016-0121-0>.
10. Shi, L., Wang, J., Zhang, G., Cheng, X., & Zhao, X. (2017). A risk assessment method to quantitatively investigate the methane explosion in underground coal mine. *Process Safety and Environmental Protection*, 107, 317–333. <https://doi.org/10.1016/j.psep.2017.02.023>.
11. Tripathy, D. P., & Ala, C. K. (2018). Risk assessment in underground coalmines using fuzzy logic in the presence of uncertainty. *Journal of the Institution of Engineers (India): Series D*, 99, 157–163. <https://doi.org/10.1007/s40033-018-0154-7>.
12. Savon, D. Y., Aleksakhin, A. V., Skryabin, O. O., & Goodilin, A. A. (2019). Occupational health and safety digitalization in the coal industry. *Eurasian Mining*, (2), 70–72. <https://doi.org/10.17580/em.2019.02.15>.
13. Zubov, V. P. (2017). State and directions of system improvement development of coal seams in the perspective coal mines of Kuzbass. *Notes of the Mining Institute*, 225, 292–297. <https://doi.org/10.18454/PMI.2017.3.292>.
14. Intima, D. P. (2017). Sampling plan for quality monitoring of suppliers of the sanitation sector. *Periodico Tche Quimica*, 14(27), 39–43.
15. Zuev, B. Yu., Zubov, V. P., & Fedorov, A. S. (2019). Application prospects for models of equivalent materials in studies of geomechanical processes in underground mining of solid minerals. *Eurasian mining*, 1, 8–12. <https://doi.org/10.17580/em.2019.01.02>.
16. Rosenbaum, M. A., Kuzmin, S. V., Antonyuk, S. A., & Do Quang Tuan (2015). Modeling of geomechanical processes on models from equivalent materials. *Journal of Mining Industry. Vietnam*, 1, 53–56.

Оцінка індивідуального ризику смертельного травмування працівників вугільних шахт під час обваллення

М. Л. Рудаков, Е. М. Работя, К. А. Кольвах

Санкт-Петербурзький гірничий університет, м. Санкт-Петербург, Російська Федерація, e-mail: rudakov_ml@nuos.pro

Мета. Створення ефективної моделі оцінки професійного ризику, обумовленого обваленнями гірських порід на вугільних шахтах країни.

Методика. Представлена математична модель, заснована на методі максимальної правдоподібності, що дозволяє оцінити ймовірність каменепаду. Використання теореми Байеса задля оцінки індивідуального ризику смертельних травм працівників вугільної шахти виправдано. Комплексний метод ефективного контролю гірського тиску ілюструється застосуванням розробленої методики комп'ютерного моделювання геомеханічних процесів, інструментальних і геофізичних методів захисту та обслуговування гірничих виробок при розробці вугільного пласта Баренцбургського родовища.

Результати. У роботі показано взаємозв'язок між ключовим статистичним показником, що впливає на рівень аварійності, і величиною професійного ризику. Обґрунтовано ключовий статистичний показник, значення якого визначається за допомогою багатофункціональної системи безпеки.

Наукова новизна. Полягає в розробці встановлення багатофункціональної системи безпеки на вугільних шахтах для контролю стану гірського масиву.

Практична значимість. Розроблена модель дозволяє більш точно, у порівнянні з існуючими методами, визначити прогнозне значення індивідуального ризику смер-

тельного травмування персоналу при обваленнях породи.

Ключові слова: вугільні шахти, смертельні травми, гірський тиск, теорема Байєса, геомеханічний процес

Оценка индивидуального риска смертельного травмирования работников угольных шахт при обрушениях

М. Л. Рудаков, Э. Н. Работа, К. А. Кольвах

Санкт-Петербургский горный университет, г. Санкт-Петербург, Российская Федерация, e-mail: rudakov_ml@nuos.pro

Цель. Создание эффективной модели оценки профессионального риска, обусловленного обрушениями горных пород на угольных шахтах страны.

Методика. Представлена математическая модель, основанная на методе максимального правдоподобия, которая позволяет оценить вероятность камнепада. Использование теоремы Байеса для оценки индивидуального риска смертельных травм работников угольной шахты оправдано. Комплексный метод эффективного контроля горного давления иллюстрируется примени-

ем разработанной методики компьютерного моделирования геомеханических процессов, инструментальных и геофизических методов защиты и обслуживания горных выработок при разработке угольного пласта Баренцбургского месторождения.

Результаты. В работе показана взаимосвязь между ключевым статистическим показателем, влияющим на уровень аварийности, и величиной профессионального риска. Обоснован ключевой статистический показатель, значение которого определяется с помощью многофункциональной системы безопасности.

Научная новизна. Состоит в анализе эффективности установки многофункциональных систем безопасности на угольных шахтах для контроля состояния горного массива.

Практическая значимость. Разработанная авторами модель позволит более точно, по сравнению с существующими методами, определить прогнозное значение индивидуального риска смертельного травмирования персонала при обрушениях породы.

Ключевые слова: угольные шахты, смертельные травмы, горное давление, теорема Байеса, геомеханический процесс

Recommended for publication by N. A. Pelipenko, Doctor of Technical Sciences. The manuscript was submitted 23.11.19.