MATHEMATICAL DESCRIPTION OF HARMFUL INDUSTRIAL FACTORS FOR ASSESSING THE QUARRY WORKERS' OCCUPATIONAL RISK

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Mining industry is highly important in the economy of each country. At the same time, the mining industry is an industry with a high level of morbidity among workers. Quarry workers are often exposed to hazardous environments, while at the same time a low level of process safety organization. This study aims to develop a mathematical description of modelling the values of harmful factors in the production environment at the workplaces of quarry workers, which will help ensure high-quality engineering control during the work shift. The initial statistical data for the development of mathematical models were obtained directly by the authors through personal observations of the technological process and measurements of the level of harmful factors in the working environment. Measurements were taken using portable digital devices. To develop mathematical description based on accumulated statistical data, polynomial regression was used. The construction of models using polynomial regression is based on the property of functional dependencies, which can be formulated as follows: with a gradual increase in the complexity of the model (polynomial degree), the magnitude of errors (approximation error, forecast error) monotonically decreases. As a result, fourth-order polynomial equations were obtained to model the values of dust concentration and noise level at certain time intervals of the work shift. The correlation coefficient of these models is R = 0.98 and R = 0.99, and the relative error is 9.76% and 6.11% of dust concentration and noise level respectively, which indicates sufficient accuracy of the model. It was established that the studied harmful factors during a normal production process, have a level of impact at which early forms of occupational diseases develop. The proposed mathematical description of modelling the values of these factors makes it possible for high-quality engineering control over current technology processes in order to avoid abnormal excesses of the values. Further research, according to the authors, should be aimed at identifying and mathematically describing other potentially harmful and dangerous factors in the working environment. The originality of the current study lies in the fact that an attempt was made to propose a non-classical approach to quickly identify deteriorating working conditions directly in the work process using mathematical modelling.

Keywords: quarry; production environment; occupational illness; risk; noise level; dustiness.

INTRODUCTION

Mining of fossil resources is a high-intensity activity that has contributed to the development of civilizations right up to the present day. It is a well-known fact that the mining industry is highly important in the economy of each country. At the same time, the mining industry is an industry with a high risk of fatal and non-fatal injuries and a high level of morbidity among workers. Quarry workers are often exposed to hazardous environments, while at the same time a low level of process safety organization. This causes a high level of occupational injuries and illnesses in the industry.

As can be seen from world experience, the mining industry is a source of negative legacy with many problems in society, primarily related to the health of workers. The solution to these difficulties can be achieved by rethinking the working methods of miners based on the assessment of occupational risk, which ultimately can contribute to harmonious social integration, environmental sustainability and economic development of the state.

In order to provide efficient and safe working conditions in the mining industry, numerous tools, a variety of safety techniques and appropriate procedures must be used. Risk assessments are aimed at identifying and optimizing risk factors to obtain information about the consequences of exposure to hazards and use this risk assessment as a decision-making tool.

During their work shifts, quarry workers are systematically exposed to dust and noise, which allows them to classify this profession as a profession with a high level of occupational risk. Although greater understanding of the risks associated with silica and other fossil materials and the development of measures to prevent dust exposure have contributed to a reduction in morbidity and mortality from silicosis and pneumoconiosis, incidence rates remain unacceptably high and sometimes continue to rise.

A common occupational disease among quarry workers is lung disease, such as silicosis and pneumoconiosis (Schlünssen et al., 2023). This disease progresses rapidly even after exposure has ceased, with decreased lung function in a significant number of affected workers. (León-Jiménez et al., 2020). The WHO and ILO require systematic research into the incidence of any occupational exposure to dust, as well as systematic research into the morbidity and mortality of occupational-acquired lung diseases, and the comparison of this information with the risk exposure level. A study examining the effects of occupational silicosis caused by exposure to granite quarries found that of 141 patients with silicosis with a duration of exposure of 23.5 years, 17.7% of patients had major opacities on baseline radiographs; after 7.5 years of follow-up, 52 (36.9%) developed significant opacities (Lee et al., 2001). For sandblasting workers, the researchers found that 82% of those affected experienced radiological progression. Initially, 8 patients (10.8%) had large opacities; at 4 years, 18 had significant opacities (24.3%) (Akgun et al., 2015).

Quarry workers are exposed to mechanical noise caused by the operation of professional equipment. It has been found that those workers who are constantly exposed to excessive noise levels tend to develop noise-induced hearing loss (NIHL) (Fuente & Hickson, 2011). The authors found a positive correlation between the incidence of NIHL and excessive noise exposure in

industrial processes (Thai et al., 2021). Researchers have found that even though workplace noise exposure is below the regulatory threshold of 85 dB(A) and may not cause immediate hearing damage, it can have a significant impact on workers' hearing health, cognitive function, psychological well-being and overall productivity (Themann & Masterson, 2019; Materu et al., 2023). According to a study (Themann & Masterson, 2019), approximately 16% of noise-exposed workers have significant hearing impairment. Currently, the integrated public health approach focuses primarily on noise control rather than on the development of protective pharmacological or genetic therapies. That is why risk assessment in a specific workplace is extremely important for the professional selection of workers and for the development of preventive measures.

The current study aims at controlling the occupational risk of quarry workers working under the influence of harmful factors in the working environment "dustiness" and "noise" by promptly detecting changes in the production process. The basis for this can be a mathematical description of modelling the values of harmful factors in the production environment. Therefore, the purpose of the study is to provide the following results:

– perform a mathematical description for each harmful factor in the working environment under study depending on the degree of its harmfulness, taking into account the further possibility of assessing the occupational risk of workers;

– development of recommendations regarding activities and fundamental decisions aimed at reducing the negative impact of harmful factors on quarry workers.

MATERIALS AND METHODS

At the request of several mining companies in Ukraine, collaboration was established by the authors of the current study to identify workplace hazards for granite quarry workers and develop measures to protect them. The working conditions of five professions that are directly involved in the production process were studied, namely: a worker splitting granite slabs and blocks; a mining master; a crane operator; a excavator driver; an electric and gas welder.

The initial statistical data for the development of mathematical models were obtained directly by the authors through personal observations of the technological process and measurements of the level of harmful factors in the working environment. Measurements were taken using portable digital devices.

To develop mathematical description based on accumulated statistical data (industrial factors values), polynomial regression was used. This choice can be explained, in particular, by the fact that this method is based on the simplicity of computational algorithms and the clarity of the results obtained, which led to its spread to solve a wide range of problems in the occupational safety field (Moraru et al., 2020).

The construction of models using polynomial regression is based on the property of functional dependencies, which can be formulated as follows: with a gradual increase in the complexity of the model (polynomial degree), the magnitude of errors (approximation error, forecast error) monotonically decreases. This property allows you to obtain a model of a given accuracy:

$$y(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + \cdots, \tag{1}$$

where $y(t)$ is the values of the modelled parameter (dust concentration or noise level) at time t; a_0, a_1, a_2, a_3 are constant coefficients of the model, which are determined by calculation.

The approximation accuracy of such a model Δ_A is assessed by the average deviation module of the actual and calculated values of the modelled indicator (in percent).

$$\Delta_A = 100 - \delta_A, \tag{2}$$

where δ_A is the approximation error (in percent), determined by the following expression:

$$\delta_A = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{x(t_i) - y(t_i)}{x(t_i)} \right| \cdot 100\%, \tag{3}$$

where $x(t_i)$, $y(t_i)$ is, respectively, the actual and calculated value of the modelled indicator at a point in time t_i.

At the same time, as evidenced by the experience of a practical solution (Kruzhilko et al., 2019), an accuracy of more than 90% can be acceptable.

However, what will the resulting mathematical description in the regression equation form provide for each harmful factor under study, and how will the modelling results make it possible to justify management decisions to improve working conditions?

If a mathematical model is based on actual statistical data and has acceptable accuracy, then this allows, without additional field measurements, to control deviations in working conditions for a specific factor from the expected ones. So, for example, if the manager responsible for working conditions at a particular workplace has at his disposal the results of the expected values of the harmful factor levels in the working environment, then an increase in the value of the actual level above the expected (calculated) by more than 10% may indicate a violation of the normal course of the technological process. Therefore, it is necessary to monitor and search for malfunctions in the operation of equipment, malfunctions of collective protection equipment, etc. The presence of such information makes it possible to timely identify problem areas of work and justify the implementation of additional preventive (as a rule, unplanned in advance) measures, which helps to prevent an increase in occupational risk.

The risk factor is directly related to working conditions, which are classified accordingly. The rules for determining the class of working conditions for workplaces are determined by national legislation in the field of labour protection. In accordance with the State Sanitary norms and Rules "Hygienic classification of work according to indicators of harmfulness and dangerous factors of the production environment, difficulty and tension of the labour process", approved by Order of the Ministry of Health dated 04/08/2014 No. 248 (https://zakon.rada.gov.ua/laws/show/z0472-14#Text), working conditions, depending on the level of exposure to harmful and dangerous production factors, are divided into several classes (subclasses). The workplaces under study may have the following working conditions and worker health risk:

– acceptable;

– the risk of harm to health increases;

– early forms of occupational diseases develop;

– occupational diseases of mild and moderate severity with loss of professional ability to work appear;

– severe forms of occupational diseases with loss of professional ability to work appear.

RESULTS

Harmful factor in the working environment "dustiness"

Modelling of dust concentration in the air of a working area

The dynamics of changes in dust concentration in the air of the working area for processing granite slabs and blocks are shown in Table 1. Concentration measurements were carried out at predetermined time intervals corresponding to the number of minutes from the start of the production process/equipment operation.

Based on statistical data (Table 1), a regression equation of working conditions according to the harmful factor in the working environment "dustiness" was obtained. This mathematical notation describes the dependence of dust concentration values on time t:

$$y(t) = 2.2 + 0.367t - 0.0065t^2 - 0.000077t^3 + 0.0000012t^4. \tag{4}$$

The deviation module for each row of Table 1 is calculated using the formula:

$$\frac{|x(t_i) - y(t_i)|}{x(t_i)}. \tag{5}$$

The estimate of the approximation error of the resulting model, according to formula (2), was:

$$\delta_A = 0.0974,$$

while the approximation accuracy, according to formula (3), is defined as:

$$\Delta_A = 100 - 9.74 = 90.26.$$

This mathematical description indicates that to model the dust concentration (silicon dioxide at a concentration of more than 60%) in the air of the working area for processing blocks, it is enough to have a fourth-order polynomial equation. The correlation coefficient of this model is R = 0.98, and

the relative error is 9.76%, which indicates sufficient accuracy of the model.

Table 1. Results of modelling dust content in the working area for processing granite slabs and blocks

t, min	Actual data (measured) $x(t)$, mg/m³	Estimated data $y(t)$, mg/m³	The deviation module
1	3.00	2.56	0.15
4	3.00	3.56	0.19
7	4.10	4.43	0.08
10	5.00	5.15	0.03
13	6.40	5.73	0.10
16	6.50	6.17	0.05
19	6.50	6.45	0.01
22	6.50	6.58	0.01
25	6.30	6.57	0.04
28	6.20	6.42	0.04
31	6.00	6.14	0.02
34	5.70	5.74	0.01
37	5.40	5.24	0.03
40	4.70	4.64	0.01
43	4.00	3.98	0.01
46	3.70	3.27	0.12
49	2.20	2.52	0.15
52	1.90	1.78	0.06
55	0.70	1.06	0.51
58	0.60	0.40	0.33

A graphical representation of the dynamics of actual and calculated values of dust concentration is presented in Figure 1.
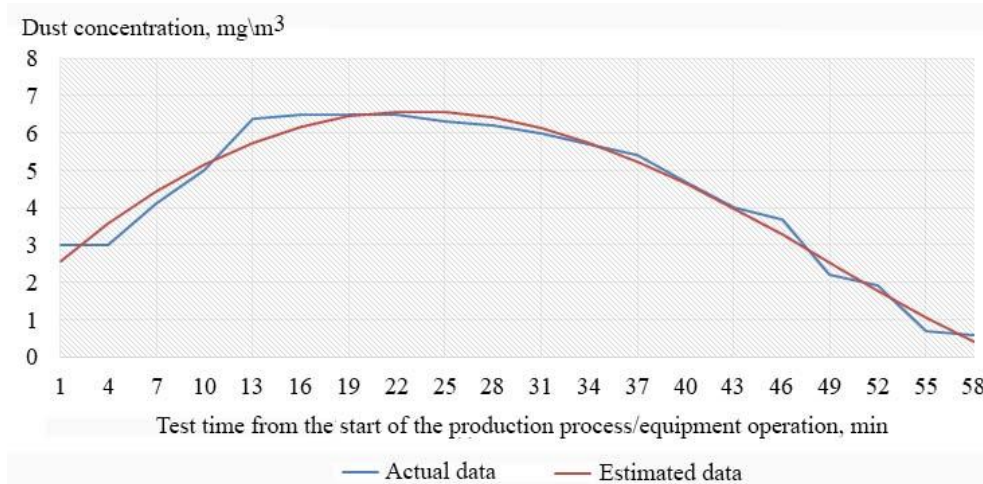

Figure 1. Dynamics of dust concentration values at workplaces for processing granite slabs and blocks (actual and estimated data)

Based on the results of the analysis, it was established that, according to (Moraru et al., 2020), a significant part of the working time, due to the dust factor, is spent in hazardous working conditions. Considering that the main factor of dust in the working areas of transportation, preparation and mixing of materials is silicon dioxide (concentrations more than 60%), its maximum permissible concentration (MAC) is 1 mg/m³. Consequently, a certain excess of dust concentration over the MAC (Table 2) will correspond to the relevant professional risk.

Similar conditions are observed in similar jobs in other countries. For example, the current permissible exposure limit for crystalline silica in the United States is 0.05 mg/m³ over an 8-hour operating period. However, this limit can be exceeded by more than 300 times. Research statistics on the identification of occupational diseases in Spain, North America, and Israel among workers involved in stone processing demonstrate that such working conditions are favourable for the development of silicosis (Barnes & Glaspole, 2023).

Table 2. Comparison of excess dust concentration relative to the MPC with the risk to worker health

Degree of excess dust concentration	Risk to worker health[*]	Recommendations
1.1 ... 3.0 times	the risk of harm to health increases	Measures to improve working conditions are necessary
3.1 ... 10.0 times	early forms of occupational diseases develop	Measures to improve working conditions are necessary

[*]based on source: https://zakon.rada.gov.ua/laws/show/z0472-14#Text

Activities aimed at reducing negative impacts

To reduce the negative impact of dust on workers, the following actions are proposed:

1. Eliminate the source of dust by replacing equipment.

2. Optimization of the technological process. Sealing of equipment that is a source of dust, installation of a powerful ventilation system (installation of autonomous dust and gas filtering devices and air conditioning systems in the cabs of dump trucks in excavators). Application of dust suppression methods. Timely repair and regular maintenance of machines and mechanisms according to technological regulations.

3. Organization of periodic medical examinations and treatment and preventive measures. Conducting additional training.

4. Ensuring control over the use of dust respirators, safety glasses, and dust suits.

Harmful factor in the working environment "noise"

Modelling the dynamics of noise level changes

The dynamics of actual changes in noise levels at workplaces processing granite slabs and blocks are shown in Table 3. Noise measurements were carried out at predetermined time intervals corresponding to the number of minutes from the start of the production process/equipment operation.

Based on the processing of statistical data given in Table 3, a regression equation was obtained that establishes the dependence of noise level values on time t:

$$y(t) = 84.88333601 + 0.75410512t - 0.05362711t^2 + 0.00125588t^3 - 0.00000876t^4. \qquad (6)$$
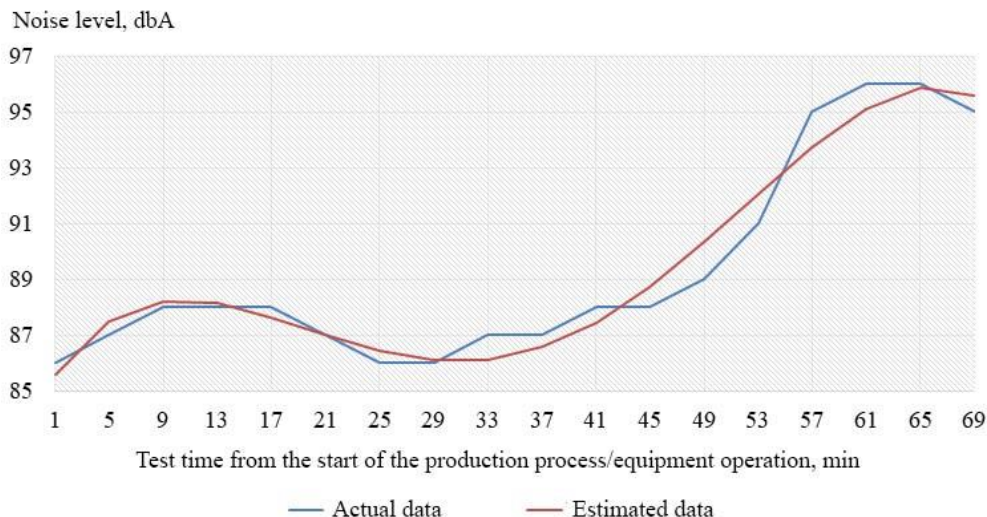
The deviation module for each row of Table 3 is calculated using the formula (5).

Table 3. Calculation results of noise levels at workplaces for processing granite slabs and blocks

Actual data (measured)		Estimated data	
t, min	x(t), dB(A)	y(t), dB(A)	The deviation module
1	86	85.59	0.0048
5	87	87.46	0.0053
9	88	88.18	0.0020
13	88	88.13	0.0015
17	88	87.64	0.0041
21	87	87.00	0.0000
25	86	86.42	0.0049
29	86	86.09	0.0010
33	87	86.11	0.0102
37	87	86.57	0.0049
41	88	87.46	0.0061
45	88	88.74	0.0084
49	89	90.33	0.0149
53	91	92.06	0.0116
57	95	93.74	0.0133
61	96	95.11	0.0093
65	96	95.85	0.0016
69	95	95.60	0.0063

The estimate of the approximation error of the resulting model was:

$$\delta_A = 0.0611,$$

while the accuracy of approximation of the resulting model is:

$$\Delta_A = 100 - 6.11 = 93.89.$$

This mathematical description indicates that to model noise pollution in a work area, it is also sufficient to have a fourth-order polynomial equation. The correlation coefficient of this model is $R = 0.99$, and the relative error is 6.11%, which indicates sufficient accuracy of the model.

A graphical representation of the dynamics of actual and estimated noise concentration values is presented in Figure 2.

Noise level, dbA

Test time from the start of the production process/equipment operation, min

— Actual data   — Estimated data

Figure 2. Dynamics of noise level values at workplaces for processing granite slabs and blocks (actual and estimated data)

So, the working conditions at workplaces for processing granite slabs and blocks in terms of the "noise" factor are such that workers are exposed to noise in the range between 85 and 95 dB(A). According to the source (https://zakon.rada.gov.ua/laws/show/z0472-14#Text), such conditions there are characterized by early forms of occupational diseases develop.

Thus, Wang et al. (2023) found that with constant exposure to mechanical noise (noise from technological equipment, at high frequencies) at a level of 88.7 dB(A), the hearing loss risk is 13.4%, while the noise-induced deafness risk is 4.1%. If the noise level is higher, that is, 89.1 dB(A), then the hearing loss risk and the noise-induced deafness risk increase accordingly to 14.3% and 4.5%, respectively.

Measures aimed at reducing the negative impact of noise

For measures aimed at reducing the negative impact of noise on workers, the following are proposed:

1. Replacement of equipment with less noisy equipment (if it is not possible to replace equipment, timely repair and machines' regular maintenance, technological regulation mechanisms, and control of permissible noise levels is recommended).

2. Optimization of the technological process (development of a rational operating mode). Coating the internal walls of machine cabins and control stations with soundproofing and sound-absorbing materials.

3. Treatment and preventive measures.

4. Use of personal protective equipment: headphones, earplugs, helmets with antiphons.

DISCUSSION

The current study found that in the Ukrainian mining industry, the working conditions of quarry workers are harmful and contribute to the development of early forms of occupational diseases associated with the negative effects of dust and noise.

The current study attempts to propose a non-classical approach to quickly identify deteriorating working conditions directly in the process of work. For this purpose, a mathematical description of hazardous factors in the working environment was developed, which showed high accuracy in modelling the values of these factors.

What makes it possible to use simulation results to improve the efficiency of planning occupational safety measures compared to traditional technology based solely on visualization of measurement results? Two aspects should be noted.

First aspect. An occupational safety specialist who conducts operational monitoring of working conditions only needs to carry out (one-time, single, "spot") measurements of the levels of production factors at predetermined points in time. At the same time, he supplements the corresponding mathematical model with the value of the time interval corresponding to the measurement. Next, an automated calculation of the value of the modelled factor is carried out. If the calculated value does not exceed (or exceeds by no more than 10%, taking into account the accuracy of the obtained models) pre-calculated values corresponding to the normal course of the technological process, we can conclude that no additional measures are required. Otherwise, the specialist must select an event from the list of recommended ones that can be applied in specific production conditions.

At the same time, other researchers also concluded that the main method of protecting workers from high risk of noise exposure is the current engineering control of occupational noise exposure (Wang et al., 2023).

When working with equipment that creates high-intensity noise, collective protective measures are recommended, such as muffling and sound insulation, or organizing the work process in such a way that the duration of the worker's exposure to the harmful factor is as short as possible (Kruzhilko et al., 2023; Wang et al., 2023). If organizational and technical measures do not ensure sufficient safety for workers, then in addition to this, personal protective equipment (PPE) should be used.

Second aspect. The resulting mathematical models will allow a more flexible and adequate assessment of occupational risk for different professions (or jobs). To do this, it is necessary to develop a risk assessment methodology using modelling results and automated calculation capabilities.

CONCLUSION

The study examined only two types of harmful factors, dust and noise pollution. Both factors, during a normal production process, have a level of impact at which early forms of occupational diseases develop. The proposed mathematical description of modelling the values of these factors in the process of work has shown high accuracy. This makes it possible for high-quality engineering control over current technology processes in order to avoid abnormal excesses of the values of these factors. Further research, according to the authors, should be aimed at identifying and mathematically describing other potentially harmful and dangerous factors in the working environment.

In addition, for a full analysis and subsequent preventive work in the industrial safety system, a risk assessment methodology should be developed using the results of the proposed mathematical approach. In the future, this will make it possible to algorithmize and automate risk assessment calculations.

Author's statements

Contributions

All authors contributed to the study's conception and design.

Conceptualization: O.K., N.V.; Data curation: V.M.; Formal Analysis: O.K., S.V., F.G.; Investigation: O.K., V.M., N.V., S.V., F.G.; Methodology: O.K., V.M., N.V.; Project administration: O.K., N.V.; Supervision: O.K; S.V.; Validation: V.M., F.G.; Visualization: F.G.; Writing – original draft: O.K., V.M., N.V., S.V., F.G; Writing – review & editing: O.K., V.M., N.V., S.V., F.G.

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All the authors of this manuscript confirmed that the data supporting the findings of this study are presented in this article.

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The authors declare that generative AI was not used to assist in writing this manuscript.

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