Baltic J. Modern Computing, Vol. 13 (2025), No. 2, 436-452
https://doi.org/10.22364/bjmc.2025.13.2.08

Predictive Mathematical and Computer Model for Determining Harmful Effects of Dust Pollution on the Environment and Workers

Yevhenii LASHKO[1], Serhii SUKACH[1], Ivan LAKTIONOV[2],
Olha CHENCHEVA[1], Dmytro RIEZNIK[1], Olena KORTSOVA[3,4]

[1]Institute of Education and Science in Mechanical Engineering, Transport and Natural Sciences, Department of Civil and Labour Safety, Geodesy and Land Management, Kremenchuk Mykhailo Ostrohradskyi National University, 20 Universytetska str., Kremenchuk, 39600, Ukraine
[2]Faculty of Information Technologies, Department of Computer Systems Software, Dnipro University of Technology, 19 Dmytra Yavornytskoho av., Dnipro, 49005, Ukraine
[3]Institute of Education and Science in Mechanical Engineering, Transport and Natural Sciences, Department of Ecology and Biotechnologies, Kremenchuk Mykhailo Ostrohradskyi National University, 20 Universytetska str., Kremenchuk, 39600, Ukraine
[4]Promecologia Scientific Technological Centre, Ltd, 2/7 Likaria Bohaievskoho str., Kremenhcuk, 39600, Ukraine

elashko@kdu.edu.ua, ssukach@kdu.edu.ua,
Laktionov.I.S@nmu.one,ochencheva@kdu.edu.ua,
dreznik@kdu.edu.ua, lenakortsova@yahoo.com

ORCID 0000-0001-9691-4648, ORCID 0000-0002-6834-0197, ORCID 0000-0001-7857-6382,
ORCID 0000-0002-5691-7884, ORCID 0000-0003-1258-6136, ORCID 0000-0002-8101-322X

Abstract. The paper is devoted to mathematical modeling and computer simulation of the process of movement of dust particles in the working area of quarries and adjacent territories in order to protect workers of mining enterprises. The object of the research is a three-dimensional digital model of the relief of a quarry that is currently under development. The subject of the research is simulation the trajectory of dust particles and determining the zones of their maximum permissible concentration, taking into account the prevailing meteorological characteristics of the area. The scientific and practical value of the research results of this article lies in the fact that for the first time the regularities of aerodynamic processes occurring in the working area of quarries and adjacent territories, taking into account the exact shape of the contour of the quarry itself and the corresponding profile of its geological section, were determined by mathematical modeling and computer simulation methods.

Keywords: forecasting, simulation, emissions of harmful substances, atmospheric air, deposits, dust particles.

1. Introduction

In the modern mining industry, up to 80% of production is extracted by open pit mining. The creation of open pits causes changes in the microclimate, primary terrain and hydrography of the area. At the same time, open-pit mining is being improved by intensifying all industrial processes (from drilling and primary crushing, mainly through blasting, to loading and transporting rock mass), using more and more high-performance machines (drilling rigs, excavators, loaders), as well as rail, road and conveyor transport. In addition, current technologies related to the use of crushers, screens, etc. are being introduced in quarries during the development of rocks [Honcharevskyi et al., 2013].

This development of open-pit mining is accompanied by a sharp increase in the amount of emissions of various harmful substances into the atmosphere: dust, toxic gases, and other chemicals hazardous to human health, which causes various disorders in the animal and plant life. The intensity of dust and gas pollution in and around quarries depends on a number of natural, technological and technical factors. Their ratio determines the level of concentration of dust and other harmful substances in the atmosphere of open-pit mines. At the same time, the number of cases of exceeding the maximum permissible concentrations and creating hazardous situations is increasing.

The type of deposit to be developed, its geological and hydrogeological characteristics, shape and conditions of mineral occurrence, chemical composition and physical and mechanical properties of the mineral are determined by analyzing the mining and geological conditions of the deposit. The need for such an analysis is due to the fact that at the design stage and during operation, depending on geological and mining data, an efficient development technology and appropriate equipment are selected, classified into groups based on the intensity of the emission of harmful mixtures and dust during its operation. Based on the mineralogical composition of mining operations, dust content standards are set and preventive measures are developed to prevent the increased content of harmful mixtures and normalize the atmosphere in the quarry space and beyond.

For example, the most unfavorable process for the atmosphere of quarries is blasting, which dramatically worsens the composition of the atmosphere in terms of dust and gas criteria. The hazard of blasting is exacerbated by the fact that harmful mixtures are released from the extracted rock mass not only during the explosion, but also afterwards, during loading and transportation.

When assessing the impact of open pit mining on the atmosphere, it is also necessary to take into account the order of operations, the relative position and concentration of equipment in relation to the direction of air flows, the location and composition of rock mass along the contours of pits and openings, as well as the wind pattern and speed, climatic conditions of the area and the microclimate of pits. Taking into account the above, it is necessary to characterize the atmosphere of production spaces in order to properly select methods of intensifying natural and organizing artificial air exchange during open-pit mining.

Therefore, the task is to build a predictive mathematical and computer model of the spread of dust pollution in quarries during their planned activities. Modern methods of mathematical modeling and computer simulation make it possible to research the movement of multifractional particles and determine the stable patterns that arise in this process, as well as to analyze not only the parameters of individual particles, but also the overall parameters of aerodynamic systems.

This research considers mathematical modeling and computer simulation of the process of movement of dust particles in the working area of quarries and adjacent territories in order to protect workers of mining enterprises. The object of the research is a three-dimensional digital model of the relief of a quarry that is currently under development. The subject of the research is the simulation the trajectory of dust particles and the identification of the zones of their maximum permissible concentration, taking into account the prevailing meteorological characteristics of the area. The main tasks that arise during such simulation are obtaining profiles of concentrations of harmful substances, determining distances and dangerous wind speeds that correspond to the formation of maximum concentrations of pollutants from sources. The article contains a mathematical description of the determination of dust and gas emissions from massive (volley) explosions, the design of a three-dimensional parametric model of a quarry, and computer simulation of dust pollution.

The scientific and practical value of the research results of this article lies in the fact that for the first time the regularities of aerodynamic processes occurring in the working area of quarries and adjacent territories, taking into account the exact shape of the contour of the quarry itself and the corresponding profile of its geological section, were determined by mathematical modeling and computer simulation methods, which will make it possible to implement them at the national level both in the field of labor protection and in the field of environmental protection technologies.

2. Methods, tools and approaches to research

2.1. Generalized research approaches

The research of dust sources, its movement in the atmosphere, its impact on human health, and methods for simulation these processes covers a wide range of approaches considered in the modern scientific literature.

For example, (Liu et al. 2019) researched the impact of a dust removal system during tunnel construction using CFD simulation technology. This method allowed for a detailed analysis of the effectiveness of the dust removal system in the context of mechanized tunnel construction, which helped to reduce the level of dust pollution. Its advantage is the high accuracy of simulation the distribution of dust in real conditions, but this research requires significant computing resources, which limits its application on a full scale.

The authors (Xiu et al., 2020) used numerical simulation to research the character of dust pollution in coal mines and determine the optimal airflow parameters for dust control. The use of CFD methods for simulation emissions and ventilation allows for accurate pollution predictions, but this accuracy depends on the model settings and the realism of the input data. In addition, the method is highly dependent to changes in ventilation conditions and the mineralogical composition of the extracted material.

A research (Zhou et al., 2022) examined the dynamics of dust pollution in mines using the DPM-DEM model. This approach allows for a more accurate assessment of the movement of dust particles and their interaction with the air flow, which makes it possible to accurately identify areas of high pollution. However, the model has limitations during simulation complex ventilation conditions where a large number of turbulent flows occur, and requires large computing power for full implementation.

The literature review also includes researches that focus on other aspects of pollution, such as the use of more complex numerical models to assess the risks and effectiveness of dust emission reduction technologies.

In (Liaskoni et al. 2023), a highly detailed simulation of wind dust emissions in Europe was carried out using the WRF-Chem system. The method allowed to take into account the complex interactions between dust particles and the atmospheric condition, which ensures high accuracy of the forecast of PM_{10} and $PM_{2,5}$ concentrations. The main advantages of the approach are the spatial and temporal resolution and complexity of data processing, but the method is very resource-intensive and dependent to the quality of input parameters.

In another research (Tong et al., 2018), the Monte Carlo method was used to assess the health risk of workers at construction sites. The approach provides flexibility in simulation uncertainties, allowing assessing variations in dust exposure under different scenarios. However, the effectiveness of the method largely depends on the reliability of the input data and the number of iterations.

The authors (Askarova et al., 2021) have developed three-dimensional CFD models of solid fuel combustion processes to reduce harmful emissions. The advantage of the approach is the realistic consideration of heat and mass transfer and chemical reactions in the furnace. However, the results require careful calibration and validation, which increases the complexity of using such CFD models in practice.

Statistical methods, such as multivariate analysis of variation (MANOVA), have been used (Giancristofaro et al., 2015) to analyze regional differences in odor perception. Although statistical tests are an effective tool for assessing differences between groups, the results are dependent to subjective factors and data selectivity.

An important contribution to the research was made by researchers (Konglok et al., 2016) who used the fractional step method to numerically solve the problems of pollution spreading under different classes of atmospheric stability. The method provides increased computational stability and allows for variable meteorological conditions, although its effectiveness decreases in cases of highly turbulent flows.

The authors (Kumar et al., 2020) conducted multiphase CFD simulation and laboratory testing of the Vortecone device for air dust removal. The combination of numerical simulation and experimental data allowed for highly accurate results, but multiphase CFD calculations require significant computational resources.

In (Oyjinda et al., 2017), simplified numerical diffusion models were used to simulate pollution in the vicinity of industrial areas. The advantage of this approach is the speed of calculations and the ability to quickly adapt the model, but the simplification of physical processes limits the accuracy of predictions in complex conditions.

Thus, a review of the available literature shows that modern research actively uses both complex physical and chemical models (CFD, atmospheric models) and statistical and stochastic methods (Monte Carlo, MANOVA) to analyze dust pollution and its consequences. The choice of methodology largely depends on the objectives of the research: from predicting concentrations on a large scale to local risk assessment or optimization of engineering solutions.

The research of this article is a logical sequential continuation of our own theoretical and experimental researcher in the field of mathematical modeling and computer simulation of the aerodynamic process of movement and removal of dust particles in the working area, which are reflected in scientific publications (Chencheva et al., 2023; Lashko et al., 2024).

We improved the known dependencies of dust pollution dispersion, which for the first time take into account local meteorological characteristics, as well as particle size and quarry topography, which allowed creating a mathematical description for further computer simulation. A limitation of the research is that it does not take into account emission factors for different dust sources, such as drilling and crushing, which could provide more accurate and general predictions in the future.

It is also worth noting that calculating air pollution using the «EOL+» software version 5.3.8, which implements the Methodology for Calculating Air Concentrations of Harmful Substances Contained in the Emissions of GRD-86 Enterprises approved at the state level in Ukraine at (Order of the Ministry of Ecology and Natural Resources of Ukraine, 2021), does not provide correct results for volley emissions, taking into account the influence of terrain. At the same time, it is important to improve this methodology in order to bring it closer to European environmental requirements (Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast), 2024), which is relevant to the topic of the research.

2.2. Structural and algorithmic description of a computer-oriented model

The COMSOL Multiphysics® version 5.6 is designed for simulation three-dimensional fluid and gas flows in technical and natural objects, as well as visualizing these flows using computer graphics (CFD Modeling and Simulation. COMSOL Multiphysics, 2020). The simulation flows include stationary and unsteady, compressed, incompressible and uncompressed liquid and gas flows. The use of various turbulence models and an adaptive computational grid allows simulating complex fluid motions, including flows with strong swirling, combustion, and free-surface flows.

This software is based on the finite volume method of solving fluid dynamics equations and uses a rectangular adaptive mesh with local refinement. This technology allows importing geometry from CAD systems and exchanging information with finite element analysis systems. The use of this technology allows solving the problem of automatic mesh generation – to generate a mesh, it is enough to set only a few parameters, after which the mesh is automatically generated for the design area with geometry of any degree of complexity.

2.3. Mathematical description of the system under study

The most powerful source of instantaneous dust emission and formation of dust and gas clouds in the atmosphere of quarries is massive (volley) explosions (Fig. 1).

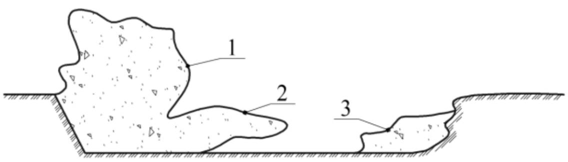

Figure 1. Scheme of dust and gas clouds formation during massive explosions in a quarry: 1 – primary cloud, 2 – secondary cloud, 3 – cloud formed due to shock wave and seismic oscillations

The mineralogical composition of dust is usually close to the mineralogical composition of blasted rocks.

The chemical composition of dust is also close to that of rocks, but some particles may be introduced from other sources. Poisonous dust contains lead, mercury, chromium, manganese and other toxic elements. Non-poisonous dust includes quartz dust (dangerous due to silicosis) and coal dust.

The dispersion composition of dust is determined by natural and technical and technological factors and differs in the size of dust particles that accumulate in the atmosphere of open pit mining. The shape of the dust particles determines the rate of their deposition and depends on the method of rock destruction. The true integrity of a single dust particle is equal to the original one.

The height of rise of dust and gas aerosols is calculated by the formula:

$$h_0 = \frac{\Delta t}{(\gamma_a - \gamma) - t_c / \left[g(cb)^2 R_1 - 4{,}3\right]}, \tag{1}$$

where Δt – the temperature difference of the ambient explosion products at a height of 10–15 m from the surface to be blown up, C^o; γ – the vertical temperature gradient, C^o/100 m, m; g – the free fall acceleration, m/s$^{(2)}$; c, b – the dimensional experimental constants (c=11,5; b=0,2); R_1 is the primary radius of the dust and gas cloud, m.

The primary radius of a dust and gas cloud is calculated by the formula:

$$R_1 = \sqrt[3]{\frac{3V}{4\pi}}, \tag{2}$$

where V – the volume of gases released during the explosion of an explosive, m^3.

The volume of gases released during the explosion of an explosive is calculated by the formula:

$$V = mAV_0, \tag{3}$$

where m=0,6÷0,75 – a coefficient that takes into account the actual amount of gases that enter the atmosphere (some gases remain in the exploded rock mass), 1/kg; V_0 – the volume of gases formed during decomposition; 1 kg of explosive (V_0=0,6÷1,1) m^3; A – the mass of explosive, kg.

A secondary dust and gas cloud occurs after blasting in the dust and gas throwing zone at the foot of the ledge within the radius of rock fragments:

$$R_2 = k\sqrt{A} / r\sqrt{p_i} / n\left(S / d^2\right), \tag{4}$$

where k – a coefficient that takes into account the type and design of the explosive charge; p – the density of the rock to be blown up, kg/m$^{(3)}$; r – the advancement of the face, m; S – the cross-sectional area of the face to be blown up, m^2; D – the diameter of the well, m.

The above mathematical dependencies were used as the basis for computer simulation of dust pollution spread. The initial data for the calculation are grouped in Table 1. The components of these data include the characteristics of the source of pollutant emissions, namely blasting, multifractional particles models in the range from 1,4 to 50 μm and meteorological characteristics that determine the conditions for dispersion of pollutants in the air, created by directional airflow computer model.

Table 1: Initial data of preprocessing

Parameters of the dust and air mixture	
Volume, m^3/s	0,01
Emission capacity determined	
Calculation, g/s	470
Calculation, tones per year	5,64
Average annual wind rose, %.	
N	10,8
NE	8,5
S	10,1
SE	11,9
S	12,9
SW	14,2
W	19,9
NW	11,7
Wind speed (based on average long-term data), the recurrence of exceeding which is 5%, m/s	9–10

Additionally, the topography of the open pit and surrounding areas was taken into account, as shown in Figure 2.

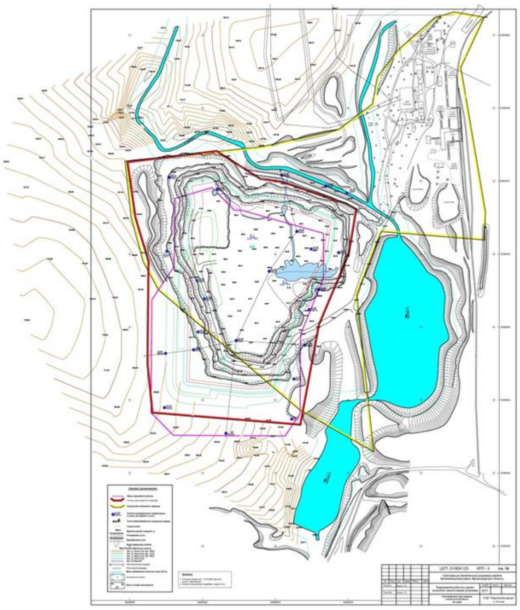

Figure 2. Surface plan from the field development and reclamation project

On this topographic plan, the deposit is marked in purple, the boundaries of the license area are marked in red, and the boundaries of the land allotment are marked in yellow. All of these data were used to build three-dimensional parametric models as a calculation space for computer simulation of the movement of dust particles in it.

3. Research results

3.1. Computer model

A three-dimensional model of the studied quarry as an initial structural element is shown in section in Fig. 3. It was built using SolidWorks computer-aided design software.

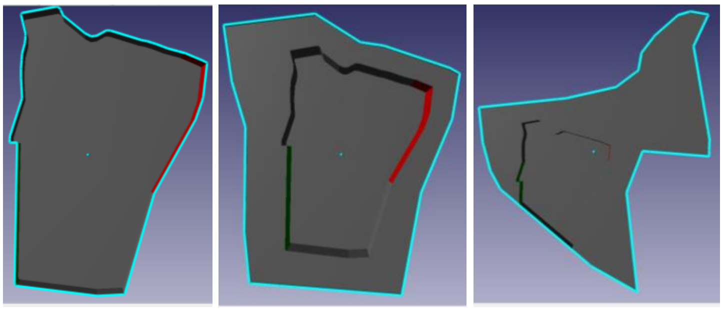

Figure 3. Three-dimensional models of the studied quarry in the section with indication of boundary restrictions

To verify the theoretical positions, computer simulation was carried out using COMSOL Multiphysics® version 5.6, the results of which are shown in Figs. 4–6. The results show the movement of particles directly in the open pit and adjacent areas in the form of vectors, where red indicates maximum values and blue indicates minimum or infinitesimal values.

The main purpose of the prediction model is to assess the possible environmental response to the direct or indirect impact of planned activities, and to address the challenges of future rational use of natural resources in relation to expected environmental conditions. At the same time, it is also important to protect employees at workplaces from dust pollution that can lead to respiratory diseases.

Management of production processes includes current (operational) and perspective (long-term) aspects. In this case, strategic management is used for operational management and forecasting of the mining enterprise, i.e., identification of prospects and development of fundamental solutions to prevent possible negative impact on environmental components and health of employees.

For long-term forecasting, computational (analytical, approximation) models based on the solution of the turbulent diffusion equation are most often used. These are plume models, finite-difference models, etc., which form the basis of the Methodology for Calculating Air Concentrations of Harmful Substances Contained in Industrial Emissions (GRD-86) (Order of the Ministry of Ecology and Natural Resources of Ukraine, 2021).

The practical effectiveness of short-term air pollution forecasts is clearly demonstrated when the sources are known and measures can be taken to reduce emissions during periods of unfavorable weather conditions.

For operational forecasting, statistical models of linear and nonlinear regression are widely used. For operational forecasting of air pollution during emergency salvo emissions, it is necessary to use computational (analytical) models – «tangle» models – which are used to predict the spread of impurities from instantaneous point sources.

The development of forecasting methods begins with the identification of periods with significant air pollution. Then, correlations are established between the degrees of air pollution observed during these periods and some meteorological variables or a certain combination of them, which are considered as predictors.

The long-term forecasting of environmental pollution from quarry emission sources was carried out using the method of software (electronic) calculation and simulation, which is based on the use of software products approved for use at the state level, which, in turn, are based on the algorithms of existing model calculation approaches. In particular, during the environmental impact assessment, the dispersion was calculated using the «EOL+» software package.

The forecasting results in the production of profiles of concentrations of harmful substances, determination of distances and dangerous wind speeds corresponding to the formation of maximum concentrations of pollutants from enterprise sources.

The most interesting is the forecasting of air pollution during salvo emissions. In these cases, the pollution forecast is performed using the expected change in emissions, taking into account specific meteorological conditions (predictors).

The choice of predictors is usually based on general physical ideas about the possible causes of changes in impurity concentrations, such as changes in wind direction or speed, atmospheric stability, leaching or transformation of impurities, etc.

In addition to the previously mathematically calculated data, the topographic plan of the existing quarry surface was used as the initial data for the long-term forecast, and meteorological characteristics that determine the conditions for dispersing pollutants in the air (average annual wind rose) were used as predictors.

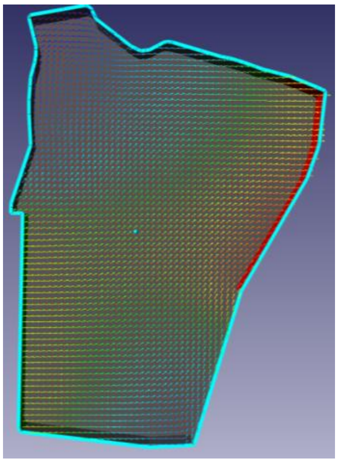

Figure 4. Velocity of particles in the air flow, displayed in vector form in the range from 0 to 10 m/s, directly in the deposit

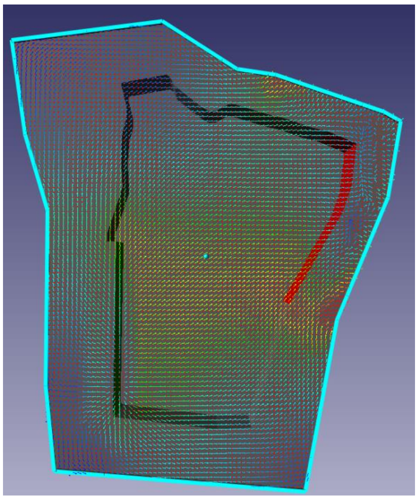

Figure 5. Velocity of particles in the air flow, displayed in vector form in the range from 0 to 10 m/s, within the license area

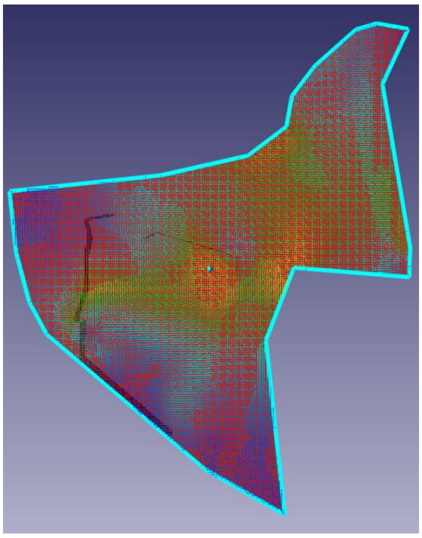

Figure 6. Velocity of particles in the air flow, displayed in vector form in the range from 0 to 10 m/s, within the land allotment

By means listing of software air flow velocities exceeding the critical ones, which affect the ability to blow dust from work space, were determined (Fig. 7). At the same time, by means formula (3) blasting operations accounted during predicting the overall balance of harmful substances in the quarry space (Fig. 8).

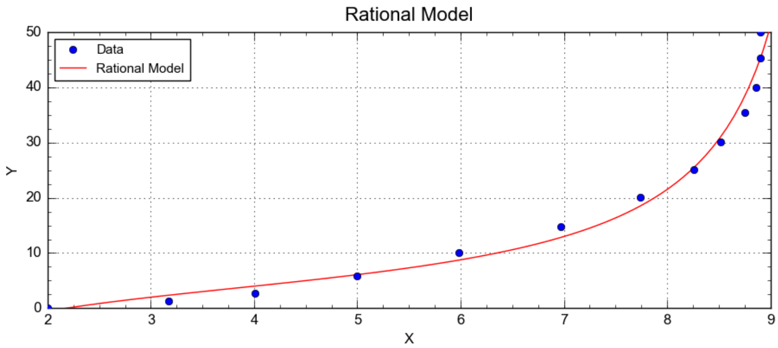

Figure 7. Dependence of specific dust blowing *c*, m/cm^2 (*y*-axis) on air flow velocity *v*, m/s (*x*-axis)

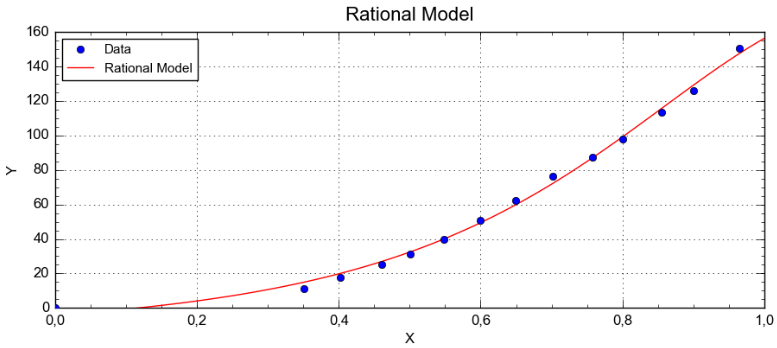

Figure 8. Dependence of the amount of dust generated during the explosion g_n, g/m^3 (*y*-axis) on the specific consumption of explosive A, kg/m^3 (*x*-axis)

As a result of computer simulation, it was established that the movement of dust particles according to the prevailing meteorological characteristics is directed to the territory of economic structures while maintaining its intensity within the land allotment. The nature of the distribution of dust movement vectors is somewhat different from the wind rose and indicates a significant impact on its annual distribution not only of the transforming wind directions, but also of its speed and the shape of the quarry contour. Therefore, it can be concluded that workers are exposed to dust from the quarry during its development, especially during volley emissions from blasting operations.

3.2. Experimental validation of the model

Considering that the concentration of harmful particles in the air changes over time, it is necessary to additionally perform several iterations of calculations, namely at the moment of the explosion flare and the subsequent phase of rarefaction. It is during the rarefaction phase that dust particles begin to settle, being directly influenced by the direction and speed of air movement.

One of the most common measures during the construction and operation of industrial facilities in the quarry area is the wind rose, which reflects the frequency of winds blowing from different directions. However, this is often not enough to assess the direction of distribution and concentration of industrial emissions, as the concentration of harmful substances in the dust of a gas cloud or a stream plume is significantly affected by wind speed and atmospheric turbulence. Accordingly, the quarry space is identified as a linear source, accumulated along its longer or shorter axis according to the dominant wind directions. For intermediate directions, the source is projected on a long axis directed normal to the wind direction. The corresponding parameter is used to assess the impact of emissions:

$$K = \sum_{i=1}^{m} C_x p_i, \tag{5}$$

where C_x – the concentration of hazardous mixtures along the plume axis at a distance x at a given wind speed and direction, g/m^3; p – the probability or frequency of wind repetition of a given wind speed and direction. The calculation is carried out in different directions, based on the results of which a plan of the zone adjacent to the quarry is drawn up with perimeter isolines K.

The concentration of the mixtures at different distances from the pit contour as a linear source can be determined by the Setton formula:

$$C_x = \frac{K_0 M}{u} e^{\frac{y^2}{c^2 x^{2-n}}}, \tag{6}$$

where K_0 – the specific concentration equal to the concentration of harmful substances from a pollution source of 1 g/s at a wind speed of 1 m/s:

$$K_0 = \frac{2000}{\frac{2-n}{3} - \frac{h^2}{c^2 x^{2-n}}}, \tag{7}$$

where c – the scattering coefficient (c=0,05 at n=0); n – a coefficient that depends on the temperature gradient of the atmosphere, surface roughness and the surface to be washed (n=0 under average meteorological conditions); x – the distance along the calculated wind direction from the source to the line perpendicular to the wind direction and passing through the point of determining the concentration of mixtures, m; h – the conditional height of the linear source emission, m; M – the intensity of 1 m of the source length, g/s; u – the calculated wind speed, m/s; y_2 – the normal distance from the calculated point to the line passing through the center of the linear source perpendicular to the wind direction.

According to the formula:

$$e - \frac{y^y}{c^2 x^{2-n}}, \tag{8}$$

calculate the decrease in concentration along the width (at n=0 it is equal to $e - \frac{y^y}{c^2 x^{2-n}}$).

Therefore, the next step is to use this methodology in an operating quarry, where the calculations of the concentration of harmful substances in the explosion products can be used to reflect the expected distribution of dust particle movement vectors in the quarry itself and adjacent areas.

The above mathematical dependencies were used as the basis for computer simulation of the determination of dust concentrations (Fig. 9, 10).

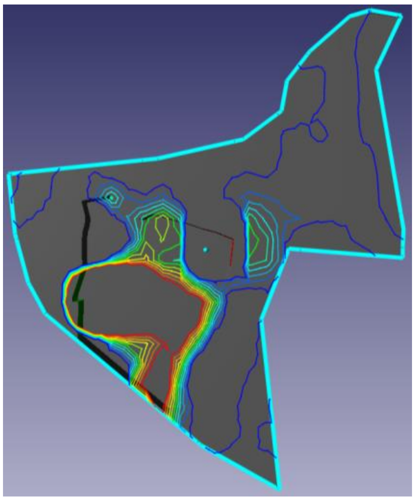

Figure 9. Concentration of particles in the air flow at the moment of the explosion flare, displayed in isolines form in the range from 0 to 5 mg/m^3, within the land allotment

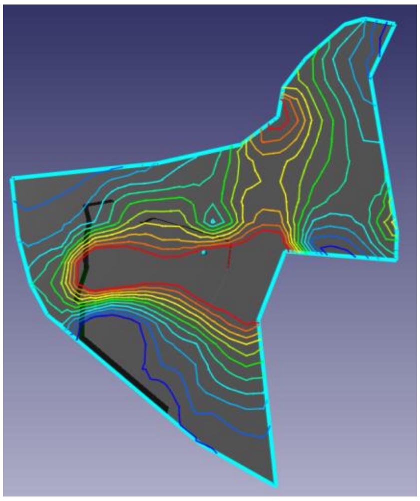

Figure 10. Concentration of particles in the air flow at the phase of rarefaction, displayed in isolines form in the range from 0 to 5 mg/m^3, within the land allotment

The results were validated by conducting field studies directly on the site (Table 2).

Table 2: Change in the dispersion composition of settling dust, depending on the distance from the explosion site

Distance from the explosion site, m	Dispersion composition, % by dust fractions, μm				
	1,4	1,4-4	4-15	15-50	50
40	63,09	23,46	9,03	1,12	1,30
60	68,79	23,13	6,76	0,92	0,40
90	65,74	22,69	9,89	1,66	0,02
120	70,21	19,90	8,62	1,24	0,03
200	74,31	17,52	7,33	0,80	0,04
300	75,11	19,50	4,80	0,57	0,02
600	79,87	15,77	3,70	0,50	0,16

Comparing the results of computer simulation and field measurement data, it is worth noting their convergence. The maximum concentration of different fractional dust particles is observed at the time of formation of the primary dust-gas cloud (explosion flare) directly in the deposit space. Further dispersion of dust particles is determined by the direction and speed of movement of air masses at the walls of the quarry and adjacent territories. Dust particles of larger fractions settle faster, and smaller ones continue their movement over long distances, where can be workers.

4. Discussion and suggestions for future research

The generalized results of the research are important in several aspects, which should be highlighted. Firstly, the mathematical description of aerodynamic processes occurring in the quarry and adjacent areas made it possible to establish quantitative indicators of key parameters of the entire system functioning, taking into account the shape of the quarry contour and the profile of the geological section. Secondly, computer simulation allowed us to determine the speed and trajectories of dust particles and set the zones of their maximum permissible concentration, taking into account meteorological characteristics. It is worth noting that these data are fully consistent with those obtained as a result of field studies at the facility, which indicates the sufficient efficiency of the proposed predictive model. Thirdly, the maximum concentration of multifractional dust particles is observed at the time of formation of the primary dust-gas cloud and further dispersion of dust particles is determined by the direction and speed of movement of air masses at the walls of the quarry and adjacent territories. The presented research complements the known data on the movement of particles in a two-phase flow in terms of a better understanding of the aerodynamics of the process. Thus, modern software tools allow obtaining results that demonstrate full agreement with field measurements, making it possible to implement them at the national level in the field of labor protection and environmental protection technologies.

Prospects for further research should be related to the assessment of the impact of all harmful substances entering the recirculation zone of the quarry from internal and external sources, including loading and unloading and transport operations, which will allow deriving the equation of their overall balance. Prospects for further research also include the use of air curtains in working premises, which will prevent air from entering the premises from the outside, while creating an air and dust barrier to protect workers (Naserzadeh et al., 2017).

5. Conclusions.

As a result of the comprehensive research, the following can be noted:

1) computer simulation of dust particle movement in the working area of quarries and adjacent territories, based on the obtained mathematical dependencies, showed that the maximum concentration of different fractional dust particles (more than 5 mg/m^3) is observed at the time of formation of the primary dust-gas cloud directly in the deposit space. Further dispersion of dust particles is determined by the direction and speed of movement of air masses at the walls of the quarry and adjacent territories. Dust particles of larger fractions settle faster and smaller ones continue their movement over long distances;

2) the most intense release of multifractional dust from the primary cloud is observed at a distance of 40–600 m from the explosion site;

3) the distribution of dust particle motion vectors differs from the wind rose and indicates a significant impact on its annual distribution not only of the transforming wind directions, but also of its speed and the shape of the quarry contour;

4) in terms of a better understanding of the aerodynamics of the process, air flow rates that exceed the critical ones (from 2 m/s) that affect the ability to blow dust from work surfaces were determined;

5) during predicting the overall balance of harmful substances in the quarry space, it is necessary to take into account the consumption of explosives.

All of the above leads to the general conclusion that the results of the predictive computer model can be effectively applied, which can be recommended for implementation in the mining sector in order to prevent the negative impact of pollutant emissions on environmental components and the health of workers.

6. Acknowledgments

The research was carried out under the contract for research work commissioned by Promecologia Scientific Technological Centre, Ltd dated 04.12.2024 No. 597/24-CSGL, which was used at the national level by the Ministry of Ecology and Natural Resources of Ukraine for public discussion of the quarry development project to establish compliance with the requirements for environmental protection and employees of the enterprise. Some of the above research results are publicly available on the Internet in accordance with the Law of Ukraine «On Access to Public Information» dated 08.10.2023 No. 2939-VI.

References

Askarova, A., Bolegenova, S., Maximov, V., Bolegenova, S., Askarov, N., Nugymanova, A. (2021). Computer Technologies of 3D Modeling by Combustion Processes to Create Effective Methods of Burning Solid Fuel and Reduce Harmful Dust and Gas Emissions into the Atmosphere. *Energies*, **14**(5), 1236. https://doi.org/10.3390/en14051236.

Chencheva, O., Lashko, Ye., Rieznik, D., Cheberyachko, Yu., Petrenko, I. (2023). Research of the aerodynamic process of carbon dust removal from the working zone. *Municipal Economy of Cities*, **1**(175), 208–220. https://doi.org/10.33042/2522-1809-2023-1-175-208-220.

CFD Modeling and Simulation. COMSOL Multiphysics. URL : https://www.comsol.com/cfd-module.

Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast). European Parliament. URL : https://eur-lex.europa.eu/eli/dir/2024/2881/oj/eng.

Giancristofaro, R.A., Bonnini, S., Corain, L., Vidotto, D. (2015) Environmental odor perception: testing regional differences on heterogeneity with application to odor perceptions in the area of Este (Italy). *Environmetrics*, 26, 418–430. https://doi.org/10.1002/env.2341.

Honcharevskyi, K., Pikovets, V., Mushtaiev, O. (2013). Methodology for calculation of pollutant emissions into the atmosphere during mining (open method). *Ecological Sciences*, **2**(4), 68–93.

Konglok, S. A. Pochai, N. (2016). Numerical computations of three-dimensional air-quality model with variations on atmospheric stability classes and wind velocities using fractional step method. *IAENG International Journal of Applied Mathematics*, **46**(1), 112–120.

Kumar, A., Schafrik, S. (2020). Multiphase CFD modeling and laboratory testing of a Vortecone for mining and industrial dust scrubbing applications. *Process Safety and Environmental Protection*, 144, 330–336. https://doi.org/10.1016/j.psep.2020.07.046.

Lashko, Y., Chencheva, O., Laktionov, I., Rieznik, D., Halchenko, N. (2024). Mathematical and Computer Simulation of the Process of Movement of Respirable Dust Particles in the Working Area. *Baltic Journal of Modern Computing*, **12**(3), 270–285. https://doi.org/10.22364/bjmc.2024.12.3.04.

Liaskoni, M., Peter, H., Bartik, L., Perez, A., Karlický, J., Vlček, O. (2023). Modelling the European wind-blown dust emissions and their impact on particulate matter (PM) concentrations. *Atmospheric Chemistry and Physics*, 23, 3629–3654. https://doi.org/10.5194/acp-23-3629-2023.

Liu, W., Huang, X., Chen, H., Han, L. (2022). Analyzed and Simulated Prediction of Emission Characteristics of Construction Dust Particles under Multiple Pollution Sources. *Computational Intelligence and Neuroscience*, 7349001. https://doi.org/10.1155/2022/7349001.

Liu, Q., Nie, W., Hua, Y., Jia, L., Li, C., Ma, H., Wei, C., Liu, C., Zhou, W., Peng, H. (2019). A study on the dust control effect of the dust extraction system in TBM construction tunnels based on CFD computer simulation technology. *Advanced Powder Technology*, **30**(10), 2059–2075. https://doi.org/10.1016/j.apt.2019.06.019.

Naserzadeh, Z., Atabi, F., Moattar, F., Nejad, N. M. (2017). Effect of barriers on the status of atmospheric pollution by mathematical modeling. *Bioscience Biotechnology Research Communications*, **10**(1), 192–204. https://doi.org/10.21786/bbrc/10.1/29.

On Approval of the Procedure for Determining the Values of Background Concentrations of Pollutants in the Atmospheric Air, Order of the Ministry of Ecology and Natural Resources of Ukraine No. 286 (2021) (Ukraine). https://zakon.rada.gov.ua/laws/show/z0700-01#Text.

Oyjinda, P., Pochai, N. (2017). Numerical Simulation to Air Pollution Emission Control near an Industrial Zone. *Advances in Mathematical Physics*, 1–7. https://doi.org/10.1155/2017/5287132.

Tong, R., Cheng, M., Zhang, L., Liu, M., Xiaoyi, Y., Li, X., Yin, W. (2018). The construction dust-induced occupational health risk using Monte-Carlo simulation. *Journal of Cleaner Production*. 184. https://doi.org/10.1016/j.jclepro.2018.02.286.

Xiu, Z., Nie, W., Yan, J., Chen, D., Cai, P., Liu, Q., Du, T., Yang, B. (2020). Numerical simulation study on dust pollution characteristics and optimal dust control air flow rates during coal mine production. *Journal of Cleaner Production*, 248, 119197. https://doi.org/10.1016/j.jclepro.2019.119197.

Zhou, G., Liu, Y., Kong, Y., Hu, Y., Song, R., Tian, Y., Jia, X., Sun, B. (2022). Numerical analysis of dust pollution evolution law caused by ascensional/descensional ventilation in fully mechanized coal mining face based on DPM-DEM model. *Journal of Environmental Chemical Engineering*, **10**(3). https://doi.org/10.1016/j.jece.2022.107732.

Received January 28, 2025, revised April 27, 2025, accepted June 4, 2025