Information systems modeling

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EVALUATION OF THE AEROLOGICAL CONDITION DURING OPEN-PIT MINING OPERATIONS BASED ON THREE-DIMENSIONAL MODELS OF QUARRIES

Abstract. The relevance lies in the need to improve the existing production system for monitoring and forecasting mining conditions and to increase industrial safety during blasting operations and intensive operation of mining equipment. In the context of production growth, which involves an increase in production volumes and the size of the open pit, changes in the surrounding landscape, in particular, due to storage and the subsequent transition to mining from the lower horizons of the open pit, building a predictive model of the nature of air currents and the composition of the atmosphere is a prerequisite for planning mining operations. **The purpose of the research** is the mathematical and computer simulation of the process of movement of particles of different fractions of dust and gas clouds in the air of the surface layers of quarries and adjacent working areas of mining enterprises for further development and implementation of individual and collective protection systems for workers. **Results of the research**: The possibility of using three-dimensional computer simulation to assess and predict the state of the atmosphere in quarries in order to obtain visual and quantitative information on the distribution of air flows throughout the modeled space, including the surface layers of the quarry and the surrounding area, under certain meteorological conditions, was proved. The known dependencies of dust pollution dispersion were improved to take into account the particle size and the quarry topography for the first time, which allowed us to create a mathematical basis for further computer simulation. The obtained values of dust intensity in the lower part of the wind speed range are close to the "maximum specific dust blowing" indicator, which is used by specialists of design organizations when developing the documentation necessary to establish the absence of excessive impact on both environmental components and the health of workers. **Conclusions:** prospects for further research should include model accuracy, emission factors, and data integration.

Keywords: mathematical and computer simulation; dust pollution; aerology; careers.

Introduction

At the current stage of development of knowledge-intensive information technologies, it is increasingly possible to conduct research on physical processes that occur in various technological cycles and the natural environment, the state of which to some extent determines the conditions for their implementation [1, 2]. The relevance of the study lies in the need to improve the existing production system for monitoring and forecasting the conditions of mineral extraction and to improve industrial safety during blasting operations and intensive operation of mining equipment. In the context of production growth, which involves an increase in volumes production and the size of the open pit, changes in the surrounding landscape, in particular, due to storage and the subsequent transition to mining from the lower horizons of the open pit, building a predictive model of the nature of air currents and the composition of the atmosphere is a prerequisite for planning mining operations. Creating such a prognostic model involves solving a number of tasks: creating a virtual geometric image of the quarry itself based on the current geodetic survey database; setting the calculation problem in unambiguous conditions corresponding to the average annual values of meteorological observations; taking into account the impact of the surrounding area on the distribution of air flows inside the quarry.

Analysis of research and publications. Mathematical and computer simulation is an important tool for assessing and managing dust pollution in quarries. It allows us to determine the dynamics of dust dispersion and develop effective strategies to reduce its impact on the environment and workers' health. Recent studies have considered various approaches to modeling and assessing dust pollution, which have both some advantages and some disadvantages.

For example, the computer model presented in [3] has a time and space limitation, which significantly complicates the establishment of the correspondence of the data obtained in this way to the results of field measurements.

The approach proposed by the authors of [4] is based on simplified mathematical equations that do not take into account all the factors of influence, in particular, dust fractionation.

Another of these approaches is the parameterization of dust emissions from quarries and waste heaps, based on field measurement results and mathematical simulation [5]. This allows us to accurately identify emission sources and assess their impact on local pollution levels. At the same time, the limitation of this approach is the failure to take into account meteorological characteristics that significantly affect the spread of dust pollution.

Another study uses an advanced dust dispersion model to predict dust deposition from surface quarries [6]. This model takes into account the variability of wind direction and atmospheric stability, which improves the accuracy of predictions. However, insufficient attention has been paid to the topography of the quarry, which significantly affects the dispersion of dust particles by changing the direction and speed of the wind in the near-surface layers of the atmosphere.

Numerical simulation using computational fluid dynamics (CFD) allows us to determine the distribution of dust in quarries under different atmospheric conditions [7]. This includes simulation the movement of dust particles and their deposition depending on the wind direction and the location of the explosion. A continuation of the development of the approaches of this study is the possibility of displaying the expected distribution of dust particle motion vectors in the quarry itself and adjacent areas.

Therefore, the calculation of such problems in the steady-state mode using the standard (k-ε) turbulence is a complex process that requires taking into account many factors, such as emission sources, atmospheric conditions and geometry of the quarry.

The goal of the research is mathematical and computer simulation of the process of movement of particles of different fractional dust in the air of the surface layers of quarries and adjacent working areas during open pit mining on the basis of three-dimensional models of quarries. To achieve this goal, the following tasks need to be completed:

1. To establish the possibility of using three-dimensional computer simulation to assess and predict the state of the atmosphere inside quarries in order to obtain visual and quantitative information on the distribution of air flows throughout the modeled space, including the surface layers of the quarry and the surrounding area.

2. To determine the local meteorological conditions that affect dust dispersion, as high wind speeds can increase dust dispersion, while inversion can trap dust on the surface.

3. To modify known models of dust dispersion to take into account particle size and quarry topography, as smaller dust particles disperse more easily in the atmosphere, which can increase their concentration in the air.

Presentation of the main material

To assess dust pollution of territories based on the dispersion of dust particles in the atmosphere, the scattering formula is used Seton, which takes into account the particle deposition rate, meteorological conditions and the source of dust emission:

$$C = \frac{E}{\pi VHL}, \tag{1}$$

where C – the concentration of dust in the air (mg/m³); E – the intensity of dust emission (g/s); V – the average wind speed (m/s); H – the height of the emission source (m); L – the characteristic size of the dispersion zone (m).

This formula provides an approximate value of dust concentration in an open area and takes into account uniform dispersion without complex aerodynamic effects (e.g. turbulence). It is often used in mining and environmental monitoring in an extended form of recording:

$$C = \frac{E}{\pi VHL} \cdot \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{(z-H)^2}{2\sigma_z^2} \right), \tag{2}$$

where x, y, z – the coordinates of the point where the concentration is determined; σ_x, σ_y, σ_z – dispersion parameters that take into account the dispersion of pollutants in different directions.

The fractional composition of dust has a significant impact on its dispersion in the atmosphere, as particles of different sizes have different settling velocities and aerodynamic properties. To account for fractionation, the formula Seton can be modified as follows:

$$C = \sum_{n=1}^{n} \frac{E_i}{\pi VHL} \cdot \exp\left(V_{s_i} z / V\right) \times \\ \times \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{(z-H)^2}{2\sigma_z^2} \right), \tag{3}$$

where E_i – the dust emission rate for a particular i-fraction (g/s); V_{si} – the settling velocity of particles of a given fraction (m/s), determined by Stokes' law:

$$V_{s_i} = \frac{g d_i^2 (\rho_d - \rho_a)}{18\mu}, \tag{4}$$

where d_i – the diameter of the particle *of* the i-fraction (m); ρ_d – the density of dust particles (kg/m³); ρ_a – the density of air (kg/m³); μ – the dynamic viscosity of air (Pa·s); g – the acceleration of free fall (m/s²).

Summation by fraction therefore allows the contribution of each dust fraction to the total concentration to be taken into account. Settling factor $exp(-V_{si}z/V)$ reflects the effect of gravitational settling of particles, which depends on their size. Larger particles settle faster, while fine dust remains in the air longer. Particle dispersion is simulated by Gaussian distributions, as in the classical formula [8].

This modification makes it possible to calculate the concentration of fine dust (PM_{10}), $PM_{2.5}$) separately from coarse particles, which is important for determining the effectiveness of dust collection systems and assessing health risks for workers [9].

The topography of the quarry affects dust dispersion by changing the wind direction and speed, creating stagnant air zones and local turbulence.

To take these factors into account, the formula Seton can be supplemented with a terrain factor and wind speed variation depending on the height and depth of the pit:

$$C = \sum_{n=1}^{n} \frac{E_i}{\pi V_{eff} HL} \cdot \exp\left(V_{s_i} z / V_{eff}\right) \cdot K_{ter} \times \\ \times \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{(z-H)^2}{2\sigma_z^2} \right), \tag{5}$$

where V_{eff} – the effective wind speed taking into account the terrain, defined as:

$$V_{eff} = V_o \cdot (1 - h/H_w)^{\beta}, \tag{6}$$

where V_0 – the wind speed over the open pit (m/s); h – the depth of the open pit (m); H_w – the height of the open pit walls (m); β – an empirical coefficient (usually 0,3–0,5; depending on the steepness of the slopes).

K_{ter} – a terrain coefficient that takes into account local terrain features (turbulence, depressions, swirls):

$$K_{ter} = 1 + \left(h/H_w\right) \cdot \alpha, \qquad (7)$$

where α – an empirical coefficient (≈ 0,1–0,5; depending on the shape of the quarry and its impact on air circulation).

This modification takes into account a decrease in wind speed in the quarry through the walls (V_{eff}), increased local turbulence due to uneven terrain (K_{ter}), and particle deposition taking into account changed wind conditions *($exp(-V_{siz}/V_{eff})$)*.

This modification is suitable for assessing dust pollution in quarries and allows predicting dust accumulation in stagnant areas and determining the effectiveness of dust protection measures and equipment. The initial data preprocessing are grouped in Table 1.

The components of this data include the characteristics of the source of pollutant emissions, namely blasting, and meteorological characteristics, which determine the conditions for the of pollutants in the air dispersion [10]. Additionally, the topography of the open pit and surrounding areas was taken into account, as shown in Fig. 1, 2.

Table 1 – **Initial preprocessing data**

Parameters of the dust and air mixture	
Volume, m^3/s	0,294
Speed, m/s	1,5
Temperature, ºC	29
Emission capacity determined	
Calculation, g/s	500
Calculation, tonnes per year	6
Average annual wind rose, %.	
North	10,8
North-East	8,5
East	10,1
South-East	11,9
South	12,9
South-West	14,2
West	19,9
South-West	11,7
Wind speed (based on average long-term data), the recurrence of exceeding which is 5%, m/s	9–10

Thus, updated images were used Sentinel-2 with the subsequent overlay satellite of mining on the mining horizon contours (red) and land allotment (yellow). At the same time, geological sections up to the mining boundary were drawn with the corresponding heights and the rock outcrop and mineral layers in the form of various types of andesite.

Fig. 1. Topographical plan of the project for the development and reclamation of the Korolivske andesite deposit in Berehove district, Zakarpattia region

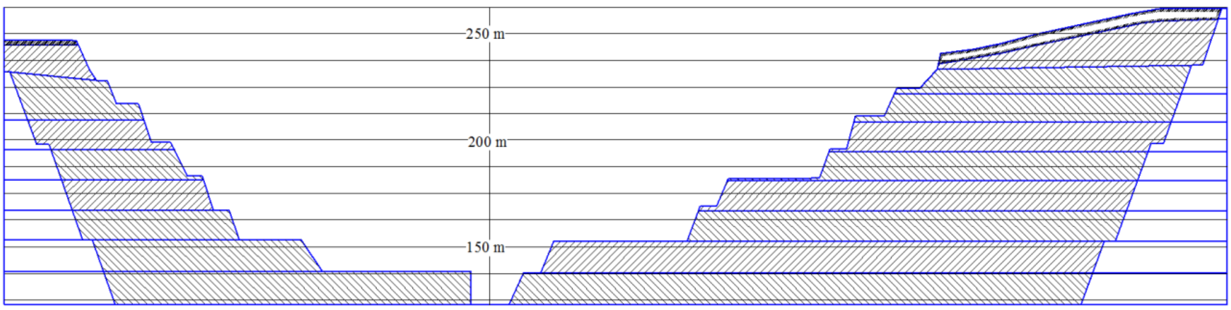

Fig. 2. Geological sections of the project for the development and reclamation of the Korolivske andesite deposit in Berehove district, Zakarpattia region.

In Ukraine, the OND-86 methodology is used to calculate local air pollution from industrial emissions, which is reduced to a sequence of analytical expressions obtained by approximating the difference solution of the turbulent diffusion equation [11]. The OND-86 methodology allows calculating the maximum possible distribution of emission concentrations under moderately unstable atmospheric conditions and averaged over a 20–30 minute interval, but does not take into account such factors as the stability class of the atmosphere and the roughness of the underlying surface. The methodology is applicable to calculate impurity concentrations at a distance of no more than 100 km from the source.

The results of this research were presented during a public discussion of the quarry development project at the national level by the Ministry of Ecology and Natural Resources of Ukraine to improve the OND-86 methodology and bring it closer to European environmental requirements [12].

The main purpose of assessing the aerological situation during open pit mining operations based on three-dimensional models of pits is to study the nature of air flow distribution on the surface and in the pit space, taking into account the actual terrain and the scale of the pit. This study allows us to identify the impact of blasting operations and quarry side zones on the formation of recirculation zones, eddy currents and the degree of airflow attenuation in different areas of the quarry, depending on the wind speed at the surface.

To verify the theoretical provisions of the spatial model, computer simulation was carried out using COMSOL Multiphysics software based on the numerical solution of the well-known Navier-Stokes equations for incompressible fluid. A number of studies have been analyzed, which made it possible to obtain two-dimensional information on the nature of air currents at the upper and deep horizons of the quarry, to identify patterns of air mass distribution inside the quarry, taking into account the climatic features of the territory [13, 14]. However, two-dimensional simulation provides information only in one of the quarry sections and does not reflect the influence of both the surface relief and the quarry side zones on the nature of the air flow distribution in the quarry space [15, 16].

The computer simulation results show the movement of particles directly in the quarry and adjacent areas in the form of vectors, where red indicates the maximum values and blue indicates the minimum or infinitesimal values. The graphical display of the results is shown in Fig. 3 and 4.

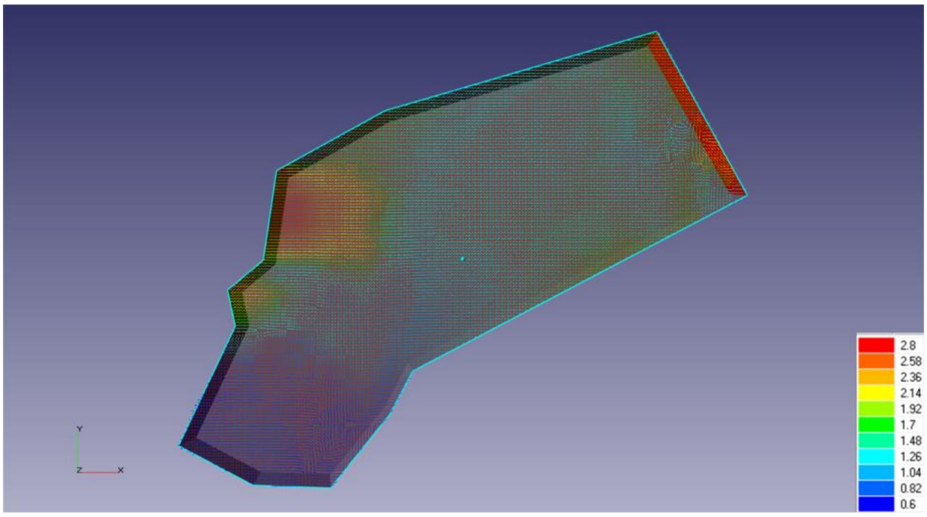

Fig. 3. Vector representation of dust particle velocity (m/s) within the center line of the mining contour

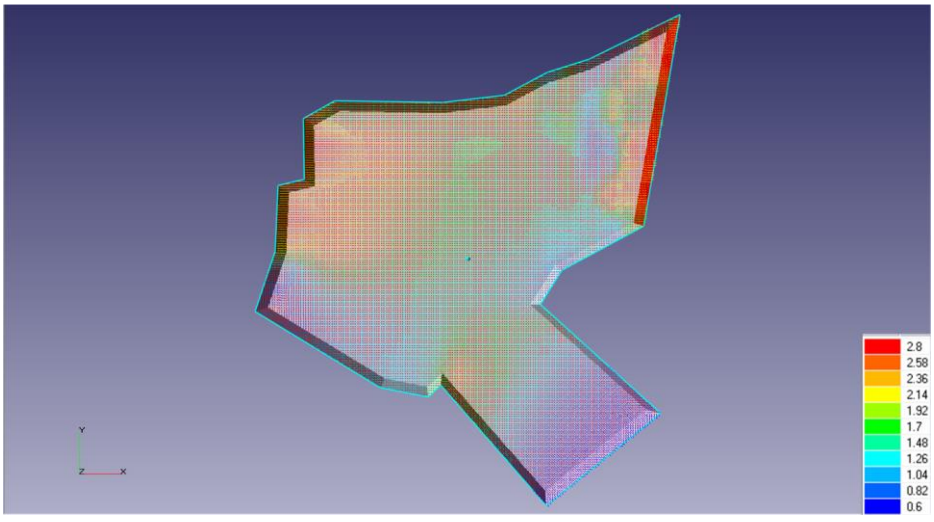

Fig. 4. Vector representation of dust particle velocity (m/s) within the land allotment contour

Based on the results of three-dimensional computer simulation, visual and quantitative information on the distribution of air flows in the entire modeled space, including the near-surface layers of the quarry and the surrounding area, was obtained.

The results show that, in contrast to two-dimensional simulation, the presence of waste heaps and terrain features leads to a change in the direction of the air flow that bends around the quarry with its suction in the lateral parts into the quarry space, which, depending on the angle of inclination of the quarry wall, leads to a decrease in the angle of opening of the air jet, an increase in the size of the recirculation zone and the formation of vortex zones near the surface zone of the quarry. This distribution of air flows leads to even greater weakening in different areas of the quarry, depending on the wind speed at the surface.

In terms of assessing the aerological situation during open-pit mining operations based on three-dimensional models of quarries, it is also necessary to study the pollution of the surface layer of the atmosphere according to the dependence of dust intensity Westphal D. L. et al. [17] and the DEAD scheme [18].

These dependencies provide the minimum discrepancy in results over the entire range of wind speeds considered. It is worth noting that both approaches are based on the functional dependence of the mass flow on the dynamic velocity at the height dust in the 4th and 3rd steps, respectively.

A summary of calculated data obtained from the results of computer simulation is by dependence graphs, which show the total intensity (Fig. 5) dust (5) in the form of dust concentration (*C*) with variation of either wind flow velocity (*V*) (Table 1) or the calculated value of the dynamic velocity (V_d) obtained from the results of computer simulation at the height dust within the middle line of the mining contour, respectively.

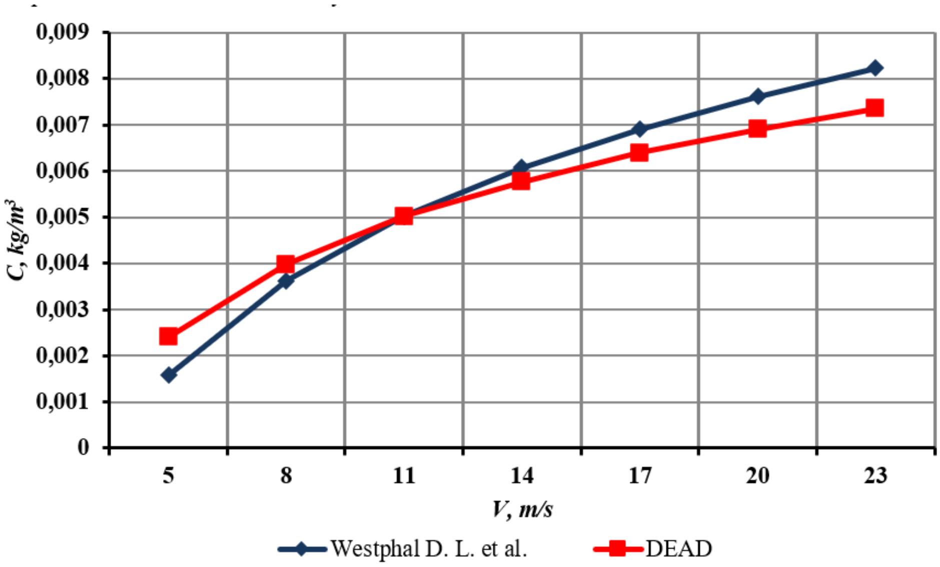

Fig. 5. Dependence of the calculated dust intensity on the air flow rate

Thus, the main feature of the calculated dust intensities is the absence of a numerical value at a wind speed of 5 m/s for the finest dust ($PM_{2.5}$).

This fact is explained by the fact that the maximum velocity value obtained from the computer simulation results is higher than the corresponding dynamic velocity value, i.e., no dust emission of this fraction occurs within the framework of this model (DEAD scheme).

In addition, at low wind speeds (no more than 8 m/s), for dust of almost any fraction, the intensity values dust calculated using the DEAD scheme are slightly higher than the similar calculated data according to the dependence of Westphal D. At a wind speed of 11 m/s, the results of dust intensity calculations using both approaches are the closest. Further increase in wind speed (which is much less common) leads to the fact that the calculated (according to the dependence Westphal D. L. et al.) pollination intensity significantly exceeds the similar values calculated using the DEAD scheme.

The calculated intensity data dust are necessary for solving the convective-diffusion equation of dust distribution during describing the boundary conditions on the surface dust. Given that this equation is linear, it will be sufficient to perform numerical experiments on the spatial and temporal distribution of dust concentration in the area under study. Knowing the corresponding ratios dust intensity, it is possible to obtain dust concentration values corresponding to the emission of dust particles according to the DEAD scheme.

As a result, the forecast of the spatial and temporal distribution of dust concentration will be determined in a certain range of values.

Further research should focus on model accuracy, emission factors, and data integration. For example, there is a need to improve the accuracy of the models, especially in the context of short-term weather changes, as the models do not always accurately reflect short-term fluctuations in dust concentrations due to the lack of local meteorological data. At the same time, further research on emission factors for different dust sources, such as drilling and crushing, is needed to provide more accurate predictions.

The widespread use of geostatistical methods such as kriging can improve the spatial prediction of dust concentrations, allowing for the creation of detailed pollution maps.

Conclusions

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

1. The possibility of using three-dimensional computer simulation to assess and predict the state of the quarry atmosphere in order to obtain visual and quantitative information on the distribution of air flows throughout the modeled space, including proved the surface layers of the quarry and the surrounding area, under certain meteorological conditions, has been.

2. The known dust pollution dispersion dependencies were improved to take into account the particle size and the quarry topography for the first time, which allowed us to create a mathematical basis for further computer simulation.

3. The obtained intensity values dust in the lower part of the wind speed range are close to the "maximum specific dust blowing" indicator, which is used by specialists of design organizations when developing the documentation required to establish the absence of excessive impact on both environmental components and the health of workers.

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Оцінювання аерологічного стану під час здійснення відкритих гірничих робіт на основі тривимірних моделей кар'єрів

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Анотація. Актуальність полягає у необхідності вдосконалення чинної виробничої системи моніторингу та прогнозування умов видобутку корисних копалин і підвищення промислової безпеки під час проведення вибухових робіт й інтенсивної експлуатації гірничо-видобувного обладнання. В умовах зростання виробництва, яке передбачає збільшення обсягів видобування та розмірів кар'єра, зміну прилеглого ландшафту, зокрема, за рахунок складування та подальший перехід на видобуток із нижніх горизонтів кар'єра, побудова прогностичної моделі щодо характеру повітряних течій і складу атмосфери є необхідною умовою під час планування гірничих робіт. **Метою дослідження є** математичне та комп'ютерне моделювання процесу руху частинок різнофракційного пилу та пило-газової хмари у повітрі приземних шарів кар'єрів і прилеглих робочих територій гірничо-видобувних підприємств задля подальшого розроблення та запровадження систем індивідуального та колективного захисту працівників. **Результати дослідження:** доведено можливість використання тривимірного комп'ютерного моделювання для оцінювання та прогнозування стану атмосфери кар'єрів із метою отримання візуальної та кількісної інформації щодо розподілу повітряних потоків у всьому модельованому просторі, включно з приповерхневими шарами кар'єра та прилеглої території, за визначених метеорологічних умов. Удосконалено відомі залежності розсіювання пилового забруднення, які вперше враховуватимуть розмір частинок і рельєф кар'єру, що дозволило створити математичне підґрунтя для подальшого комп'ютерного моделювання. Отримано значення інтенсивності пилення у нижній частині діапазону швидкості вітрового потоку близькі до показника «максимального питомого здування пилу», який використовується фахівцями проєктних організацій під час розроблення документації, необхідної для встановлення відсутності наднормового впливу як на компоненти довкілля, так і на стан здоров'я працівників. **Висновки:** перспективами подальших досліджень мають бути питання точності моделей, емісійні фактори й інтеграція даних.

Ключові слова: математичне та комп'ютерне моделювання; пилове забруднення; аерологія; кар'єри.