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Numerical analysis of aerodynamic regime near tailings storage facility

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Abstract. Tailings formed during the mining and beneficiation of iron ore are sources of intensive dust generation. In order to assess the intensity of dust formation and determine the effectiveness of methods of its reduction, it is necessary to know the local velocity of the air flow near the various surfaces of the tailings storage facility. For the theoretical solution of this problem, a CFD model was developed, which allows determining the velocity field of the air flow when flowing around the tailings storage facility. The model allows you to obtain the value of the wind speed near the surfaces of the structure and, based on this information, to make a forecast of possible dust formation. The constructed CFD model is based on the use of an aerodynamic model of potential motion. The modeling equation is the Laplace equation for the velocity potential. To build a numerical model, the idea of establishing a solution in time is used, therefore numerical integration of the "unsteady equation" for the velocity potential is carried out. Numerical integration is carried out using the finite-difference method of total approximation. The results of the computational experiment are presented.

1. Introduction

The extraction of iron ore in various regions of the world leads to very intensive dust generation, which negatively affects human health [1]. The enrichment of iron ores in Kryvbas (Ukraine) involves the generation of processing waste and the storage of this waste in special tailings storage facilities. The dust emitted from them poses a significant threat to environmental pollution and human health. Deposition of dust on the surface of the earth leads to deterioration of its productivity.

Reducing dust emissions from tailings is a very important problem in the field of environmental protection, which remains relevant and far from being solved. To find ways to solve this problem, it is necessary to conduct a complex of studies. One of the tasks within this problem is the study of the intensity of dust removal from different areas of the tailings repository under different aerodynamic regimes. This is due to the fact that the most important parameter that affects the intensity of dust emission from a certain surface is the speed of the air flow near this surface, that is, the local speed of the flow.

Figure 1 shows the diagram of the detachment of dust particles from the surface of a coal stack

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under the influence of wind load: at a low local air speed, particles move along the surface of the load (creep) or near the surface (saltation). But when the local speed of the air flow exceeds the "limit" value (the so-called threshold speed, pickup velocity), there is a separation of particles from the surface (suspension) and their drift with the air flow. It is this drift that forms the dust cloud near the tailings repository.

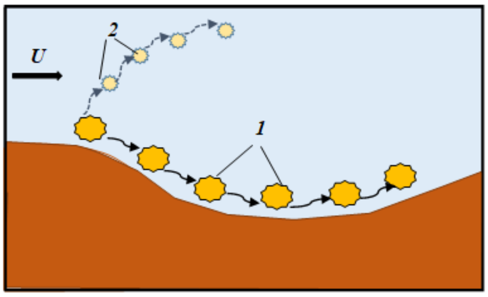

Figure 1. Scheme of dust particles detachment: 1 – creep movement; 2 – suspension.

To determine the speed of detachment of dust particles from the surface, experimental research methods are used [2]. This rate is related to the nature of the dust (e.g., dust from various tailings), dust moisture, dust particle size, material density, etc. Therefore, experimental studies reflect the value of this parameter for specific conditions. But knowing only the threshold velocity is not a complete solution to the problem of assessing the danger of dust pollution near the tailings repository. In order to analyze and develop a strategy for reducing the intensity of dust emission, it is necessary to know and predict the local velocity of the air flow near different areas of the tailings storage facility. If such a local speed will exceed the threshold speed, then this area should be considered as a "source" of dust emission. Thus, there is an important task of calculating the local air velocity near different areas of the tailings storage facility.

Prediction of dust pollution zones is an important task for the solution of which the method of M. Berlyand [3] and various types of Gaussian models [4 – 8] are most often used. In the work [5], the main attention is paid to the monitoring of the dust level in different areas of the territory, the characteristics of dust, the individual exposure to dust, and the forecasting of the concentration of dust in different places in the adjacent territories using the AERMOD software. Thus, the main goal of the research work [6] is to improve the existing Gaussian models with respect to the diffusion coefficients during the movement of the dust plume. Research [7] is aimed at forecasting the concentration of solid dust particles. The paper compares the results of modeling at different distances according to the Gaussian model with the data of measurements that were carried out in this area. Significant differences are shown due to the fact that this model does not take into account obstacles in the path of movement of pollution particles. From an aerodynamic point of view, any obstacles significantly affect the change in the wind speed profile. A large volume of research work is devoted to the modeling of dust dispersion. Much of the research has focused on large-scale patterns of global or regional dispersion. Various models of dust dispersion, which were developed specifically for the mining industry, are presented in [8].

The purpose of this work is to develop a numerical model of aerodynamics for calculating the local air velocity during the interaction of the wind flow with the tailings embankment.

2. Methods

To build the CFD model, the numerical integration of the Laplace equation for the velocity potential is used, namely, the finite-difference splitting scheme is used.

A model of potential movement is used to simulate the process of wind flow around the tailings storage facility. The basic equation of this model has the form [4]:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0 \tag{1}$$

where P – air flow rate potential.

The following boundary conditions are set for the modeling equation (1) in the *SQRG* calculation domain (figure 2) [4]:

– at the *SQ* boundary, where the air flow enters the calculation area, a condition $\frac{\partial P}{\partial x} = U$ is met, where U, m/s – the value of the wind speed at altitude $h = y$, $U = U_1 \cdot (y / y_1)^{n_1}$, where U_1, m/s – wind speed at the level y_1=1 m, n_1=0.16 [3].

– at the boundary of the exit of the air flow *RG*, a boundary condition is imposed, having the form $P = P_0 + const$, where P_0 – some constant;

– the condition holds on all impermeable boundaries $\frac{\partial P}{\partial n} = 0$, n – external unit normal vector.

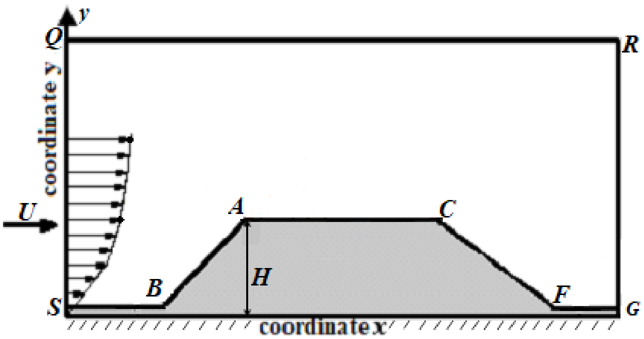

Figure 2. Scheme of the calculation area of the tailings storage facility (scenario 1): *SQRG* – calculation area, *BACF* – tailings storage facility, *U* – air flow velocity.

Determination of the speed potential in the research area allows you to calculate the longitudinal and transverse components of the air flow speed vector based on such dependencies [4]:

$$u = \frac{\partial P}{\partial x}, \; v = \frac{\partial P}{\partial y}. \tag{2}$$

After calculating the velocity field of the air flow over the surface of the tailings storage facility, the local velocity should be compared with the threshold velocity and the zone of possible dust formation, which may lead to atmospheric air pollution, should be determined.

The theoretical determination of the local velocity of the air flow near different areas of the tailings storage facility is a difficult task, since the boundaries of the tailings storage facility have a complex geometric shape. The only way to solve this problem is to use numerical methods. But it should be noted that in the presence of a complex geometric shape of the tailings storage, streamlines with significant curvature appear. In these conditions, difference schemes that do not lose stability under such conditions should be used to build a CFD model.

The following approach was used for the numerical integration of equation (1). Equation (1) was written in the "evolutionary" form [4, 9]:

$$\frac{\partial P}{\partial t} = \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2}, \tag{3}$$

where t – fictitious time. While $t \to \infty$, the solution of the equation (3) leads to the solution of the Laplace equation (1), that is, the method of establishing the solution by time is used.

The number of solutions is equal (3) to be placed on a rectangular retail grid. The value of the potential of the security is determined in the centers of retail markets. For the molding of the folding geometry of the rosewood region, the marking method is used [4].

For numerical integration of equality (3), the method of total approximation is victorious [9]. The design of the two-rocker method can be seen in the splitting scheme:

– at the first step:

$$\frac{P_{i,j}^{n+\frac{1}{2}} - P_{i,j}^{n}}{\Delta t} = \frac{-P_{i,j}^{n+\frac{1}{2}} + P_{i-1,j}^{n+\frac{1}{2}}}{\Delta x^2} + \frac{-P_{i,j}^{n+\frac{1}{2}} + P_{i,j-1}^{n+\frac{1}{2}}}{\Delta y^2}; \tag{4}$$

– at the second step:

$$\frac{P_{i,j}^{n+1} - P_{i,j}^{n+\frac{1}{2}}}{\Delta t} = \frac{P_{i+1,j}^{n+1} - P_{i,j}^{n+1}}{\Delta x^2} + \frac{P_{i,j+1}^{n+1} + P_{i,j}^{n+1}}{\Delta y^2}. \tag{5}$$

Each difference equation (4) and (5) partially approximates equation (3), but in sum it is a complete approximation of equation (3). The unknown value of the velocity potential in relations (4) – (5) at each splitting step is determined as follows (6) – (7):

– at the first step:

$$P_{i,j}^{n+\frac{1}{2}} = P_{i,j}^{n} + \Delta t \frac{-P_{i,j}^{n+\frac{1}{2}} + P_{i-1,j}^{n+\frac{1}{2}}}{\Delta x^2} + \Delta t \frac{-P_{i,j}^{n+\frac{1}{2}} + P_{i,j-1}^{n+\frac{1}{2}}}{\Delta y^2}; \tag{6}$$

– at the second step:

$$P_{i,j}^{n+1} = P_{i,j}^{n+\frac{1}{2}} + \Delta t \frac{P_{i+1,j}^{n+1} - P_{i,j}^{n+1}}{\Delta x^2} + \Delta t \frac{P_{i,j+1}^{n+1} - P_{i,j}^{n+1}}{\Delta y^2}. \tag{7}$$

The calculation ends when the condition is met $\left|P_{i,j}^{n+1} - P_{i,j}^{n}\right| \le \varepsilon$, where ε – a small number, $\varepsilon = 10^{-3} \div 10^{-6}$, n – iteration number.

To start the calculation, when solving the "evolutionary" equation (3), it is necessary to set the value of the velocity potential in the calculation area, namely, it is assumed that $P_{t=0} = 0$.

After finding the velocity potential field, the components of the air flow velocity vector are determined:

$$u_{i,j} = \frac{P_{i,j} - P_{i-1,j}}{\Delta x}, \; v_{i,j} = \frac{P_{i,j} - P_{i,j-1}}{\Delta y}. \tag{8}$$

The components of the air flow velocity vector are determined on the sides of the difference cells. As a result of the numerical simulation, a code was developed for conducting a computational experiment based on the constructed numerical model. FORTRAN algorithmic language was used for programming.

3. Results and discussion

A computational experiment was conducted on the basis of the developed numerical model. Parametric studies were performed for such scenarios:

1. Scenario 1: The tailings storage facility has height H=5 m, the shape of the tailings storage facility is a trapezoid (figure 2).
2. Scenario 2: The height of the tailings storage facility is increased by h=3 m; the area KE – highway length 6 m (figure 3). The increase in the height of the tailings storage facility is related to the technology of its operation.
3. Scenario 3: The tailings storage facility has the dimensions and shape as in scenario 2, but a screen with a height of h_1=3 m (figure 4).
4. Scenario 4: The tailings storage facility has the dimensions and shape as in scenario 2, but two high screens are installed on the top tier of the tailings storage facility h_1= h_2=3 m (figure 5).

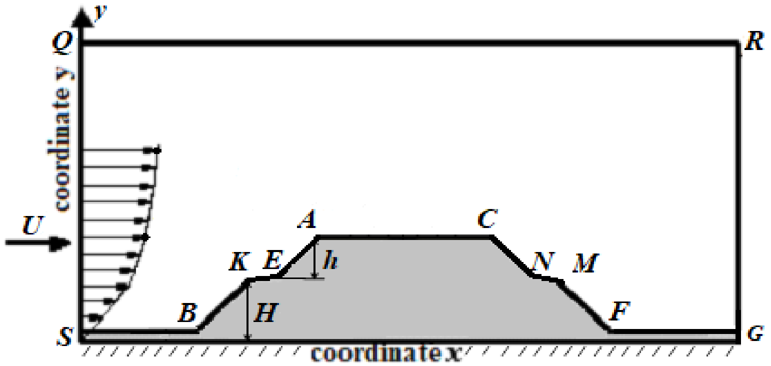

Figure 3. Scheme of the calculation area (scenario 2): *H*, *h* – the height of tailings storage facility.

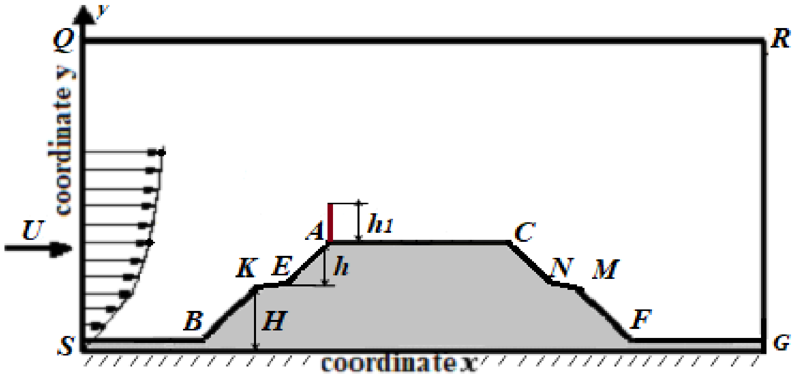

Figure 4. Scheme of the calculation area (scenario 3): *H*, *h* – the height of tailings storage facility; h_1 – height of screen.

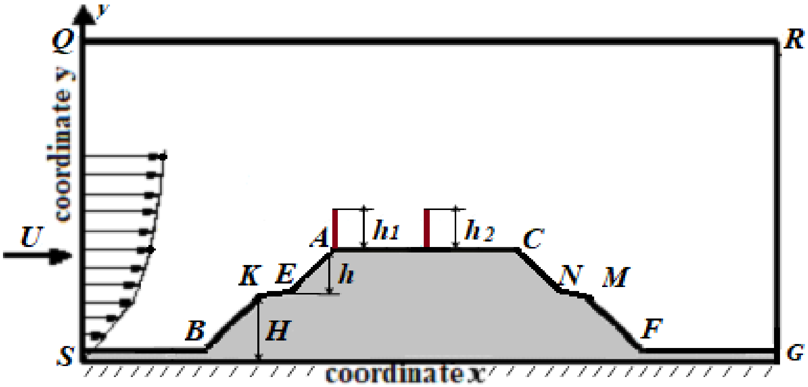

Figure 5. Scheme of the calculation area (scenario 4): *H*, *h* – the height of tailings storage facility; h_1, h_2 – height of screens.

The purpose of the computational experiment was to calculate the speed of the air flow along the upper surface, where intense dust formation takes place (line AC in figures 4-5). When conducting computational experiments, the calculation was carried out for the following parameters: air flow speed U=6.5 m/s; length of the upper part of the tailings storage facility 50 m – the *AC* line.

The following figures show the wind speed values for each scenario along the upper part of the tailings storage facility – the *AC* line.

Analysis of the data in figures 5-9 shows that the increasing height of the tailings storage facility (scenario 2) led to a sharp increase in the speed of the air flow along its upper part (figures 6-7). This is due to the fact that the wind speed increases with height, in addition, there is a change in the aerodynamic regime of the flow around the tailings storage facility due to a change in its shape, which leads to a local increase in the flow speed at its upper part. Thus, the increase in the height of the tailings storage facility, which is periodically carried out when iron ore production is increased, leads to the inevitable process of increasing dust formation in the tailings storage facility. It can also be seen that starting from a mark of about 20 m from the left border of the tailings storage facility, the air flow speed stabilizes, i.e., a "flow around a horizontal" plate is realized. Besides, if a screen is used on the upper border of the tailings storage facility to create an aerodynamic "shadow" in order to reduce the

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value of the air speed, then it can be seen that the "influence" of the screen occurs at a length of about 10 m from it.

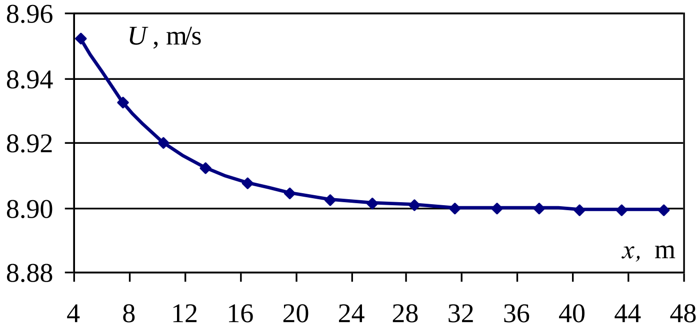

Figure 6. The wind speed along the upper part of the tailings storage facility (scenario 1).

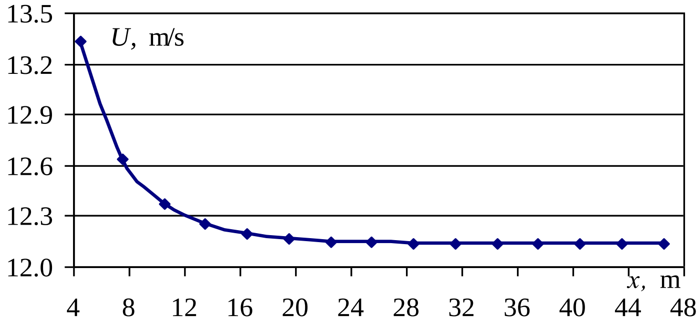

Figure 7. The wind speed along the upper part of the tailings storage facility (scenario 2).

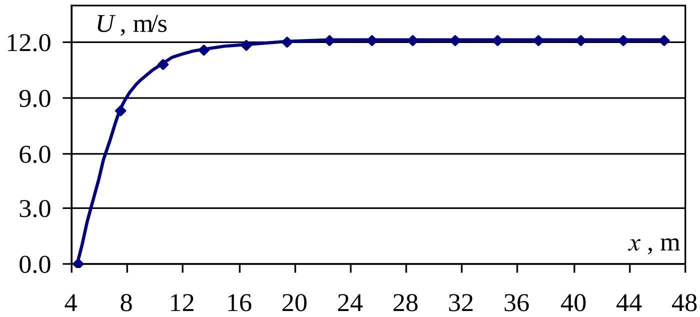

Figure 8. The wind speed along the upper part of the tailings storage facility (scenario 3, with one screen).

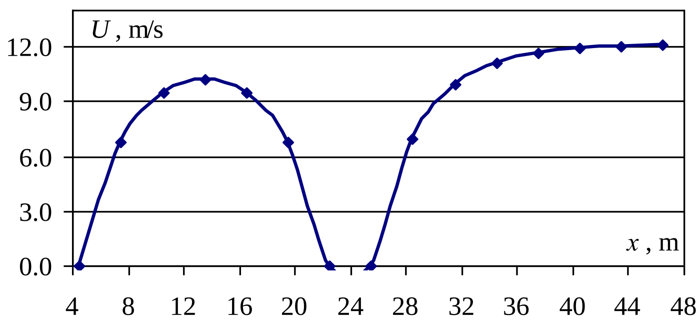

Figure 9. The wind speed along the upper part of the tailings storage facility (scenario 4, with two screens).

Besides, it is necessary to compare the value of the wind speed in the area affected by the screen with the speed of detachment of dust particles: will it be sufficient to extinguish the dust formation process in specific conditions. Also, if the system of screens is used (figures 5, 9), it can be seen that with this approach, local zones of air speed reduction are formed, but the effectiveness of the screen system can be determined by comparing the obtained air speed in these zones with the speed of particle separation dust The number of screens, their height, location can be determined using the developed numerical model. The calculation time of one scenario is 5 seconds.

4. Conclusions

1. A numerical model has been developed that allows analyzing the aerodynamic regime, which is implemented during the interaction of the wind flow and the tailings storage.

2. This model makes it possible to determine the aerodynamics of the flow, taking into account the complex geometric shape of the tailings storage facility and the uneven profile of the air flow speed in the area of possible dust formation.

3. The results of the computational experiment showed that to solve the problem of reducing the intensity of dust formation, the screens located in the tailings storage facility can be used. The number of such screens, their size, location must be determined taking into account specific geometric and physical conditions.

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