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Numerical modeling of the wind regime on the beaches of the wash of the artificial storage facilities for mineral processing waste

Yevhen Lapshyn[1], **Mykola Biliaiev**[2,5], **Viktoriia Biliaieva**[2], **Zariana Halchenko**[1], **Volodymyr Medianyk**[3] **and Valentyn Buketov**[4]

[1]M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Simferopolska St., 2a, Dnipro, 49005, Ukraine
[2]Ukrainian State University of Science and Technologies, Lazaryan St., 2, Dnipro, 49010, Ukraine
[3]National Technical University "Dnipro Polytechnic", Dmytro Yavornitskyi Ave., 19, Dnipro, 49000, Ukraine
[4]Universidad Nacional de San Agustin de Arequipa, Institute of the Center of Renewable Energy and Energy Efficiency, San Agustin Street 107, PE-04000 Arequipa, Peru

[5]Corresponding author: water.supply.treatment@gmail.com

Abstract. A 2D numerical model has been developed to estimate the airflow velocity field when flowing around the dam of an artificial storage facility for mineral processing waste. To solve the aerodynamic problem of determining the air flow velocity field when flowing around such hydraulic structures with a complex geometric shape, a potential motion model was applied. The numerical integration of the equation for the velocity potential is carried out using the Liebman method. The geometric shape of the tailings storage facility is formed in a discrete model using the marking method. A computer program was created to implement the developed numerical aerodynamics model. Based on the processing of the results of computational experiments, coefficients were obtained that allow us to quickly determine the value of the air flow velocity at the beginning and end of the tailing pond beach, i.e. in the area of the most intense dust emission. This allows for a quick prediction of the risk of dust air pollution at different tailing pile heights.

1. Introduction

Mining companies play an important role in the country's export potential, as well as in the sustainable development of the regions where they are located [1-5]. However, each such enterprise is accompanied by waste storage facilities for mineral processing waste, which are mostly artificial formations on the earth's surface. Most of the artificial storage facilities for mineral processing waste (MPW) are characterized by significant geodetic heights, are long-term and intensive sources of dust pollution in the atmosphere [3-7]. When designing such MPW, the regulatory documents stipulated that the particulate matter fractions capable of dust formation would be under the water layer, and those remaining on the beach surface would not be transported by air, given the height of the beach and the likely value of wind speed. However, the lack of available land for new MPW around mining enterprises at the end of the twentieth century, i.e. at the time when most MPW should have been shut down according to the original projects, prompted the construction of dams above the design heights. This changes the conditions of the dust formation process on the surface of the MPW beaches, creating the possibility of involving particulate matter fractions that were not involved in this process according to the original design. One of the most important factors in the process of dust formation on the MPW beach is the wind speed near its surface, which increases with the height of the seawall, so starting from a certain point, the beach surface falls into the area of such high wind speeds that intense dust pollution begins. Thus, when increasing the height of the revetment dams, it is extremely important to determine at what height for a given area, taking into account the specific meteorological conditions of a particular region, the problem of intensive removal of solid particles in the form of dust from the beach surface arises.

Taking into account the complex geometry of the outer surface of the MPW embankment dam, formed by the sequential repetition of the slope and the dam shelf when moving to a new embankment tier (figure 1), powerful aerodynamic models – CFD models – should be used to theoretically solve the problem of determining the wind speed along the beach. This approach has been successfully used by domestic and foreign experts in modeling the wind regime [1, 2]. However, well-known models of this class, such as ANSYS CFX, require a very significant amount of time to calculate the airflow velocity field when flowing around structures with such a complex geometric shape as the MPW. According to various estimates, the calculation time for one variant can be several days [8-9]. This is very inconvenient for the practice of engineering calculations, given the large number of design options that need to be considered when justifying the direction of the modernization of the MPW.

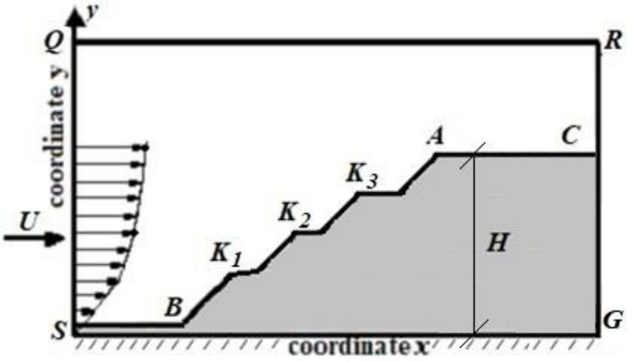

Figure 1. Computational scheme for the numerical model: U is the velocity of the incoming air flow at infinity, m/s; H is the height of the dam of the MPW, m.

Another drawback of the known attempts to model the wind regime near objects similar to the MPW is the invariability of the velocity of the incoming air flow at infinity [8]. Such an assumption is possible, for example, for coal stacks in port areas [9, 10], the height of which does not exceed ten meters. However, in the case of the Ore Mining and Processing Plant (MPP), when the height of the dams reaches from 20 to 100 meters (table 1) [11, 12], it is unacceptable to ignore the change in the velocity of the incoming air flow at infinity.

Table 1. Height of the dams of different MPW [11, 12].

Title of the MPW	Height of dam, m
MPW Tsentralnoho MPP	10
MPW "Obiednane"	50
MPW "Myroliubivske"	55
MPW "Voikove"	62
MPW Pivnichnoho MPP	76
MPW Inhuletskyi MPP	112

The purpose of the paper is to develop fast calculation methods for assessing the risk of dust formation on the beaches of the MPW when building up the revetment dams above the height provided for in the original design of their creation. To do this, it is necessary to determine the distribution of wind speed along the beach surface at the current level of the MPW embankment depending on the speed of the incoming air flow and the height of the revetment dyke by numerical methods that do not require significant calculation time and take into account changes in the value of the speed of the incoming air flow at infinity.

2. Methods

When creating a geometric model of the air flow area, the lateral surface of the dike of the headwall was represented by a broken line formed by a successively inclined segment of 6 m in length with an angle of inclination of 30 degrees and a horizontal segment of 5 m in length (figure 1). The height of the first such element is 5 m, and each subsequent one is 3 m, which corresponds to the conditions of most of the domestic mining and processing plants (table 1) [11, 12].

The change in the velocity of the incoming air flow at infinity was taken into account using the model of M.E. Berland [3]. This made it possible to calculate the value of the wind speed at an arbitrary height by the value of the speed of the incoming air flow at a control height above the earth's surface according to the power law [4-7]:

$$V_B = u_1 \left(\frac{y}{y_1} \right)^{n_1}, \tag{1}$$

where V_B is the value of the incoming air flow velocity at a height of y, m/s; u_1 is the incoming wind speed at a height of y_1, m/s; y_1 is the regulated height of wind speed measurement, m; n_1 is the empirical coefficient, which for the conditions under consideration is 0.16 [11].

Note that the OY axis is directed upward and corresponds to a certain height on the ground. The scheme of the computational domain used in the application of the potential motion model is shown in figure 1.

2.1. Theoretical part

A specific aerodynamic model must be used to thoroughly estimate the wind speed at the beach location. The potential motion model was used for this study. The basic equation of this model is the Laplace equation for the velocity potential

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

whose solution allows to determine the components of the wind speed vector based on the following formulas

$$u = \frac{\partial P}{\partial x}, \qquad v = \frac{\partial P}{\partial y}, \tag{3}$$

where P is the velocity potential, 1/s; x is the longitudinal coordinate, m; y is the vertical coordinate, m; u is the longitudinal component of the velocity vector, m/s; v is the vertical component of the velocity vector, m/s.

Based on the fact that at the boundary of the air flow outlet *RG* the condition of potential constancy is set, and at all impermeable boundaries the condition of zero of the normal velocity component is met, while at the boundary *SQ*, where the air flow enters the computational domain, the condition of potential gradient constancy is met, the following boundary conditions are used to determine the wind speed field based on the Laplace equation (figure 1):

$$P = P_0, \qquad \frac{\partial P}{\partial n} = 0, \qquad \frac{\partial P}{\partial x} = V_B, \tag{4}$$

where P_0 is some constant, 1/s; n is the vector of the external single normal, m.

Thus, the model takes into account the change in the velocity of the incoming air flow with height at the input boundary. Further, there is a "deformation" of the wind flow velocity field due to the flow around the dam of the MPW collapse.

Using these assumptions and formulas (1)-(4), CFD model was developed to analyze the wind regime formed by the flow around the MPW. The model is based on the numerical integration of the 2D equation for the velocity potential by the Liebman method [2-4].

2.2. CFD model

Since it is necessary to determine the airflow velocity field when it flows around the MPW, i.e., in a region with a complex geometric shape, the solution to equation (2) is found numerically. For this purpose, a rectangular difference grid is used, the flow area is divided into control volumes and the following finite-difference approximation of the Laplace equation, i.e., the Liebman method:

$$\frac{P_{i+1,j}-2P_{i,j}+P_{i-1,j}}{\Delta x^2}+\frac{P_{i,j+1}-2P_{i,j}+P_{i,j-1}}{\Delta y^2}=0,$$

that allows to determine the desired value $P_{i,j}$ in each difference cell:

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

where $P_{i,j}$ is the value of the air velocity potential in the cell; Δx is the size of the cell along the coordinate x; Δy is the size of the cell along the coordinate y; i is the cell number along the coordinate x; j is the cell number along the coordinate y.

The iterative calculation according to dependence (5) is terminated if the condition

$$\left|P_{i,j}^{n+1}-P_{i,j}^{n}\right|\le\varepsilon,$$

where n is the iteration number; ε is a small number.

After the velocity potential field is calculated, the component of the air flow velocity vector is calculated by the following formulas

$$u_{ij}=\frac{P_{i,j}-P_{i-1,j}}{\Delta x}, \qquad v_{ij}=\frac{P_{i,j}-P_{i,j-1}}{\Delta y},$$

where u_{ij} - horizontal component of the air flow velocity vector; v_{ij} - vertical component of the air flow velocity vector.

Note that the velocity potential is determined in the centers of the difference cells, and the components of the air velocity vector are calculated on the sides of the difference cells. To form a complex geometric shape of the dam of the MPW embankment in the discrete model, the following marking method is used [14].

Using the developed CFD model, a computer program based on the algorithmic language FORTRAN was created.

3. Results and discussion

The numerical model was used to conduct parametric studies and calculate the wind speed fields along the MPW beach (figures 2-4), i.e., along the A-C line (figure 1), for various scenarios in the range of wind speed changes at infinity (table 2). Since each of the scenarios differed in the height of the MPW (figure 1, table 2), it became possible to determine the risk of dust formation when increasing the height of the revetment dam. It was assumed that within 95 m from the corner point A (figure 1) there is a part of the beach where there is little dust formation, and then, in the area from 95 to 105 m, there is a region with intense dust emission, followed by a water mirror of the clarifier pond.

Table 2. Characteristics of calculation scenarios.

Scenario no.	Height of the dam, m	Wind speed values, m/s
1	8	1.5; 3.0; 4.0; 5.0;
2	11	1.5; 3.0; 4.0; 5.0;
3	14	1.5; 3.0; 4.0; 5.0;

The results shown in figures 2 - 4 allow us to determine the wind speed (V_{b1}) in the area 10 m from the corner point A and the wind speed (V_{b2}) in the area starting 95 m from the corner point A, i.e., at the beginning of the beach. And to compare these wind speed values with the wind speed V_B according to the Berland model (1), the values of the following coefficients were determined:

$$k_1 = \frac{V_{b1}}{V_B}, \qquad k_2 = \frac{V_{b2}}{V_B}, \tag{6}$$

where k_1 - coefficient of air flow velocity behind the dam; V_{b1} - air flow velocity directly behind the dam, m/s; k_2 - coefficient of air flow velocity at the beach border; V_{b2} - air flow velocity at the beach border, m/s.

Each of the coefficients k_1 and k_2 indicates the excess of wind speed in a certain part of the beach over the wind value at the height of the shelf of the revetment dam. While the ratio of these coefficients characterizes the uneven distribution of wind speed along the length of the beach:

$$k = \frac{k_2}{k_1}, \tag{7}$$

where k is the coefficient of unevenness of the air flow velocity along the beach.

The results of the data analysis presented in figures 2-4 show that the highest value of the air flow velocity is observed near the corner point A, i.e., directly behind the dam (figure 1). Further, the value of the air flow velocity decreases along the beach surface (line A-C, figure 1). The most intense decrease in velocity occurs at a length of about 16 m from the corner point A. Further, the air flow velocity gradually decreases, so we can speak of an almost uniform flow of the flow along the beach. In addition, as follows from the figures above, an increase in the value of the parameter u_1 leads to an increase in wind speed along the MPW beach. It should be noted that the calculation time for one scenario is 5 seconds.

Based on the processing of the computational experiment data, the following values of the coefficients k_1, k_2 and k, were obtained, which turned out to be invariant with respect to the air flow rate at infinity and the height of the embankment dam:

$$k_1 = 1.35, \qquad k_2 = 1.29, \qquad k = 0,96. \tag{8}$$

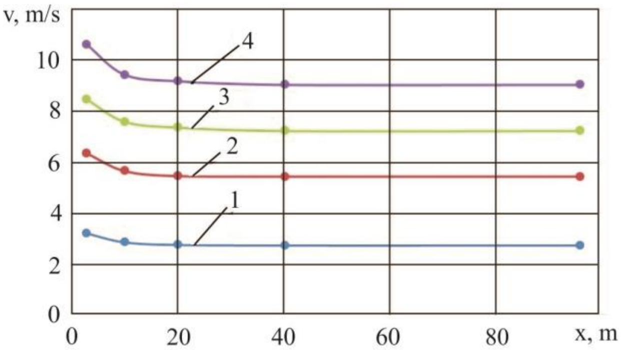

Figure 2. Distribution of wind speed along the MPW beach in the calculations under Scenario 1 (table 2): 1 - u_1=1.5 m/s; 2 - u_1=3 m/s; 3 - u_1=4 m/s; 4 - u_1=5 m/s.

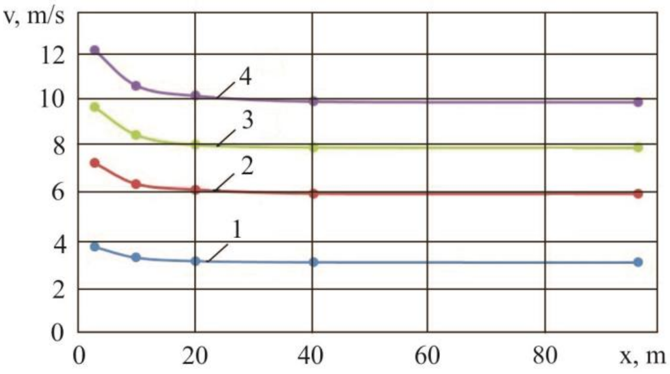

Figure 3. Distribution of wind speed along the MPW beach in the calculations under Scenario 2 (table 2): 1 - u_1=1.5 m/s; 2 - u_1=3 m/s; 3 - u_1=4 m/s; 4 - u_1=5 m/s.

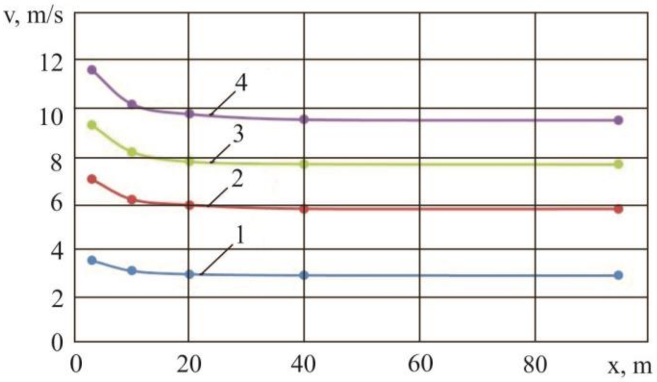

Figure 4. Distribution of wind speed along the MPW beach in the calculations under scenario 3 (table 2): 1 - u_1=1.5 m/s; 2 - u_1=3 m/s; 3 - u_1=4 m/s; 4 - u_1=5 m/s.

Thus, using formulas (6), at the stage of rapid assessment of the value of the air flow velocity in certain parts of the beach, we can use the following dependencies

$$V_{b1} = k_1 V_B , \qquad V_{b2} = k_2 V_B , \qquad V_{b2} = 0{,}96 V_{b1} . \tag{9}$$

The use of the calculated dependencies (8) makes it possible not to resort to a computational experiment to expressly determine the air flow rate in certain areas of the beach in order to assess the risk of dust formation when building up the dams of the MPW above the height provided for in the initial design of their creation.

4. Conclusions

An effective numerical model has been built enabling researchers to determine the air flow velocity field in real time when flowing around the dams of the MPW dumping. Based on these calculations, it is possible to estimate the flow velocity along the beach of the MPW, where dust formation areas are formed, and on the basis of this information to assess the risk of dust removal from the beach. The distinctive feature of the developed numerical model is its ability to consider the complex geometric shape of the tailing pile, requiring only a few seconds to conduct a computational experiment.

Based on the processing of the computational experiment data, coefficients were obtained that make it possible to determine the value of wind speed at the beginning and end of the beach without calculations using numerical aerodynamics models, which greatly simplifies the assessment of the risk of dust formation on the MPW beach.

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