DESIGNING AND CONSTRUCTION OF ROADS, SUBWAYS, AIRFIELDS, BRIDGES AND TRANSPORT TUNNELS

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MODELING THE SNOW DEPOSIT PROCESS ON THE HIGHWAYS IN THE FLOWVISION

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Statement of the problem. The problems of snow deposit modeling on the highways with crash barriers during blizzards in the FlowVision.

Results. The highway section passing in the embankment as an experimental section has been considered. The geometric model of the highway section was created. The information resources for creating a hydrodynamic model of snowflow stream of highway embankment with barrier barriers during blizzard were identified. The modeling of the snow deposit process in the experimental section using the FlowVision during blizzards with different parameters was carried out.

Conclusions. It was concluded that it is possible to use the FlowVision to improve the methodology for snow protection designing and determining of snow removal parameters for winter road maintenance.

Keywords: winter road maintenance, highway, snow deposit, modeling, blizzard.

Introduction. In wintertime, snowstorms are one of the most dangerous weather events in regards to road safety. Snowstorms are commonly accompanied by poor visibility, strong gusty side winds, and snow accumulation on the road surface, which tend to cause dangerous situations including bringing traffic to a halt.

During snowstorms, road services are on high alert with continuous patrolling tracks and clearing roads from snow and mobile heating points organized. With extended periods of snowstorms and large amounts of snow, road traffic is limited. Hence during winter highway maintenance, monitoring the current state of the road surface and preventing critical situations is a top priority aimed at improving road safety.

Snow drift on roads is determined by the physical processes of the snow-wind flow around the cross-section of the roadbed and the deposition of blizzard snow takes place due to a change in its speed.

For an experimental study of the processes of snow deposition during blizzards adjacent to various obstacles, “aerodynamic tunnels” have long been commonly used where the snow-storm activity was recreated. "Aerodynamic tunnels" were designed in Russia [1, 8], Japan [17], France [20], USA [14, 21], China [15, 18], Romania [16] and other countries [12, 13, 19]. At the same time, full-scale models have not been employed much due to high construction costs. Modeling was performed by means of scaled-down models in accordance with the criteria of the similarity theory.

Currently due to a rapid development of special software tools, it has become possible to make use of computer software systems where any physical processes can be simulated with a high degree of accuracy including snow transport during blizzards.

The objective of the study is to substantiate the physical parameters for modeling snow deposits on highways with barrier fences under various modes of blizzard passage. The object of the study is the FlowVision software package. The subject of the study is snow deposition during a blizzard on the highway section passing through an embankment.

1. The physical formulation of the problem of snow deposits on an embankment of a highway subsoil. The experiments performed when blowing the models of embankments in the “wind tunnel” allowed us to confirm the hypothesis that the pattern of movement of the snow and wind flow during a blizzard corresponds to that of movement of a liquid flow adjacent to a solid, flat, towering obstacle [6]. According to this scheme, a snow-wind stream approaching a towering obstacle experiences compression caused by this obstacle.

Let us look at the physical formulation of the problem using the highway subsoil scheme as shown in Fig. 1.

As highway subsoil is a volumetric obstacle, a braking zone is formed in front of the embankment where the speed of the snow and wind flow drops and the direction of its movement changes. A zone with increased speeds is formed above the embankment, as the same volume of snow and wind flow passes here through the reduced section as at a far distance from the obstacle. This zone is located above the windward edge and partially above the carriageway of the subsoil; at the leeward edge of the roadbed, a drop in the speed of the snow and wind flow is observed. A drop in the speed over the embankment at the same height depends on the geometric parameters of the top of the subsoil mostly on its width. The greater the width of the subsoil is, the greater the decrease in the speed of the snow and wind flow over the leeward edge is.

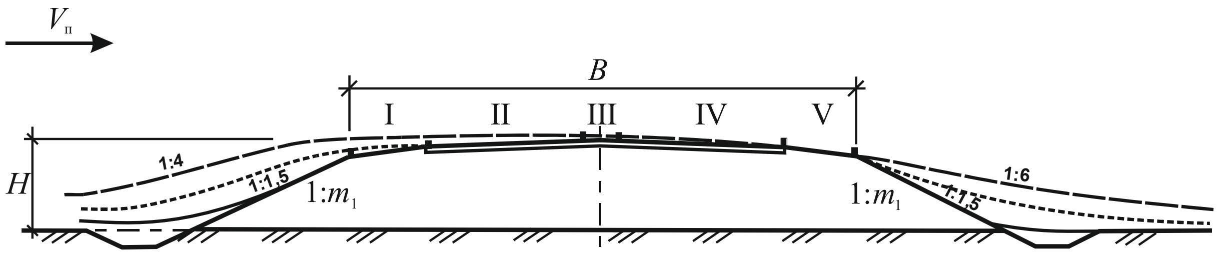

Fig. 1. Scheme of the formation of snow deposits on an embankment of a highway subsoil with design sections: I — windward shoulder, II — windward roadway, III — dividing line, IV — leeward roadway, V — leeward shoulder

2. Use of the FlowVision software package for studying snow deposition. Presently the most commonly used software systems for modeling physical processes are Flow3D, Fluent, Simulation CED developed in the USA and the FlowVision developed in Russia by TESIS which was used in [10].

The FlowVision software package is designed for numerical modeling of three-dimensional flows of liquid and gas [10]. The calculations are based on reliable mathematical models of physical processes, effective numerical methods for their implementation, high-precision difference schemes. The implemented models of physical processes make it possible to study complex currents, including the flow of snow and wind around the motorway embankment. In modeling the snow and wind flow is taken as a two-phase flow of a viscous incompressible fluid [5, 7].

The main task of the FlowVision is the numerical solution of the equations of computational fluid dynamics, the major one is a system of Navier-Stokes equations which describes the motion of a viscous incompressible fluid [10]. The equation of motion for 3D flow is as follows:

$$\rho\left(\frac{\partial\upsilon}{\partial t}+\upsilon\frac{\partial\upsilon}{\partial x}+v\frac{\partial\upsilon}{\partial y}+\omega\frac{\partial\upsilon}{\partial z}\right)=x-\frac{dp}{dx}+\mu\left(\frac{\partial^2\upsilon}{\partial x^2}+\frac{\partial^2\upsilon}{\partial y^2}+\frac{\partial^2\upsilon}{\partial z^2}\right);$$

$$\rho\left(\frac{\partial v}{\partial t}+\upsilon\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+\omega\frac{\partial v}{\partial z}\right)=y-\frac{dp}{dy}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right); \qquad (1)$$

$$\rho\left(\frac{\partial\omega}{\partial t}+\upsilon\frac{\partial\omega}{\partial x}+v\frac{\partial\omega}{\partial y}+\omega\frac{\partial\omega}{\partial z}\right)=z-\frac{dp}{dz}+\mu\left(\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}+\frac{\partial^2\omega}{\partial z^2}\right);$$

and the continuity equation is the following:

$$\frac{\partial\upsilon}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial\omega}{\partial z}=0, \qquad (2)$$

where υ, v, ω are the components of the flow speed in the coordinates x, y, z; ρ, p, μ is the density, pressure and viscosity of the air; t is the time.

The system of Navier — Stokes equations can be employed to describe the process of snow and wind flow around various obstacles including the transverse profile of a road embankment.

The FlowVision software package is divided into three parts: a preprocessor, a solver, and a postprocessor [10]. In the preprocessor:

— a geometric model of the investigated object is imported and designed in various computer-aided design systems;

— boundary conditions are interactively specified on surfaces;

— all the initial data and parameters of the problem are set.

The solver provides a numerical solution to the problem and is “invisible” to users. Its operation boils down to proceeding with the calculations and ending them.

The FlowVision postprocessor enables visual analysis of complex 3D fluid flows.

3. Designing a geometric model of a highway with barriers. In order to simulate snow accumulation on motorway embankments, a geometric model of a motorway with barriers was designed in the preprocessor and a set of parameters of the hydrodynamic model that determine the interaction of substances in the computational area was specified.

In order to develop a geometric model, a real section of the highway on the federal highway M-4 “Don”, km 530, was used. The geometrical parameters of the route section are provided in Table 1.

A test section of the track has several rows of barriers to improve traffic safety. A diagram of a barrier fence with the required geometric dimensions is shown in Fig. 2.

Table 1

Geometric parameters of a section of the federal highway M-4 “Don”, km 530

Parameter	Numerical value	Parameter	Numerical value
Road category	I Б	Width of a highway, m	7.5 × 2
Embankment height, m	2.0	Width of a curb, m	3.75 m
Length of a section, m	10.0	Width of a dividing line, m	0.5 m
Number of traffic lanes	4	Width of traffic lanes	1.0 m
Width of subsoil, m	25.0	Location of slopes	1:4

At a standard barrier height $H = 0.75$ m and a clearance height h = 0.44 m, its transparency is $\delta = 0.6$. At the selected site, constant video surveillance is performed using video cameras located on the route which are part of the weather monitoring system [3, 11].

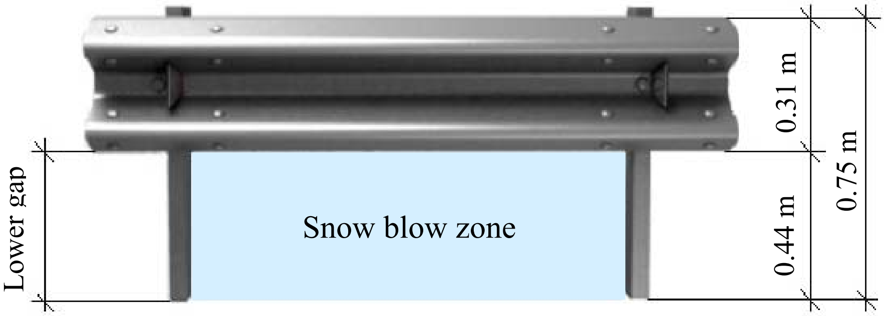

Fig. 2. Scheme of a barrier

A video image of a section of the motorway on the federal highway M-4 “Don”, km 530 in winter is shown in Fig. 3. The layout of the barriers is shown in Fig. 4.

Fig. 3. Video image of a section of the federal highway M-4 “Don”, km 530

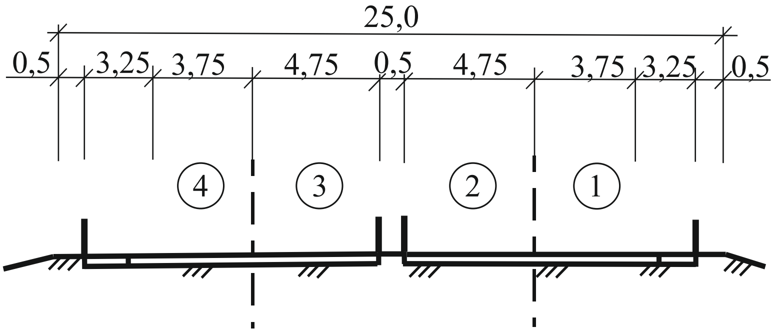

Fig. 4. Scheme of placing barriers at the highway section

Snow dependence of the highway section was analyzed. In accordance with the Highway Guidelines (СП) 34.13330.2012 the height of a snow-hard embankment h is given by the formula[1]

$$h = h_s + \Delta h, \tag{3}$$

where h_s is the estimated height of the snow cover with an increase possibility of 5 %; m, Δh is elevation of the embankment edge above the estimated level of the snow cover for making it snow-hard, m.

The estimated height of the snow cover with an increase possibility of 5 % in the area of the experimental site is h_s = 0.48 m [9], the elevation of the edge of the embankment above the calculated level of snow cover for roads of category I must be assigned at least 1.2 m, thus the height of the embankment will be h = 1.68 m.

As the embankment in this area has a height of 2.0 m, it does not belong to the category of “moderately covered” or “highly covered”. But the site is interesting to investigate as it has 4 rows of barrier fences that reduce the speed of the snow and wind flow and contribute to the deposition of snowstorms on the road surface, and there are also no snow protection tools with the entire volume of snow brought in during a snowstorm with access to the carriageway [2].

The geometric model was designed in the 3D MAX program using the “Cube Modeling” technique. It is a closed geometrical figure similar to a parallelepiped with an embankment located at an angle of 90 ° to the entrance to the channel. The geometric model of the test section of the highway with barriers is shown in Fig. 4.

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[1] Highway Guidelines (СП) 34.13330.2012. Highway. M.: Minstroy Rossii, 2018. 112 p.

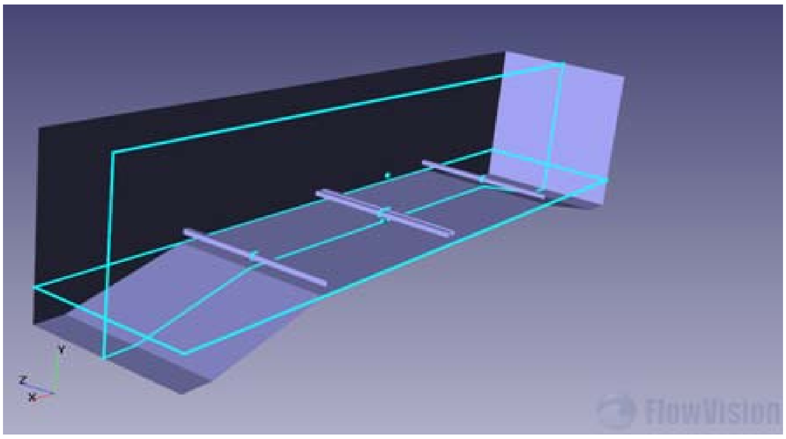

Fig. 4. Geometric model of the test section of the highway with barriers on the federal highway M-4 "Don", km 530

The channel length is determined by the distance from the streamlined body to the boundaries of the region, which is set so that the boundary conditions specified at these boundaries do not disturb the flow adjacent to the streamlined body. In this task, it is required to allow the flow in the area of the barriers, which were taken as the flow object. The width of the canal was chosen in accordance with the length of the highway section. The height of the channel is taken in accordance with the fact that at this height there will be no influence of the flow object on the field speed of the snow and wind flow. The field speed of the snow and wind flow is defined as the flow speed in a free state with no obstacles. The major dimensions of the model and the aerodynamic channel are shown in Table 2.

Table 2

Sizes of the model of a highway embankment and aerodynamic channel

Parameter	Value of a parameter
Sizes of the model of the highway embankment	
Width along a traffic lane, m	25
Width along the embankment bottom, m	41
Sizes of the model of the aerodynamic channel	
Length, m	85
Height, m	10
Width, m	10

4. Substantiation of the parameters determining the interaction of substances in the estimated area. In the software package FlowVision, creating a hydrodynamic model includes general installations; specification of substances; definition of geometric objects; phase formation; setting the initial data; designing and setting the boundary conditions.

The list of parameters of general settings and their characteristics are shown in Table 3.

Table 3

Parameters of the general settings identified for the entire estimated area

Parameter	Value	Substantiation of the choice of a parameter
Temperature, K	268	The temperature determining estimated area. The other temperatures in the project are set relative to it, if they are necessary, if not, the temperature is set by default for all the processes. In the studies, the temperature was taken to be –5 ° C which corresponds to the average air temperature during blizzards
Pressure, Pa	101325	Pressure in the estimated area. Taken to be corresponding to the normal atmospheric pressure
g-density, kg/m^3	1.3163	Density of the environment. Unless the layers are determined, the density is specified as identical for the entire environment

In order to simulate the snow and wind flow, the air flow was determined by means of the "Air_Gas (Equilibrium)" substance and selected from the database of substances available in the software. Its characteristics were set automatically.

Snow is defined by means of the substance "Water_Solid", that is, water in a solid state of aggregation. But as the density of water in this state is 917.5 kg/m^3 by default (at a temperature –5 °C) does not correspond to that of snow, the numerical value of the density of snow was entered manually and adopted in compliance with the data obtained from a special reference book [4]. For modeling, the value of snow density $\delta = 50$ kg/m^3 was taken corresponding to the type "Loose Dry Newly Fallen Snow".

Snow and wind flow is two-phased [5, 7] and each phase is determined by substances and physical processes. For each physical process, a mathematical model is set up in the FlowVision software package and employed for simulation. A description of the parameters that determine the interaction of substances in the estimated area during snowstorms is provided in Table 4.

Table 4

Description of the parameters determining the interaction of the substances in the estimated area

Type of a phase and a description	Substances	Physical processes	Mathematical model
Solid phase Wind flow	Air_Gas (Equilibrium)	Movement	Navier-Stokes model
		Turbulence	KES
Dispersion phase Snow	Water_Solid	Phase transfer	Convection and diffusion
		Movement	Movement

In order to simulate the transfer of snow in the estimated area, a computational model and boundary conditions for the elements limiting the computational subarea were specified. Boundary conditions are necessary to set the parameters of the environment located at the boundary of the computational area as well as to link two different volumes. Boundary conditions are specified on actual existing boundaries (e.g., on the surface of a body in a gas flow) and artificially outlined boundaries which separate the computational area from the rest of the world.

5. Simulation of snow sediments on highways with different modes of blizzard passage.

Simulation of snow deposits for snow and wind flows at different wind speeds during a blizzard: 15, 20, 25 and 30 m/sec was performed. The initial data for modeling are shown in Table 5 [4].

Table 5

Original calculation data

Index	Index at the flow speed, m/s			
	15	20	25	30
Mass consumption of the solid phase, kg/m^{2}sec	13.163	19.745	26.326	32.908
Mass consumption of the dispersion phase, g/m^{2}sec	10	80	270	640
Proportion of the dispersion phase in the flow, %	0.0002	0.0016	0.0054	0.03125
Atmospheric pressure, Pa	101325			
Temperature of the environment, *K* (°C)	268 (–5)			
Density of the dispersion phase, kg/m^3	50			
Density of the solid phase, kg/m^3	1.3163			

In order to perform the calculation, the geometric model was covered with a computational mesh designed in two stages. At the first stage, the initial mesh was formed.

The initial Cartesian grid is specified as three one-dimensional grids along each Cartesian coordinate axis. The number of cells of these grids is determined whose sizes are defined by the size of the model.

X axis. In this direction, the major task is to investigate the snow and wind flow in the area of the barrier fences. The number of cells is set in proportion to the fence. The cell size must be less than that of the rails in the corresponding direction. This condition is also considered when refining the mesh at the second stage.

Y axis. The major task in determining the parameters of the cells along the *Y axis* is to control the precipitated dispersed phase, thus the height of the snow cover must be proportional to the cell.

Z axis. When defining cell parameters along the *Z axis*, railing posts are considered. In order to include them in the calculation, a cell size corresponding with the rack is needed.

The parameters of the grid cells in the area of the barrier fences along the *X, Y, Z axes* are provided in Table 6.

Table 6

Parameters of the cells in the area of the barriers

Axis	Barrier size along the axis, m	Model size along the axis, m	Number of the cells along the axis, m	Cell size along the axis, m
X	0.36	85	236	≈0.36
Y	—	10	10	≈1.00
Z	—	10	28	≈0.36

The initial mesh is shown in Fig. 5.

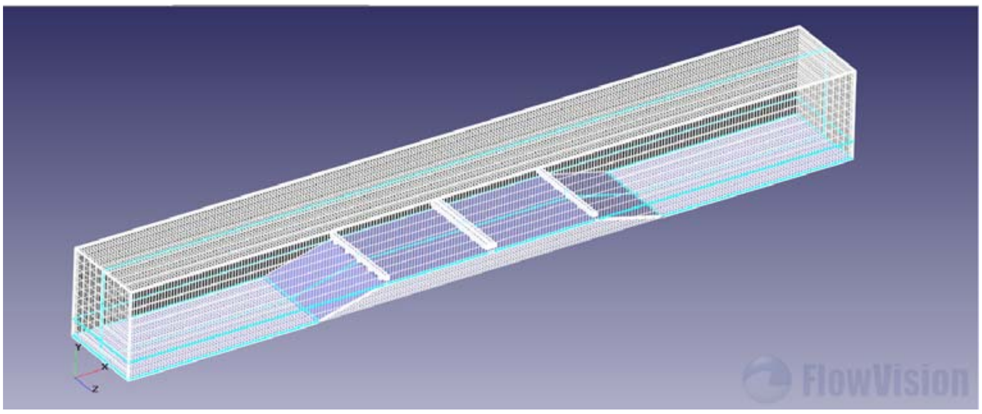

Fig. 5. Initial mesh

At the second stage, the mesh is refined to perform the calculations, i.e., adaptation of the initial mesh. Adaptation of the initial grid allows one to reduce the computational grid to the values required for the accuracy of the results without overestimating its size in areas where it is not necessary, which makes it possible to simplify the calculation. In this model, the first level is adapted when the cells of the initial computational grid are divided into two parts in height, width and length [8].

Through the course of the simulation, the following parameters were controlled:

1. The speed of the continuous phase (wind) which determines the speed and intensity of snow transfer per unit of time.

2. The speed of the dispersed phase (snow) which determines the amount of snow transferred per unit of time through a unit of area perpendicular to the snow and wind flow.

As a result of modeling, the proportions of continuous and dispersed phases were determined at different wind speeds during a blizzard: 15, 20, 25 and 30 m/s.

Figure 6 shows the distribution of the major parameters of the snow and wind flow at a wind speed of 20 m/s in graphical form.

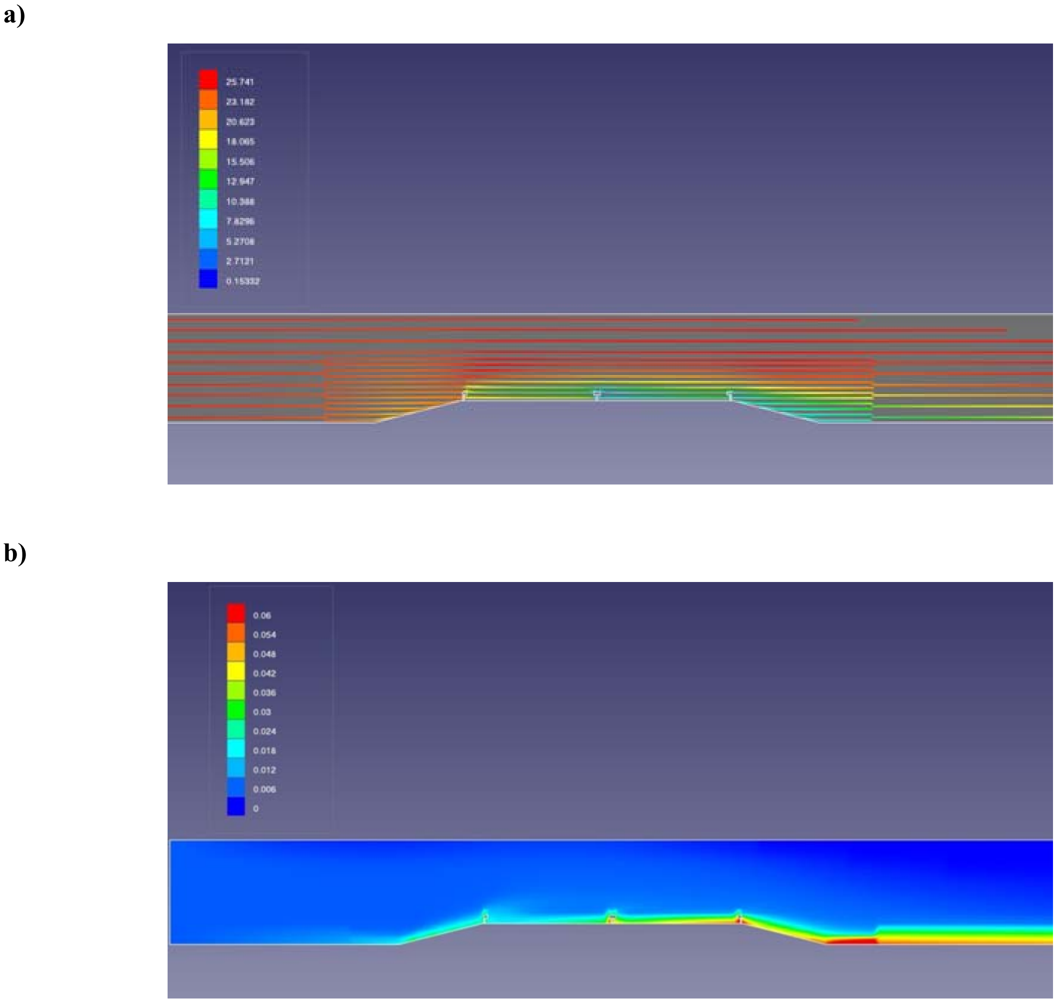

Fig. 6. Distribution of the major parameters of the snow and wind flow at the wind speed of 20: a) dispersion phase velocity; b) distribution of the dispersion phase

Through the course of the simulation, the dispersed phase was tracked in the design sections of the subsoil of the experimental section of the highway. Each design section consists of a large number of cells. Design sections are windward and leeward shoulders, windward and leeward carriageways, and a dividing line as shown in Fig. 1. The total number of cells for the experimental section was 19153.

The distribution of the dispersed phase velocity shown in Fig. 6 (a) allows one to analyze the change in the dispersed phase velocity during a flow around a highway with barriers.

As the embankment is approached on the windward side, the speed of the dispersed phase is 20 m/s, behind the first row of fences on the windward side a decrease in speed to 15 m/s is observed, after the dividing line and the second row of the barriers on the leeward carriageway, the speed drops to 8 m/s and after the third round of the barriers on the leeward side the speed is 5 m/s. A speed reduction will cause snow to fall on the road surface.

The distribution of the dispersed phase shows the amount of snow that is deposited in the design section. The graphical image in Fig. 6 (b) shows the amount of the dispersed phase in the form of color indication from blue (no deposits) to red (100 % deposits). The analysis of the simulation results allows us to conclude that up to 50 % of the dispersed phase can be deposited on the windward side of the embankment, on the leeward carriageway up to 40 % of the remaining fraction of the dispersed phase after the design section I, on the leeward carriageway up to 80 % of the remaining share after the design cross section III, and on the leeward shoulder up to 100 % of the remaining share after the design section IV. The simulation results confirm the correctness of the hypothesis about the drift of embankments with barriers [2] and, in addition to qualitative indicators, will allow a future quantitative assessment of the snow accumulation of highways.

The analysis of the distribution of the major parameters of the snow and wind station showed that when the the embankment is higher than the guiding operating mark, according to the condition of snow-carrying capacity, snow deposition during blizzards will take place due to the barriers. The position of the snow accumulation zones depends on their scheme. If on snow-covered embankments, initial snow deposits are observed on the windward slope and the shoulder, on embankments with barriers deposits will emerge on the leeward roadway and shoulder. This pattern of snow deposits is typical for the initial stage of snow drifts while the barriers function as snow blowing devices.

In order to determine the amount of snow, the following formula is used:

$$V_{snow} = V_{\%} \cdot V_{cell}, \tag{4}$$

where V_{snow} is the amount of snow, m^3, $V_{\%}$ is a volumetric proportion of the dispersion phase, %; V_{cell} is the volume of the estimated cell, m^3, $V_{cell} = 0.016079$ m^3.

As a result of the calculation, the volumes of snow deposited after a blizzard of 20 and 60 minutes in the design sections of the embankment were obtained. In order to simplify the model and speed up the calculation, snow evaporation in this study was not considered while modeling the snow and wind flow.

The result of calculating the amount of snow deposited on the experimental section of the highway after a blizzard of 20 minutes in five design sections is shown in Table 7.

Table 7

Amount of snow deposited during a blizzard of 20 minutes

Estimated section	Snow volume, m^3, at the wind speed:			
	15	20	25	30
I — Windward curb	0.17	0.40	0.75	1.24
II — Windward traffic lane	0.29	0.94	1.57	2.27
III — Dividing line	0.29	0.64	1.07	1.54
IV — Leeward carriageway	0.76	1.67	2.73	3.90
V — Leeward curb	0.52	1.15	1.88	2.69

The analysis of the simulation results shows that the implementation of calculations in the FlowVision program allows one to obtain the necessary information to investigate the dynamics of snow accumulations on the road section which can be employed to design recommendations on protecting the road section from snow or for performing snow removal operations during winter highway maintenance.

Conclusions.

1. For the first time, the simulation of the snow accumulation process on the section of the highway with barrier fences has been performed using the FlowVision software package.
2. The application of the software package for the study of snow-carrying processes is theoretically substantiated and the stages of designing a geometric model of the experimental site are identified. The resulting model can be used in the FlowVision postprocessor to simulate the process of snow accumulation on highway subsoil with barriers during snowstorms and its visual analysis.
3. For the first time, information resources have been substantiated for designing a hydrodynamic model of a snow and wind flow around a highway embankment with barriers during snowstorms considering geometric features of highways and physical properties of a snow and wind flow as a two-phase medium.
4. It has been proven that the results of modeling snow deposits with various parameters of blizzards in the FlowVision software package allow one to obtain quantitative indicators of

snow accumulation and can be employed to determine the parameters of snow removal during winter highway maintenance.

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