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Calculation and modeling of seasonally freezing soils of the highway located near Kosshy town with Frost 3D program

Abstract. *This article simulates ground conditions on a road section near Kosshy settlement (Astana, Kazakhstan) using Frost 3D modeling program. This program is used in scientific and engineering projects to assess the impact of climate change on frozen soils and engineering structures built on them. This program allowed to perform a thermal forecast for a section of road pavement, which is located in the third climatic zone, where the soil is saturated with moisture and has a high filtration rate. A three-dimensional model of the design area was also developed, taking into account the terrain and geological and lithological structure of the soil. This software complex allows to receive scientifically grounded forecasts of thermal regimes of permafrost soils under conditions of thermal impact of pipelines, production wells, hydraulic and other structures taking into account thermal stabilization of the ground. In this work we applied the program capabilities for seasonally freezing soils of Astana. Modeling in the program Frost 3D Universal allowed us to simulate and predict heat and mass transfer in the ground, as it can affect the service life of the road surface. The soil bases of highways as well as pavement layers remain in a stable frozen state during short-term temperature increases up to +6.6 °C and have a sufficient safety margin. When the air temperature rises for a short period of time, only 25 cm of the upper part of the pavement is exposed, which corresponds to the top layer of the hot highly porous asphalt concrete mix base.*
Key words: *Frost 3D, frozen soil, highway, computer modeling, epoxy resin.*

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1. Introduction

The Frost 3D Universal software complex allows you to obtain scientifically based forecasts of the thermal regimes of perennial frozen soils in conditions of thermal impact of pipelines, extractive Wells, hydraulic engineering and other structures, taking into account the thermostabilization of the soil. The software was developed on the basis of simmakers ten-year experience in the field of programming, computational geometry, numerical methods, three-dimensional visualization and parallelization of computational algorithms. The studied section of the highway is located in the area of the Karkaraly highway, 8 km from the bypass road towards the village of Kosshy.[6]

The predictive-thermal calculation of a road pavement fragment in the road climatic zone in a section of moisture saturated soil with high filtration rate was carried out. The road section is located at 50° north latitude. The size of the modeled section is 80x24 m. The ground slope is 1: 2 m. The site to be modeled is shown in Figure 1.[1]

Figure 1 - Investigated area on the map

The groundwater surface is level, intersected by the left and right boundaries of the site at a depth of 2.1 meters below ground. The temperature at a depth where there is no annual thermal variation is -1.5°C. The climatic conditions are outlined in Table 1. The average thermal conductivity of the winter snow cover is 0.28 W/(m·K). The temperature is rising at a rate of 0.06°C per year [2].

Table 1. Climatic conditions

Parameters	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Air temperature, °C	-15,1	-14,8	-7,7	5,4	13,8	19,3	20,7	18,3	12,4	4,1	-5,5	-12,1
Wind speed, m/s	4.7	4.4	5	4.5	4.5	4.1	4.1	3.7	3.8	4.6	5	4.7
Snow cover height, m	0.19	0.23	0.19	0.01	0	0	0	0	0	0	0.04	0.13

2. Methods and materials

2.1 Features of the Frost 3D program

Basic functionality of Frost 3D Universal:

- creation of a three-dimensional geometry of the calculated area, taking into account the relief of the Earth's surface and the geological and lithological structure of the soil;
- creation of a three-dimensional geometry of the foundations and foundations of pipelines, production wells, structures;
- Import three-dimensional geometries of objects in Wavefront (OBJ), StereoLitho (STL), 3D Studio Max (3DS) and Frost 3D Objects (F3O)formats;
- maintaining a database of thermal and physical properties of soils, materials of construction objects, climatic factors and parameters of cooling devices;
- designation of thermal-physical and hydrological properties and conditions of heat exchange on the surfaces of objects for three-dimensional geometric objects;

- calculation of the temperature distribution in the design area and the composition of non-frozen water, taking into account phase transformations and convective heat transfer;
- calculation of groundwater filtration;

Advantages of Frost 3D Universal:

- based on modern scientific achievements in the field of quantitative methods and mathematical modeling of thermal mass transfer processes;
- The calculation algorithms of the Frost 3D Universal program are parallel to the multi-core 64-bit CPU and GPU architecture, which made it possible to increase the calculation speed tens of times compared to sequential calculation algorithms;
- is a unique software solution that takes into account the features of the process of thermo-stabilization of frozen soil using cooling devices;
- allows a long-term forecast of the thawing of perennial frozen soils of large estimated areas (kilometers);
- takes into account the influence of the dynamics of changes in the thickness of the snow cover and the intensity of solar radiation on the temperature regime of the soil;
- ability to change thermal-physical properties and heat exchange conditions in the calculation process;
- calculation of groundwater filtration;
- convective transport of heat by filtration of groundwater takes into account.

2.2. Numerical Simulation of 3D Frost

The purpose of the study is to calculate the roadway on frozen soil in the Frost 3D program. By default, the two-dimensional estimated area is 60x60 M. it is necessary to set the beginning of the coordinates (0; 0), and the linear dimensions of the two-dimensional platform in the X and Y directions should be equal to 80 and 20 m, respectively.

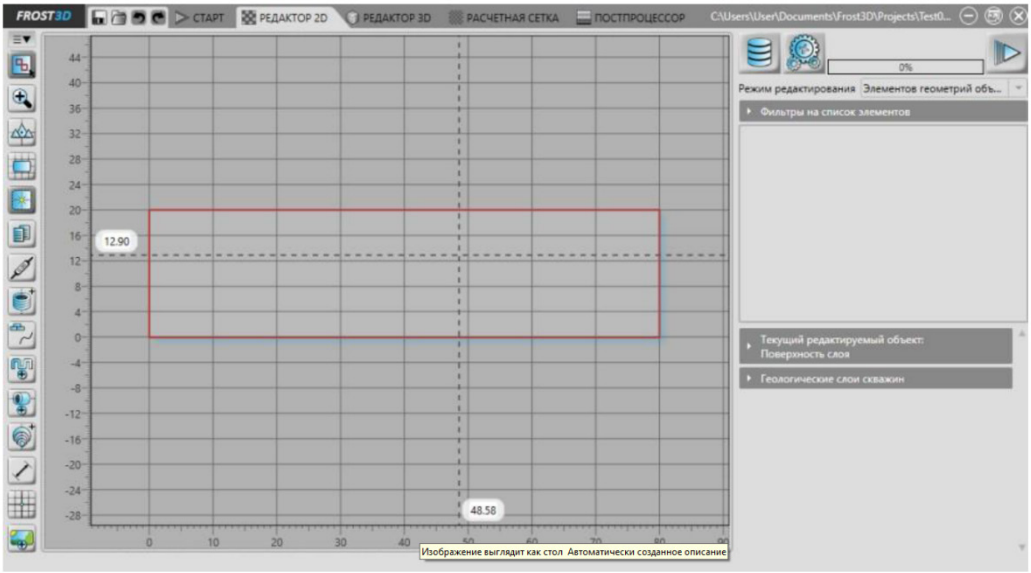

Figure 2. Two-dimensional calculation zone with a size of 80x20 mm

2.3. Creation of materials and determination of their physical properties

Within the framework of the computer model, objects are geological layers, artificial engineering geological elements, engineering structures and cooling devices. Objects have geometry (shape and position in three-dimensional space), as well as thermal-physical properties. In the Frost 3D software complex, a complete set of physical properties of an object is called a material. Materials are stored in a special database (library), which allows you to install the same

material on several objects (in other words, it gives the same physical properties to objects that are different in their objects and positions). The Frost 3D software complex allows you to process materials (physical properties of existing objects) at any stage of building a computer model [7].

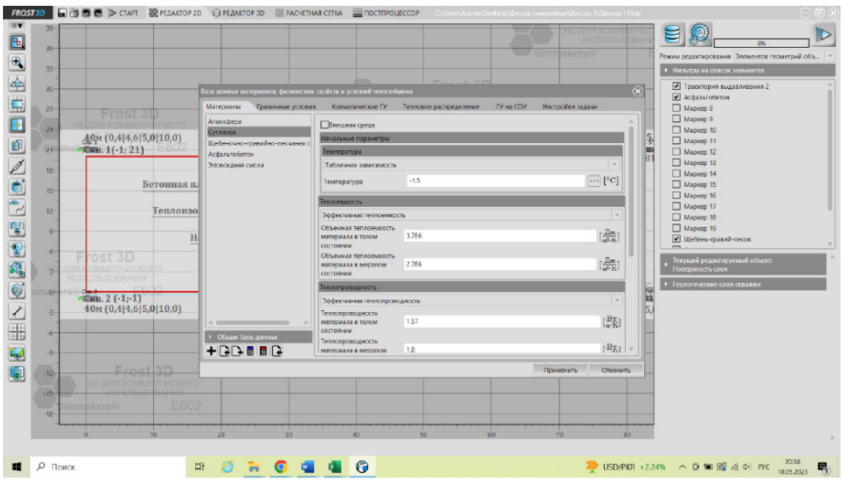

Figure 3. Geological layers and their parameters

Further, according to Table 1, the average monthly temperature values for 2018. It should be introduced from the 1st month to the 12th month of 2022.

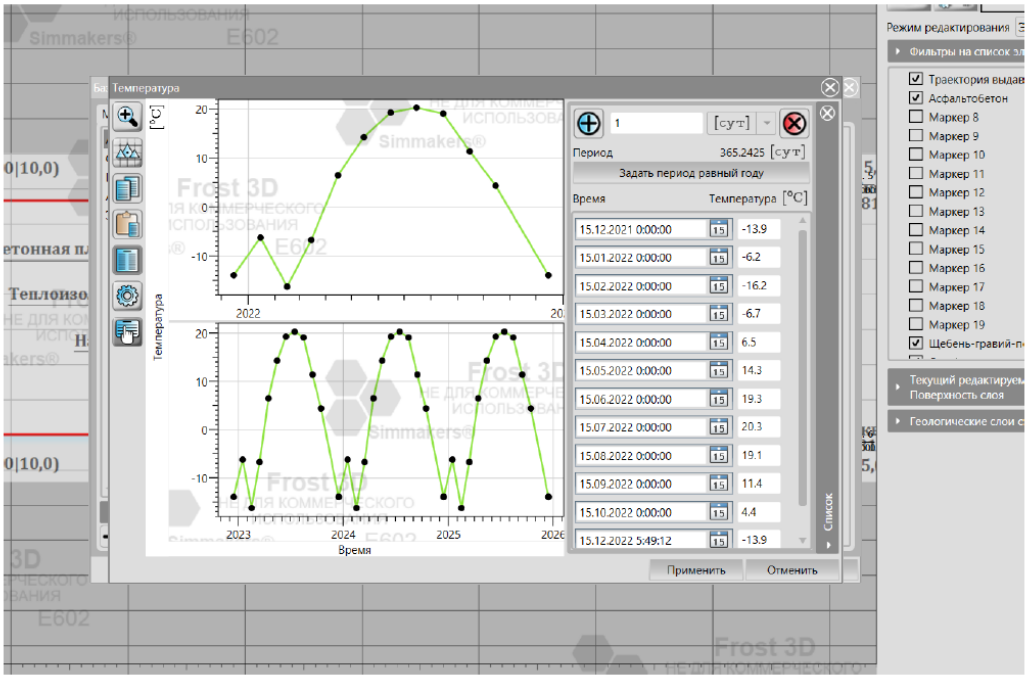

Figure 4. Dependence of temperature on time

When you are in the editing mode of geometry elements of objects on the toolbar, you need to select the “Add Geological drilling” option. Next, the geological well must be placed in the appropriate place of the site to be modeled. On the “polozhenie and priority” tab, you need to specify the value of the coordinate of the absolute sign of the estuary (equal to 40 m in the case under consideration), and in this field you can also edit the coordinates of the well, which characterize its position in the simulated area. Thus, we place 6 wells on the simulated site. Next, it is necessary to establish a common chain of geological layers for all wells (Figure 4). In the field

of properties, you need to add 4 geological layers by clicking on the" Add Layer "button in the" geological layer " field.

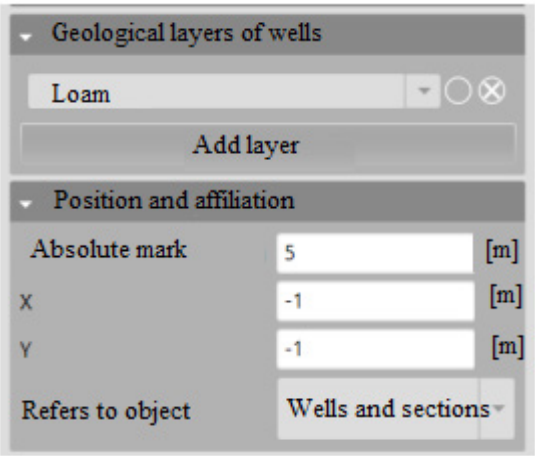

Figure 5. Sequence and power of geological layers of Wells

To build a heap, you need to select "Create element geometry (rectangle)" from the toolbar in object creation mode. All parameters of the object are located in the properties area on the right. Here you need to set the position of the hob, its height, extrusion parameters and other parameters. By analogy, the parameters of the elements of the heat insulator and the concrete slab are created, changed and set.

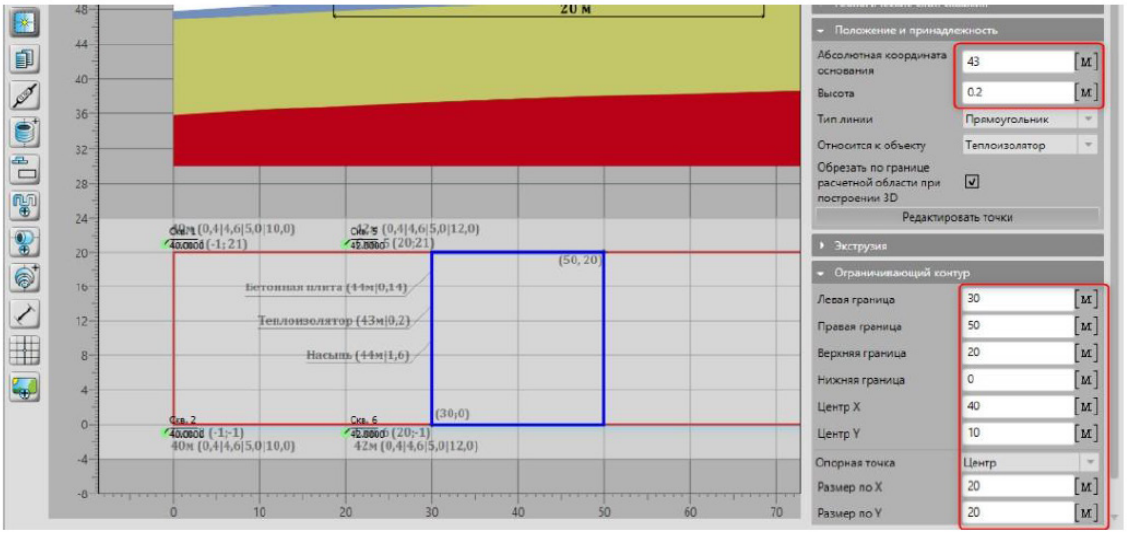

Figure 6. Concrete slab and its properties

3. Results and discussion

"Editor 2D "to restore three-dimensional geometry on given geometric objects, you need to click on the "next stage" button in the Go menu. In the "Interpolators" window that appears, enter the number of interpolation points along the Y-axis to 2 and click "Set".

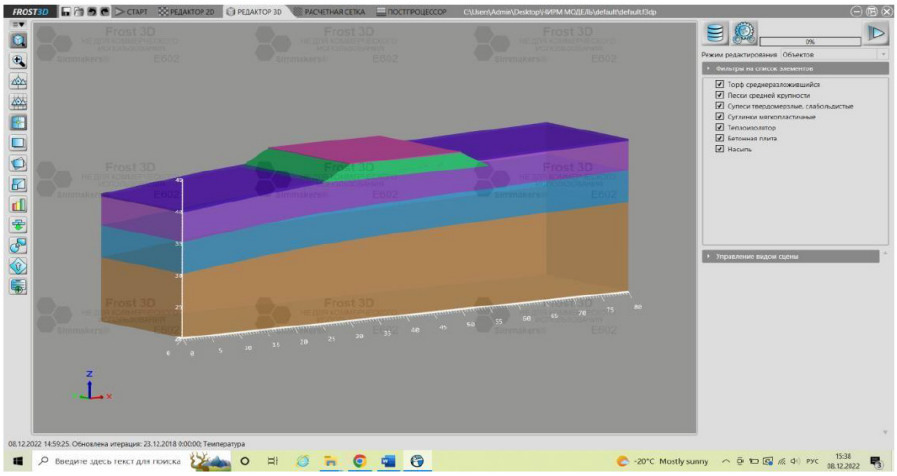

Figure 7. Geometry of a three-dimensional model obtained after Reconstruction from a two-dimensional drawing

To do this, in the "Editor 3D" tab, you need to go to the page mode of objects and select the desired page in the three-dimensional geometry of the calculated area, in the" Granichnye conditions " field, select the name of the boundary condition corresponding to this page. After completion or during the calculation process, you can view the obtained modeling results. To do this, you need to go to the" PostProcessor" Figure 8. In the figures below the mark 0 is taken as the mark corresponding to 320 m above the level of the Baltic Sea.

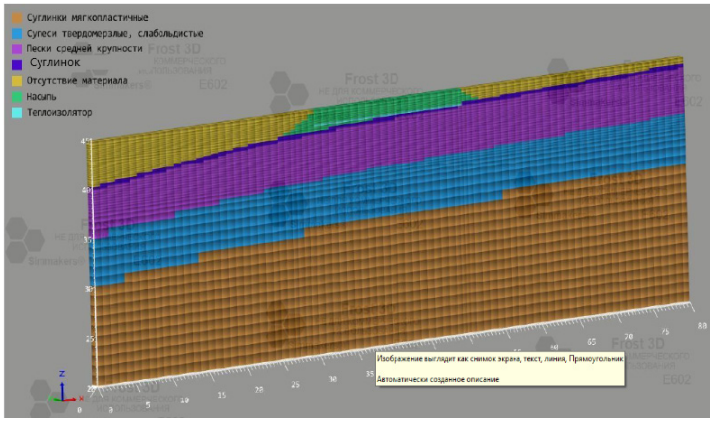

Figure 8. PostProcessor

As a result, the color distribution of the temperature is displayed, where blue corresponds to the lowest temperature, and red-to the highest temperature Figure 9.

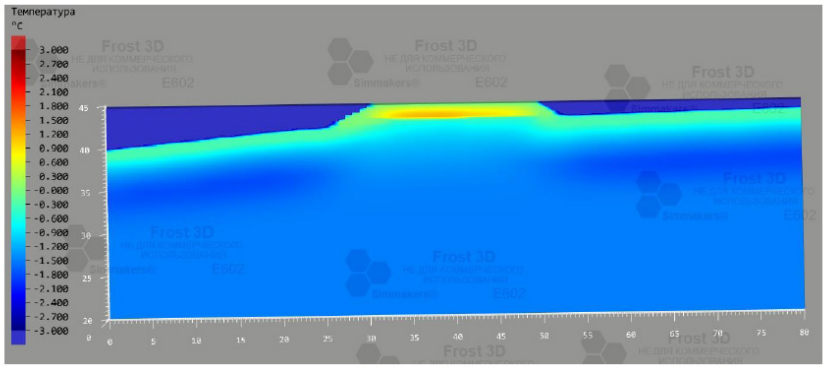

Figure 9. Three-dimensional visualization of the temperature distribution in the XZ section of the calculation area for January 2023

Recalculation of this model is carried out in the same sequence, but by adding one layer of polymer. Polymers are widely used in engineering construction, including for vapor barrier in soil. Polymers are used to create a reliable vapor barrier membrane that protects building structures from the penetration of water vapor. One of the most common polymers for soil vapor barrier is polyethylene. Polyethylene membranes have high strength, resistance to corrosion and chemical influences, as well as good adhesion to concrete and other building materials.[3]

Polymers have low thermal conductivity and volumetric heat capacity, so we use them to strengthen the vapor barrier on the ground. Epoxy resin was chosen for this work. Epoxy is a two-component material obtained by mixing epoxy resins and hardener. It is a high-strength and resistant material that has chemical resistance, adhesion, water resistance and other beneficial properties. In engineering construction, epoxy is used for various purposes, including corrosion protection of metal structures, repair of concrete and the creation of vapor barriers in the soil. In the soil, epoxy can be used to create a vapor barrier membrane membrane that protects building structures from moisture and water vapor. The use of epoxy in the soil has a number of advantages. This material has high chemical resistance and resistance to aggressive substances in the soil, such as oil and petroleum products. In addition, epoxy has a high adhesion to concrete and other materials, making it an effective material for creating a durable vapor barrier membrane in the soil. However, there are some limitations to consider when using epoxy in soil. For example, when applying epoxy to the soil, it is necessary to ensure good surface preparation and correct application of the material. In addition, it is necessary to take into account the technical requirements and recommendations of the manufacturer of the material. Changes to the calculation must be made in paragraph 2.4. where we created geological layers. Add a layer of polyamide resin 3 mm thick.[4]

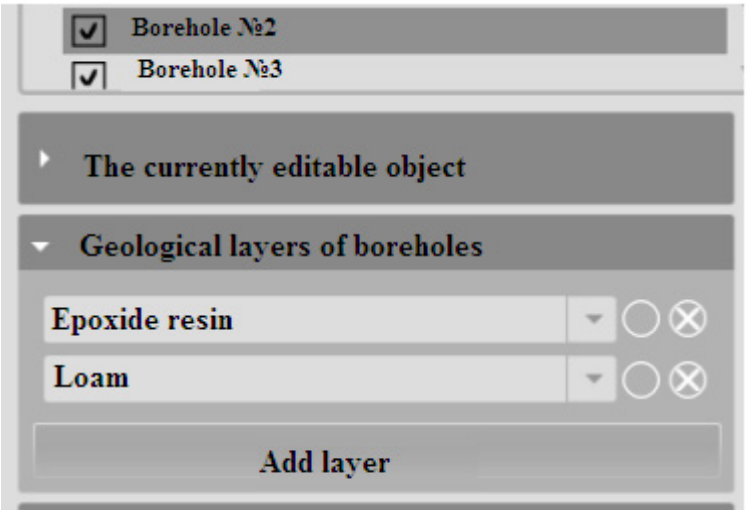

Figure 10. New sequence of geological layers of the well

The next stages of modeling are made in the same order Figure 11.

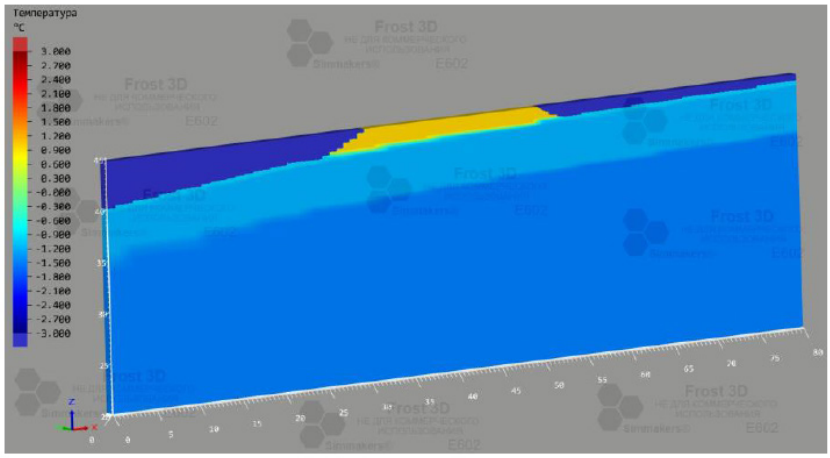

Figure 11. Three-dimensional visualization of the temperature distribution in the XZ section of the calculated area for January 2023 with the addition of a polymer layer.

As a result, the color distribution of the temperature is displayed, where the blue color corresponds to the lowest temperature, and the red color corresponds to the highest temperature. To visually show the temperature distribution, you need to adjust and display the "scale", which indicates the correspondence between color and temperature. [5]

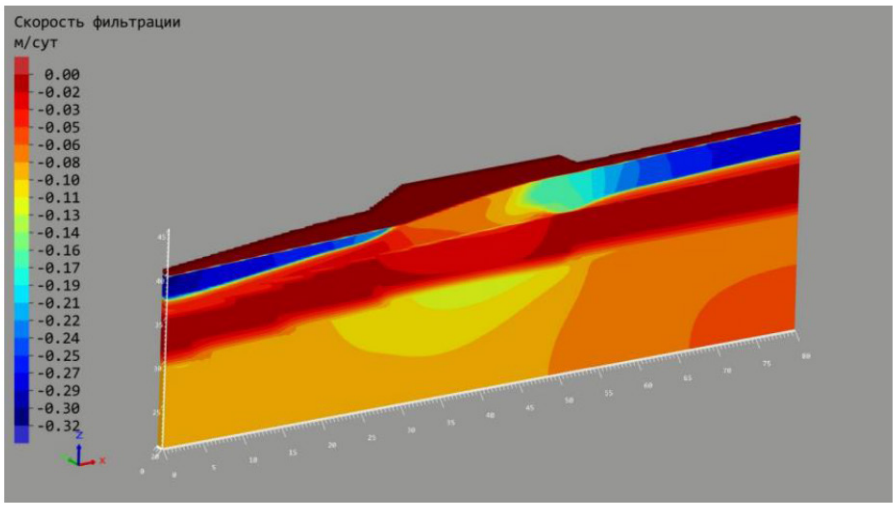

Figure 12. Mapping in the calculated area of the three-dimensional distribution of the filtration rate along the X-axis

4. Conclusions

1. As a result of the study, a thermal forecast calculation of a fragment of the road surface in the III Road climatic zone was made on a section of soil saturated with moisture with a high filtration rate.

2. Construction of a three-dimensional geometry of the calculated area, taking into account the relief of the Earth's surface and the geological and lithological structure of the soil.

3. Maintaining a database of thermal and physical properties of soils, materials of construction objects, climatic factors and parameters of cooling devices.

4. The soil bases of highways, as well as the layers of the pavement, remain in a stable frozen state at short-term temperature increases up to +6.6 °C due to subcompensation of heat (heat transfer) of the subject layers and have a sufficient safety margin.

5. During short-term increases in air temperature, only 25 cm of the top of the pavement is exposed, which corresponds to the top layer of the base made of hot highly porous asphalt concrete mixture.

6. The application of an additional layer of polymer material at a depth of 53 cm resulted in increased thermal insulation, waterproofing and prevention of frost heave.

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Қосшы қ. ауданында Frost 3D бағдарламасында автомобиль жолының маусымдық қататын топырақтарын есептеу және модельдеу

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Андатпа. Бұл мақалада Frost 3D модельдеу бағдарламасын пайдалана отырып, Қосшы кентінің (Астана, Қазақстан) маңындағы жол учаскесіндегі топырақ жағдайлары модельденеді. Бұл бағдарлама ғылыми және инженерлік жобаларда климаттың өзгеруінің мұздатылған топырақтарға және оларға салынған инженерлік құрылыстарға әсерін бағалау үшін қолданылады. Бұл бағдарлама топырақ ылғалмен қаныққан және сүзу жылдамдығы жоғары үшінші климаттық аймақта орналасқан жол жамылғысының учаскесіне жылу болжамын жасауға мүмкіндік берді. Сондай-ақ, Жердің рельефі мен топырақтың геологиялық-литологиялық құрылымын ескере отырып, жобаланған учаскенің үш өлшемді моделі жасалды. Бұл бағдарламалық кешен топырақтың термостабилизациясын ескере отырып, құбырлардың, пайдалану ұңғымаларының, гидротехникалық және басқа құрылыстардың жылу әсерінен мәңгі мұздатылған топырақтың жылу режимдерінің ғылыми негізделген болжамдарын алуға мүмкіндік береді. Бұл жұмыста біз Астананың маусымдық қатып қалған топырақтарына арналған бағдарламаның мүмкіндіктерін қолдандық. Frost 3D Universal бағдарламасындағы модельдеу бізге жердегі жылу мен массаның тасымалдануын модельдеуге және болжауға мүмкіндік берді, өйткені бұл жол төсемінің қызмет ету мерзіміне әсер етуі мүмкін.

Түйінді сөздер. Frost 3D, мұздатылған топырақ, автожол, компьютерлік модельдеу, эпоксидті шайыр.

Расчет и моделирование сезоннопромерзающих грунтов автомобильной дороги в районе г. Косши с в программе Frost 3D

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Аннотация. В данной статье с помощью программы трехмерного моделирования Frost 3D моделируются грунтовые условия на участке дороги в районе поселка Косши (Астана, Казахстан). Эта программа используется в научных и инженерных проектах для оценки влияния изменения климата на мерзлые грунты и возводимые на них инженерные сооружения. Данная программа позволила выполнить тепловой прогноз для участка дорожного покрытия, которое находится в третьей климатической зоне, где грунт насыщен влагой и имеет высокую скорость фильтрации. Так же была разработана трехмерная модель расчетной площади, учитывающая рельеф местности и геолого-литологическое строение грунта. Этот программный комплекс позволяет получать научно обоснованные прогнозы тепловых режимов вечномерзлых грунтов в условиях теплового воздействия трубопроводов, добывающих скважин, гидротехнических и других сооружений с учетом термостабилизации грунта. В данной работе мы применили возможности программы

для сезоннопромерзающих грунтов г. Астаны. Моделирование в программе Frost 3D Universal позволило нам смоделировать и спрогнозировать тепломассоперенос в грунте, так как он может повлиять на срок службы дорожного покрытия.

Ключевые слова. Frost 3D, мерзлый грунт, автодорога, компьютерное моделирование, эпоксидная смола.

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