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NUMERICAL MODELING OF THE PROCESS OF DEGRADATION OF PERMAFROST SOILS OF THE BASE OF THE RAILWAY ROADBED IN THE AREA OF PASSAGE OF CONSTRUCTION EQUIPMENT

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Abstract: When studying freezing, permafrost and thawing soils, it is absolutely necessary to develop models of processes occurring in soils and their mathematical description as a basis. This will make it possible to perform a calculated assessment of the "thawing foundation - structure" system during the entire lifetime of the object, which will make it possible to design it correctly. The article considers a soil model that allows us to consider the process of degradation of permafrost soils of the base of the railway roadbed in the zone of passage of construction equipment.

Keywords: numerical modeling, permafrost soils, permafrost degradation, temperature, thawing, freezing

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА ДЕГРАДАЦИИ МНОГОЛЕТНЕМЕРЗЛЫХ ГРУНТОВ ОСНОВАНИЯ ЗЕМЛЯНОГО ПОЛОТНА ЖЕЛЕЗНЫХ ДОРОГ В ЗОНЕ ПРОЕЗДА СТРОИТЕЛЬНОЙ ТЕХНИКИ

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Аннотация: При исследовании промерзающих, многолетнемерзлых и оттаивающих грунтов в качестве основания совершенно необходимой является разработка моделей протекающих в грунтах процессов и их математическое описание. Это позволит выполнить расчетную оценку системы «оттаивающее основание – сооружение» в течение всего срока существования объекта, что даст возможность правильно его спроектировать**.** В статье рассмотрена модель грунта позволяющая рассмотреть процесс деградации многолетнемерзлых грунтов основания земляного полотна железных дорог в зоне проезда строительной техники.

Ключевые слова: численное моделирование, многолетнемерзлые грунты, деградация мерзлоты, температура, оттаивание, промерзание

INTRODUCTION

Russia is rightly considered the coldest country in the world. Its characteristic feature is the presence of permafrost soils occupying more than two-thirds of the total area. In these areas, called the cryolithozone, thawing deformations that develop during the degradation of the base due to an increase in air temperature and permafrost are extremely important. Any design of facilities in regions with permafrost soils begins with thermophysical calculations in order to increase the efficiency of systems regulating the temperature regime of frozen foundations of embankments and recesses on railways and highways [1].

For soil in a frozen state, with an increase in temperature, even in the region of negative values, the strength of ice inclusions decreases, which is accompanied by a decrease in strength

and deformation characteristics. At zero temperature, the ice inclusions thaw and the soil experiences subsidence, which can reach significant values. The thawing process itself and the subsidence caused by it develop over time, which makes it necessary, in addition to the evolution of temperature fields, to consider consolidation during thawing for low-permeable soils.

THE MAIN PROBLEMS OF DESIGNING ON PERMAFROST SOILS

At the end of 2013, engineering and geological survey work began within the framework of the project for the development and construction of the second tracks of the railway infrastructure of the Baikal-Amur Mainline (BAM) and the Trans-Siberian Railway. The research began without scientific support and generalization of the accumulated experience, and for some design organizations this is the first experience of working on permafrost soils. Due to the extremely tight deadlines allowed for the survey of some of the objects, the survey was conducted in winter, since the first design solutions for construction should be issued in the spring.

Taking into account the above, as well as the fact that there are no clear instructions and standard solutions in regulatory documents concerning the design of measures excluding subsequent deformations in the abutment of the existing railway track bed on permafrost soils of the base, we consider it necessary to outline the experience of examination and treatment of the decreeing earthen dam and ways to improve its operational reliability.

The most common deformation of the BAM roadbed is precipitation of embankments (up to 94% of the total length of the roadbed on permafrost soils) [2]. When performing detailed diagnostics, we have to face three main types of deformations of embankments:

- thermal (thawing - compaction) deformations due to thawing during the degradation of permafrost bases;
- plastic (heaving-spreading-squeezing) deformations, due to waterlogged, heaving soils at the base of the embankment, falling into the zone of seasonal freezing-thawing;
- suffusion deformations due to the removal of pulverized clay fractions of soils from the roadbed and the base of the embankment.

Currently, thermal deformations of embankments are most common in the Western and Central sections of the BAM. Here the natural conditions are favorable for the preservation of permafrost rocks. Therefore, a new active layer was formed at the base of the mounds with a height of 1.5-6.0 m 3-5 years after their construction [3] and, despite the increase in average annual air temperatures in recent years, the depth of seasonal thawing and the temperature regime of the soils of the bases change differently depending on the average annual air temperature.

Practically all thermal precipitation of the Western and Central sections is caused by faulty drainage channels and channels of artificial structures, which provoke the development of stagnant water formations, thermokarst, filtration flows through the body of the embankment and eventually the degradation of permafrost (Fig.1).

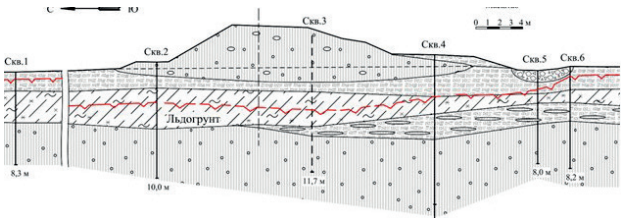


Figure 1. Long-term thawing of underground ice in the base and filtration of water through the body of the embankment

Thermal precipitation of the embankments of the Eastern part of the BAM today occurs only where strongly icy layers of soil and underground ice lie at the base of the roadbed.

Sudden thermal deformations, dangerous for train traffic, were recorded by us during the thawing of the lenses of re-vein ice. With unsecured drainage, the warming filtration flows are concentrated in the relief depressions occupied by re-vein ice. After the thawing of the ice, a

strong sod reinforced with roots and stems of shrubby vegetation prevents the filling of the cavity with the soil of the body of the embankment for some time. The filling of the cavity and the occurrence of dips occurs, as a rule, suddenly, during the passage of trains.

The experience of a detailed survey of the roadbed of the Eastern section of the BAM confirms the predictions of scientists. At the base of the embankments, regardless of their height, a "thawing bowl" with a depth of up to 5 meters or more has formed, the current rate of thawing of permafrost under the embankments does not exceed several centimeters per year.

However, the rates of thawing deformations exceed the predicted 1-2 cm/year, since thermal deformations are replaced by plastic deformations of the watered, heaving soils of the foundations of the roadbed falling into the zone of deep seasonal freezing [2, 3].

The assessment of the deformations of thawing of the base, composed of frozen soils, is aimed at establishing the possibility of allowing thawing during the operation of buildings or structures erected in the cryolithozone. If the value of the final precipitation is less than the maximum permissible, then there is no need to resort to expensive measures to preserve the frozen state of the soil during construction.

The first priority in this case will be the calculation of temperature fields in the base with the determination of the boundary of the thawing bowl within the lifetime of the structure. At the same time, it should be borne in mind that during thawing, which occurs at a constant zero temperature, ice-cement bonds are destroyed, which is accompanied by a sharp decrease in the mechanical characteristics of the base. With rapid thawing, caused, for example, by the action of local heat sources in icy cohesive soils, the stability of the thawed zone of the base can be disrupted, which leads to the extrusion of soils, accompanied by subsidence. In this regard, the most important in such cases will be the assessment of the strength of the foundation, folded thawed soil. For this purpose, the pressure on the thawed soil should be limited by the values of the calculated resistance set for both thawed soils using their characteristics φ and c in the thawed state.

Experimental determination of these characteristics should be carried out according to the unconsolidated shift scheme.

If there is no extrusion of the soil during thawing, and the pressure on the thawing soil does not exceed the calculated resistance of the soil, then the precipitation of the foundations can be determined based on the principle of linear deformability.

At low pressures (according to N.A.Tsytovich up to 400 kPa), the expression for the relative drawdown eth can be represented by a linear function of the form

$$\varepsilon_{th} = A_{th} + \delta_{th}\, p, \qquad (1)$$

where A_{th} is the thawing coefficient; δ_{th} is the compressibility coefficient of the thawing soil due to its compaction by pressure p.

The first term of the formula is called "thermal" precipitation, and the second term is "cargo", which corresponds to the nature of deformations.

NUMERICAL MODELING OF THE PROCESS OF DEGRADATION OF FROZEN SOILS

When studying freezing, permafrost and thawing soils, it is absolutely necessary to develop models of processes occurring in soils and their mathematical description as a basis. This will make it possible to perform a calculated assessment of the "thawing base – structure" system during the entire lifetime of the object, which will make it possible to design it correctly.

Thermophysical and deformation problems in which it is necessary to consider inhomogeneous bases, including layers of thermal insulation of variable thickness, taking into account unilateral heating or cooling of the object, phase transformations in the spectrum of negative temperatures, etc. are available for solution only using numerical methods. Such methods have led to the development of highly efficient pro-

grams capable of calculating temperature fields and deformations in the base.

Naturally, such programs are commercial, which is justified by the great complexity and duration of their creation. At the same time, the most valuable programs are capable, in addition to temperature, to solve the problems of joint calculation of the "foundation – structure" system.

Professors S.A.Kudryavtsev, I.I. Sakharov, V.N. Paramonov for the first time in world practice developed a mathematical model by the finite element method "Termoground" [4], which is an integral part of the software package "FEM models" developed in the company "Georeconstruction", which allows performing complex construction calculations of freezing, frost heaving and thawing processes seasonally freezing and permafrost soils of the foundations of buildings and structures in spatial formulation for scientific, design and construction organizations of the Russian Federation [4].

The freezing-thawing processes are described by the thermal conductivity equation for a non-stationary thermal regime in a three-dimensional ground space:

$$C_{th(f)}\rho_d \frac{\partial T}{\partial t} = \lambda_{th(f)}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_V \quad (2)$$

Where $C_{th(f)}$ is the specific heat capacity of the soil (thawed or frozen), J/kG·K; ρ_d – density of dry soil, kG/m^3; T – temperature, °C; t – time, s; $\lambda_{th(f)}$ – thermal conductivity of the soil (thawed or frozen), W/m·K; x, y, z – coordinates, m; q_V is the power of internal heat sources, W/m^3.

This equation makes it possible to determine the values of the incoming and outgoing heat flow from the elementary volume of the soil, leaving the main flow of the soil volume at a point in time equal to the change in the value of heat turns. In the permafrost soil model, the freezing-thawing processes are estimated non-stationary in time and non-linearly due to changes in thermophysical characteristics depending on changes in soil temperature and humidity. As a result of numerical modeling, temperature and humidity fields in the soil base are determined for each estimated period of time. [3-10].

As is known, when freezing soils, the source of forces are the deformation of heaving. Obviously, if physical experiments do not give an acceptable result, first of all, one should try to determine the heave deformations based on theoretical considerations, starting from obvious facts. One way or another, all deformations during freezing of soils are caused by the transition of water into ice. This is water present in the ground before freezing, as well as brought to the front due to migration. Thus, it is necessary to have an idea of the amount of water present in the ground initially, which is determined by the survey data, and the volume of water delivered from the melt zone.

THE INFLUENCE OF HIGHWAY ROADS ON THE DEGRADATION OF PERMAFROST

To date, extensive experience has been accumulated in the operation of buildings and structures on the Trans-Siberian and Baikal-Amur highways in permafrost conditions. Particular attention was paid to the uneven thawing of extended railway embankments depending on their orientation relative to the cardinal direction of the Earth. Solar energy is distributed in space in the form of a so-called direct directed flow of solar radiation, characterized by itself in the form of a straight line connecting the Sun and the Earth's surface. In view of the presence of the atmosphere and the Earth's surface, solar radiation already enters extended linear structures (railway embankments) in the form of three streams of solar energy: direct, diffuse or scattered and reflected from the Earth's surface.

To ensure the construction of the railway roadbed, temporary highways are being built, designed to transport soil from quarries to embankments being erected. Pritrass highways are built according to the norms of roads of the V category, as a rule, along the entire route, usually within the right-of-way. The type and design of the highway is determined on the basis of a

detailed study of local conditions and taking into account the transported soil.

The Baikal-Amur Highway passes through the territory with severe climatic conditions at 52-56 latitudes, at different angles of light and through areas of permafrost with a depth of 100 to 300 meters and high seismicity up to 9 points. During the construction of the highway and the ongoing modernization, the latest designs are used, new methods of construction and operation of facilities in difficult engineering conditions have been developed and patented.

We have given thermophysical calculations in the annual cycle of the condition of the railway embankment without measures and with measures traced in the latitudinal direction. Monthly solar radiation was taken in accordance with the norms of climatology and data from the nearest weather stations.

Fig. 2 shows the calculation results and shows plots of soil temperatures and zones of frozen soil (blue color) and thawing soil of the construction of the railway roadbed with a highway for the month of October of the tenth year of the forecast without measures to protect the permafrost soils of the base.

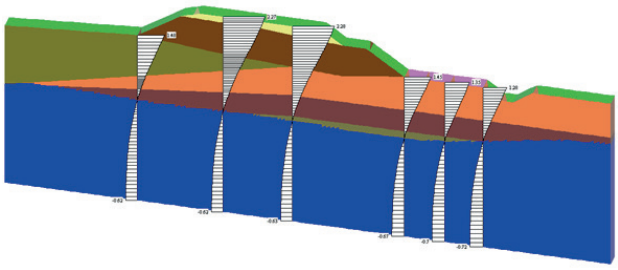


Figure 2. Plot of soil temperatures, ° C and zones of frozen soil (blue) and thawing soil of the structure for the month of October of the tenth year of the forecast without measures to protect the permafrost soils of the base.

These forecast calculations showed that due to the violation of the soil and vegetation layer in the zone of passage of construction equipment during the construction of the structure without additional measures, the degradation of permafrost soils increases by an average of 0.5 m over 10 years.

Fig. 3 shows the design scheme of the railway roadbed with measures to reduce the degradation of permafrost soils of the base in the form of cooling berms with the device of a highway.

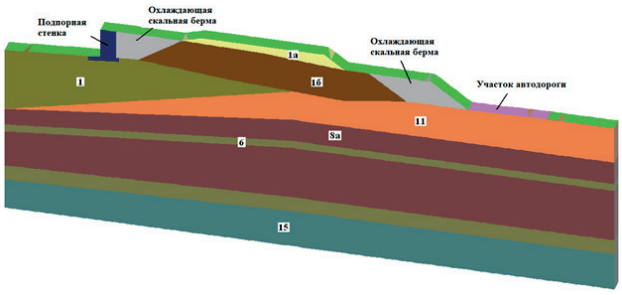


Figure 3. The design scheme of the railway roadbed with measures to reduce the degradation of permafrost soils of the base in the form of cooling berms with the device of a highway and retaining wall

Fig. 4 shows the calculation results and plots of soil temperatures, °C and zones of frozen soil (blue color) and thawing soil of the construction of the railway roadbed with a highway for the month of October of the tenth year of the forecast with measures to protect the permafrost soils of the base in the form of a cooling stone outline and retaining wall.

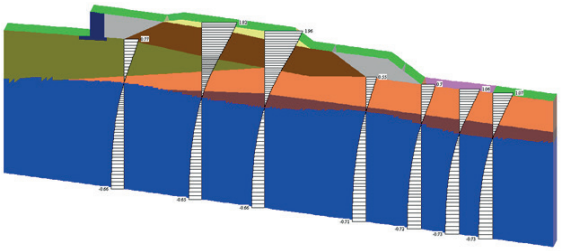


Figure 4. Plots of soil temperatures, °C and zones of frozen soil (blue color) and thawing soil of the construction of the railway roadbed with a highway for the month of October of the tenth year of the forecast with measures to protect the permafrost soils of the base in the form of a cooling stone outline and a retaining wall.

Calculations have shown that due to the violation of the soil and vegetation layer in the zone of the permafrost base of the pritass highway, during the construction of a structure with a cooling rock berm, the degradation of perma-

frost soils continues to occur by an average of 0.4 m over ten years. It is necessary to provide for measures to restore the boundary of permafrost soils in the area of the pre-mass highway for the passage of construction equipment.

To restore the boundary of permafrost soils in the area of the pre-mass highway for the purpose of passing construction equipment, it is advisable to provide a counterbanket of rocky soil, at least 1 m high and more than 5 m wide.

Figure 5 shows the design scheme of the railway roadbed with measures to reduce the degradation of permafrost soils of the base in the form of cooling berms and a counterbanket of rocky soil for the construction of a highway on it.

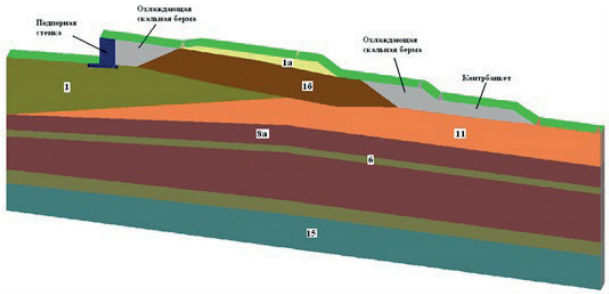


Figure 5. The design scheme of the railway roadbed with measures to reduce the degradation of permafrost soils of the base in the form of cooling berms and a counterbanket of rocky soil for the construction of a highway on it

Fig. 6 shows the calculation results and plots of soil temperatures, °C and zones of frozen soil (blue color) and thawing soil of the construction of the railway roadbed with a highway for the month of October of the tenth year of the forecast with measures to reduce the degradation of permafrost soils of the base in the form of cooling berms and a counterbanket of rocky soil for the device there is a highway on it.

Calculations have shown that the use of a counterbanket made of rocky soil for the construction of a highway on it as an event to stabilize permafrost soils showed a gradual increase in the boundary of permafrost soils by an average of 0.3 m over ten years.

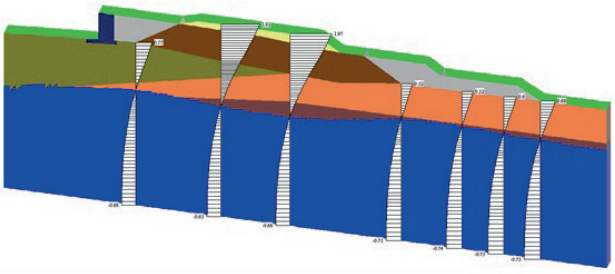


Figure 6. Plots of soil temperatures, °C and zones of frozen soil (blue color) and thawing soil of the construction of the railway roadbed with a pre-track highway for the month of October of the tenth year of the forecast with measures to protect the permafrost soils of the base in the form of a cooling stone outline and a counterbanket of rocky soil for the construction of a pre-track highway and a retaining wall on it walls.

CONCLUSIONS:

1. Any design of objects in regions with permafrost soils is advisable using thermophysical calculations in order to identify rational structures that reduce and regulate the temperature regime of frozen foundations of embankments and recesses on railways and highways.
2. The first priority in thermal engineering forecast calculations is the determination of temperature and humidity fields in the base with the establishment of the boundary of the thawing bowl within the lifetime of the structure.
3. Thermophysical and deformation problems in which it is necessary to consider inhomogeneous bases, including layers of thermal insulation of variable thickness, taking into account unilateral heating or cooling of the object, phase transformations in the spectrum of negative temperatures, etc. are available for solution only using numerical methods.
4. Predictive numerical calculations have shown that due to the violation of the soil and vegetation layer in the zone of passage of construction equipment during the construction of the structure without additional measures, there is an increase in the degradation of permafrost soils by an average of 0.5 m over ten years.

5. Numerical calculations have shown that the use of a counterbanket made of rocky soil for the construction of a highway on it as an event to stabilize permafrost soils showed a gradual increase in the boundary of permafrost soils by an average of 0.3 m over ten years

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