Geotechnical monitoring bearing capacity boring pile foundations of bridge during permafrost degradation

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Abstract. The construction and operation of bridge foundations in permafrost conditions is associated with many problems, the most urgent of which is the degradation of the frozen state of soils due to the effect of solar radiation on the thawing process. Thawing of permafrost soils of the base significantly affects structures, the design of which does not provide for thorough protection from natural factors - first of all, these are railway bridges. The changing climate has a destructive effect on permafrost soils, which is destructive for infrastructure facilities operated in the permafrost zone. The aim of the given work is to increase the efficiency of systems that regulate the temperature regime of permafrost soils of the bridges foundations which are located on railways in permafrost regions.

1. Introduction

It’s common knowledge, that natural and man-made factors significantly affect the change in the geocryological state of permafrost soils. This is due to the fact that in the process of development, the top layer of the soil is removed, the soil is partially replaced, the nature of the snow cover in certain areas changes, the effect of solar radiation, the effect of surface and ground waters on frozen soils and other factors. The process of heat exchange of permafrost foundations with the atmosphere causes a change in the temperature and moisture regimes of soils. This is leading to the intensive development of a number of cryogenic processes (thermokarst, frost heaving, frost cracking, solifluction, development of ice, new formation of frozen strata or their degradation, gully formation, etc.) conditions and significantly affect the life cycle of infrastructure facilities.

Thawing of permafrost soils of the base significantly affects structures, the design of which does not provide for thorough protection from natural factors - first of all, these are linear structures of transport infrastructure (roads and railways) and power supply facilities.

Thus, design, construction, operation and reconstruction of structures in permafrost areas should be carried out taking into account a comprehensive assessment of both engineering, geocryological and meteorological conditions, and the stress-strain state of the structure-base system with an assessment of various scenarios of possible consequences of the development of these territories.

The destruction of permafrost is classified as dangerous geocryological processes that become a source of natural and man-made emergencies.

Thanks to the development of modern technologies in the field of design, it becomes possible to predict the behavior of permafrost foundations of structures. But for the implementation of such
forecasting, it is necessary to conduct a comprehensive study of the soil massif regularities behavior taking into account all the factors. Thus, new construction projects and the reconstruction of existing ones should be carried out with theoretical reliance on the scientific industry.

It is advisable to provide measures to prevent buckling deformations during freezing and subsidence of structures during thawing in the Arctic and northern regions. The unfavorable climatic conditions of the northern regions create many problems in the construction of buildings and structures. Frozen soils contain ice and, when thawed, undergo deformations, the nature of which depends on the spatial location and configuration of ice inclusions, and the value is proportional to the mass of ground ice.

The issues of increasing the stability, reliability and durability of structures acquire great practical importance due to the increase in the rate of development of the northern regions. The foundations of structures in permafrost soils of the base are exposed to the processes of freezing, frost heaving and thawing. These processes are especially intense during the period of seasonal thawing and freezing.

Ensuring the stability and stability of railway infrastructure facilities erected in the areas of permafrost distribution on weak subsidence permafrost soils during thawing and underground ice close to the day's surface has been and still remains one of the most urgent problems of engineering permafrost.

The aim of the work is to increase the efficiency of systems that regulate the temperature regime of permafrost soils foundations of infrastructure facilities on railways and highways in permafrost regions [1, 2, 3, 4].

### 2. Assessment of the bearing capacity of bridges pile foundations in the process of permafrost soils degradation

Global climate change plays an important role in ensuring the sustainability of infrastructure structures (railways and highways, man-made structures) located in areas of permafrost [4].

According to the data of field observations of the temperature regime of permafrost rocks of the Tynda permafrost station, a tendency of the permafrost temperature increase has been observed over the past 30 years. However, it should be noted that the climate warming factor has a different effect on permafrost in various temperature and cryolithological zones. The changing climate has a destructive effect on permafrost soils, which is destructive for infrastructure facilities operated in the permafrost zone. Climate warming processes are not properly reflected in the regulatory and technical literature of the Russian Federation on the design, construction and operation of structures in the permafrost zone, because of this, the thermal engineering calculations do not take into account the climate warming factor of recent decades.

A great deal of experience has been accumulated by now in the operation of buildings and structures on the Trans-Siberian and Baikal-Amur Mainlines in conditions of permafrost and freezing soils. Some observations have shown uneven thawing of extended railway embankments, depending on their orientation relative to the cardinal direction of the Earth. Solar energy spreads in space in the form of the so-called direct directional 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 surface of the Earth, solar radiation arrives at extended linear structures (railroad embankments) in the form of three streams of solar energy: direct, diffuse or scattered and reflected from the Earth's surface.

Thermal calculations are carried out in accordance with the air temperature references, while the actual average annual air temperatures averaged over the past eleven years according to the data of meteorological stations gravitating towards the BAM and Transsib are higher than the reference ones by an average of 1.0 °C [4].

Figure 1 shows the graphs of changes in the average annual air temperature for the period 2003-2019 at the Tynda station of the Far Eastern Railway of the Russian Railways branch according to the data of meteorological stations in comparison with [4].
As it can be seen from the graphs, the average air temperature has increased by 1.1 °C over the past decade compared to [4] published in 2018 and amounted to minus 3.9 °C.

The pile foundations of infrastructure facilities are 10-20 meters in the permafrost, that is, just to the depth where the permafrost responds to climate change. We do not see the permafrost, there are some demonstrations, signs but we do not exactly understand what is happening to it. We can see from the surface that the ice on it has melted, the surface has subsided. The results of the permafrost soil temperature measurements made by the staff of the Tynda permafrost station at the base of the columnar bridge foundations bridge supports on the Far Eastern Railroad for the period from 1989 to 2020 showed an increase in soil temperature along the entire length of the pile surface from minus 3.5 °C to minus 0.5 °C [5].

This greatly affects \( F_u \) - the bearing capacity of a pile located in permafrost soil.

The bearing capacity, \( F_u, \) kH, of hanging rammed and bored piles, shells immersed with excavation and filled with concrete on permafrost soils according to [1, 2, 3, 4] is determined by the formula

\[
F_u = \gamma_t \gamma_c (RA + R_{af,i} A_{af,i})
\]  

where \( \gamma_c \) is the coefficient of pile working conditions; \( \gamma_t \) is a temperature coefficient that takes into account changes in the temperature of the foundation soils due to random changes in the outside air temperature; \( R \) is the calculated resistance of frozen soil under the lower end of the pile, shell or pillar, kPa; \( A \) - the area of the base of the columnar foundation or the area of the pile bearing on the ground, m², taken for solid piles equal to their cross-sectional area (or widening area), for hollow piles immersed with an open lower end - the gross cross-sectional area of the pile when filling its cavity cement-sand mortar or soil to a height of at least three pile diameters; \( R_{af,i} \) - design resistance of frozen soil or soil solution to shear along the lateral surface of freezing of a pile or columnar foundation within the i-th layer of soil, kPa, [1]; \( A_{af,i} \) is the freezing surface area of the i-th soil layer with the
lateral surface of the pile, and for a columnar foundation - the freezing surface area of the soil with the bottom step of the foundation, m².

In this formula the temperature coefficient is the most unpredictable which depends on multivariate analysis.

Professor D.A. Streletsky [5] proposed a regional assessment of the impact of permafrost degradation on infrastructure facilities.

Based on this assessment, we proposed a conceptual basis for a model for determining the bearing capacity of pile foundations of infrastructure facilities of the Eastern range of the Far Eastern Railroad on permafrost soils based on the studies carried out over the past more than 30 years of observations (figure 2).

The analysis of the permafrost foundation state according to this model showed that the bearing capacity of the pile during this period, when the soil temperature decreases from minus 3.0 °C to minus 0.5 °C, the bearing capacity decreases up to three times. For a bridge structure as a whole, the load-carrying capacity of the structure is taken, based on the minimum estimate of the load-carrying capacity of the superstructure element and supports.

The carrying capacity of the bridge structure is considered insufficient if the actual class of design load - as well as the mass of a single load WLF(Wheel load factor) – according to the WL-80 scheme is less than stipulated by modern design standards SR 35.13330.2011 "Bridges and pipes" [4] mandatory for use.

Thus, a slight change in the temperature of frozen soil leads to a very strong change in the foundations bearing capacity of infrastructure facilities built on it. This can be controlled only if geotechnical monitoring of the temperature of permafrost soil is constantly carried out. In addition to temperatures, it is advisable to monitor the physical and mechanical properties of frozen soil. For new construction, the composition of the soil is taken at the present time. No one assumes that the properties of the soil will change. For a geotechnical forecast of the state of the foundation of foundations in time for the periods of the life cycle of infrastructure facilities, it is advisable to carry out numerical modeling of the processes of freezing, frost heaving and thawing for a calculated period of time.

3. Technique for numerical modeling of freezing, frost heaving and thawing processes for the calculated period of time

It is the first time in world practice that professors S.A. Kudryavtsev, I.I. Sakharov, V.N. Paramonov have developed a mathematical model by the finite element method "Termoground" in the software
package "FEM-models", which allows performing complex construction calculations of the processes of freezing, frost heaving and thawing of seasonally freezing and permafrost soils of the foundations of buildings and structures in a spatial setting for scientific, design and construction organizations of the Russian Federation [6, 7, 8, 9, 10].

Freezing-thawing processes are described by the thermal conductivity equation for a non-stationary thermal regime in a three-dimensional soil space. This equation makes it possible to determine the values of the incoming and outgoing heat flux from the elementary volume of the soil, leaving the main flux of the volume of the soil at a point in time equal to the change in the value of heat turnover. In the model of permafrost soil, freezing-thawing processes are estimated not stationary in time and nonlinearly due to changes in thermophysical characteristics depending on changes in soil temperature and moisture. As a result of numerical modeling, the temperature and humidity fields in the soil base are determined for each calculation period of time [11, 12].

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

In the mathematical model by the finite element method "Termoground" in the software package "FEM-models" according to certain temperature and humidity fields in the calculated area of the frozen and thawed base, the stress-strain state of the processes of frost heaving and thawing of buildings and structures on permafrost soils is determined [13].

Freezing-thawing processes are described by the thermal conductivity equation for a non-stationary thermal regime in a three-dimensional soil space by the following equation [Fadeev AB, 1987; Comini G., et al., 1974; Guidice Del S. et al., 1978]

\[ C_{th(f)} \rho_d \frac{dT}{dt} = \lambda_{th(f)} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_v \]  

(2)

where \( C_{th(f)} \) is the specific heat capacity of soil (thawed or frozen) (J / kG K); \( \rho_d \) -is the density of dry soil (kg / m^3); \( T \) is the temperature (K); \( t \) time (s); \( \lambda_{th(f)} \) - thermal conductivity of soil (thawed or frozen) (W / mK); \( x, y, z \) - 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 temperatures of the incoming and outgoing heat flux from the elementary volume of the soil, leaving the main flux of the volume of the soil at a point in time equal to the change in the value of heat turnover.

The amount of solar radiation falling on the surface of engineering structures at any time is determined by astronomical, geographic and topographic factors and depends on the following parameters [6]:

1. Angle of incidence of rays of solar radiation on the surface of the Earth.
2. Absorption and scattering of solar radiation in the Earth's atmosphere.

The value of the angle of incidence on the horizontal surface, in turn, depends on: the position of the Earth in orbit (the rotation of the Earth around the Sun); latitude of the place; time of day (rotation of the Earth around its axis) [SP 131.13330.2018 Construction climatology].

The total solar radiation (direct and scattered) on a horizontal surface with a cloudless sky for the Eastern Polygon area of Russian Railways is located at 50-56 degrees of latitude and varies from about 120 MJ / m^2 in December to 900 MJ / m^2 in August, those approximately 7.5 times. Depending on the orientation of the cardinal points "north-south", these values change from 7 times in December to more than 2 times in July.

Thus, the algorithm of thermophysical stress-strain calculation makes it possible to determine the inflow of the solar radiation flux to the horizontally oriented in space on the surface of engineering structures in real climatic conditions of operation. This technique is the basis of the mathematical
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The Baikal-Amur Mainline passes through the territory with harsh climatic conditions at 52-56 latitudes, at different angles of light and through permafrost regions with a depth of 100 to 300 meters and high seismicity up to 9 points. During the construction of the highway and undergoing 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 presented thermophysical calculations in the annual cycle of the state of the approach railway embankment to the bridge, traced in the latitudinal direction. Monthly solar radiation was taken in accordance with climatological standards and data from nearby meteorological stations. Cloudiness in the reserve was not taken into account.

Calculations have shown that we deform the most of the section of the approach embankment of the railway from the southern side with a deformation value of up to 34 cm and thawing of the permafrost base under the embankment up to 1.8 m over a period of two years. Such thawing leads to uneven deformations of the southern and northern slopes of the embankment and its inclination, which is often observed in practice (figure 3).

**Figure 3.** Deformations of thawing of a railway embankment and permafrost soils of the base, taking into account the influence of insolation.

Solar radiation or radiant energy of the Sun is the main source of heat and light for the Earth's surface and its atmosphere; therefore, it is advisable to use the total solar radiation (direct and scattered) presented in regulatory documents as input data to obtain correct results of thermophysical calculations.

**Findings:**
1. Ensuring the stability and stability of railway infrastructure facilities constructed in permafrost areas on weak subsidence during thawing of permafrost soils and underground ice close to the day surface has been and still remains one of the most pressing and vutal problems of engineering permafrost.
2. The conceptual basis of the model for determining the bearing capacity of the pile foundations of infrastructure facilities of the Eastern test site of the Far Eastern Railway on permafrost is proposed, based on the research carried out over more than past 30 years of observations.
3. Analysis of the state of the permafrost base of bored foundations according to this model showed that the bearing capacity of the pile during this period, when the soil temperature decreases from minus 3.0 ºC to minus 0.5 ºC, the bearing capacity decreases up to three times. For a bridge structure...
as a whole, the load-carrying capacity of the structure is taken based on the minimum estimate of the load-carrying capacity of the superstructure element and supports.

4. A slight change in the temperature of frozen soil leads to a very strong change in the bearing capacity of the foundations of infrastructure facilities built on it. This can be controlled only if the geotechnical monitoring of the temperature of the permafrost soil and the physical and mechanical properties of the frozen soil is constantly carried out.

5. For a geotechnical forecast of the bored foundations state in time for the periods of the life cycle of infrastructure facilities, it is advisable to carry out numerical modeling of the processes of freezing, frost heaving and thawing for a calculated period of time and nonlinear thermophysical properties.

6. Analysis of survey and design materials showed some systemic shortcomings of heat engineering calculations, leading to unreliable modeling results and, as a consequence, to incorrect design decisions.

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