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Road and Rail Infrastructure V

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APPLICATION OF NUMERICAL SIMULATION FOR CALCULATING THE LOAD-BEARING CAPACITY OF BRIDGE SUPPORTS ON PERMAFROST SOILS

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Abstract

The Far Eastern region occupies the entire eastern part of Russia. Permafrost and seasonally frozen grounds are widespread on the territory of the Far East. Currently there is an increased attention to the development of the Far East, and besides the growth of the railway transport infrastructure is of particular importance. The issues of development and implementation of efficient technologies on modern railways are the most actual for today. Bridge piers should be classified according to their bearing capacity, depending on the bearing value of the subfoundation. The pile-trestle type bridge piers are promising for geocryological conditions in the north-eastern regions of our country. The forecasting of the temperature regime of frozen ground is one of the primary tasks in foundation calculation on permafrost. The article describes a technique for determining the bearing capacity class for pile-trestle type railway bridge piers using the numerical simulation of the thermal interaction of the foundation with a frozen ground body of the subfoundation. As a result of numerical simulation, the dependencies between the normative freezing depth, the calculated average annual ground temperature, the span value and the pier class were established. It is found that the use of numerical simulation allows obtaining higher values of the bearing capacity class of piers in comparison with analytical methods.

Keywords: railroad bridge, load-bearing capacity class, permafrost, pile bridge support type, numerical modeling

1 Introduction

The Far Eastern region infrastructure development is an important component of sustained growth of Russia economy. The transport infrastructure project construction in harsh environmental conditions requires the implementation of measures to protect against dangerous geotechnical phenomena, it also claims additional requirements for seasonality of work and work schedule. The project implementation in such conditions is characterized by high figures of labor content and material capacity, and hence the high construction cost in general.
One of the most important ways to optimize material inputs and improve efficiency is the use of modern methods in estimated studies of project engineering solutions. For example in the design of the bridges foundation in the permafrost areas, it is necessary to take into account complex thermodynamic processes in the foundation bed.
It is known that, for frozen soils, the strength and strain characteristics depend on a variety of factors: composition of the ground, humidity, structure, loading rate and, in particular, temperature [1]. Thus, the forecasting of the temperature regime of frozen soils is one of the primary tasks in the calculation of foundations on permafrost. There are two most common methods for solving the thermophysical problem of the temperature field dynamics: analyti-

cal and numerical ones. The real frozen soil body is characterized not only by the complex geotechnical units bedding, but also by nonlinear physical and thermophysical properties of the nonsteady temperature field [2]. Analytical methods allow to take into account the above factors with a relatively low accuracy, which is suitable for solving the simplest problems and approximate calculations. In the conditions of real design, numerical methods implemented in various software complexes are applied.

In accordance with [3] railroad bridge piers should be assigned a class of bearing capacity. The pier class K is the ratio of the safe temporary load k to the reference load k_c with the corresponding dynamic coefficient (1+μ).

$$K = \frac{k}{k_c(1+\mu)} \quad (1)$$

The method for determining the bearing capacity of the above manual contains instructions for calculating a shallow foundation or foundation by pit sinking in the absence of permafrost in the subfoundation. While the pile-trestle type bridge piers are promising for geocryological and climatic conditions in the north-eastern regions of our country. Thus, when designing artificial structures in the permafrost distribution areas, the question arises of expanding the existing methodology in determining the class of load-carrying capacity of piers, which are based on frozen soils.

In this paper, we propose a technique for determining the bearing capacity class for pile-trestle type bridge piers using the results of numerical modeling of the thermal interaction of foundation with a frozen soil body of the subfoundation. The results of determining the pier class by numerical simulation are also compared with those calculated accordind to the method described in [4].

2 Method of finite element implementation of the freezing-thawing processes of the software module “Termoground”

Numerical determination of the mean annual temperature is performed using the software module “Termoground”, which is a part of the “FEM-models” software package [5]. The mathematical model of the module “Termoground” is based on the model of freezing, thawing and frozen ground proposed by N.A. Tsytovich and Y.A. Kronik [6-8]. Here, to describe the non-stationary thermal regime in a three-dimensional soil body, a mathematical model is used, which is based on the Eq. (2):

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

To solve the spatial problems of freezing-thawing, three-dimensional finite elements in the form of four-node tetrahedron with shape functions are chosen [5]:

$$N_\beta = a_\beta + b_\beta x + c_\beta y + d_\beta z \quad (3)$$

where constants are calculated using determinant or matrix multiplication [9]. We write down the necessary matrices:

$$[N] = [N_i \; N_j \; N_k \; N_l] \quad (4)$$

$$[B]=\frac{1}{6V}\begin{bmatrix} b_i & b_j & b_k & b_l \\ c_i & c_j & c_k & c_l \\ d_i & d_j & d_k & d_l \end{bmatrix} \tag{5}$$

The integrals are fairly easy to compute if we use the volume L-coordinates

$$L_1 = N_i \text{ , } L_2 = N_j \text{ , } L_3 = N_k \text{ and } L_4 = N_l \tag{6}$$

The calculation of the integrals yields the following results:

$$\int_V [B]^T [D][B] dV = \frac{K_{xx}}{36V}\begin{bmatrix} b_ib_i & b_ib_j & b_ib_k & b_ib_l \\ b_ib_j & b_jb_j & b_jb_k & b_jb_l \\ b_ib_k & b_jb_k & b_kb_k & b_kb_l \\ b_ib_l & b_jb_l & b_kb_l & b_lb_l \end{bmatrix} + \frac{K_{yy}}{36V}\begin{bmatrix} c_ic_i & c_ic_j & c_ic_k & c_ic_l \\ c_ic_j & c_jc_j & c_jc_k & c_jc_l \\ c_ic_k & c_jc_k & c_kc_k & c_kc_l \\ c_ic_l & c_jc_l & c_kc_l & c_lc_l \end{bmatrix} + \frac{K_{zz}}{36V}\begin{bmatrix} d_id_i & d_id_j & d_id_k & d_id_l \\ d_id_j & d_jd_j & d_jd_k & d_jd_l \\ d_id_k & d_jd_k & d_kd_k & d_kd_l \\ d_id_l & d_jd_l & d_kd_l & d_ld_l \end{bmatrix} \tag{7}$$

$$\int_S h[N]^T [N] dS = \frac{hS_{jkl}}{12}\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 2 & 1 & 1 \\ 0 & 1 & 2 & 1 \\ 0 & 1 & 1 & 2 \end{bmatrix} \tag{8}$$

$$\int_V [N]^T Q dV = \frac{QV}{4}\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{9}$$

$$\int_S T_\infty h[N]^T dS = \frac{hT_\infty S_{jkl}}{3}\begin{bmatrix} 0 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{10}$$

For the Eq. (9), there are three other forms of recording, one for each of the remaining sides. In each of them, the values of the coefficients on the main diagonal are equal to two and the values of the non-zero coefficients outside the main diagonal are equal to one. The coefficients in the rows and columns corresponding to the nodes located outside the considered surface are zero. For the Eq. (10) there are also three other forms of recording. The zero coefficient is in the row corresponding to the node outside the surface under consideration. S_{ijk} — is the surface area containing nodes i, j, k, etc. [5].

The purpose of solving the finite element equations is to calculate the temperature at each node. For linear studies, when the ground properties are constant, the temperature at the nodes is calculated directly. However, in cases of nonlinear studies, when at the beginning of the analysis the thermal properties of soils are a function of temperature, the current properties of soils are not known; therefore, an iterative scheme is required to solve the system of equations [5]. The realized finite-element model uses a repeated replacement technique in the iterative process. For the first iteration, the original properties of the elements are used to form the stiffness matrix of the system. In a subsequent iteration the ground properties are updated, using the calculated subfuondation ground temperature from the previous iteration. The iterative process continues until the number of iterations reaches the specified maximum number or until the solution results satisfy the convergence criterion [5].

The program uses the temperature vectors changes {ΔT} between successive iterations as a measure of convergence. The vector norm of changes is called remainder and is defined as [5]:

$$R = \Delta T = \left(\sum_{j=1}^{n} \left| \Delta T_j \right|^2 \right)^{2/3} \tag{11}$$

The remainder is a measure of the size of the temperature difference between the iterations. In the normal process of convergence, the remainder will decrease and approach the zero value. A solution is considered convergent when the remainder is less than the specified accuracy of the solution [5]. Once the solution has converged and the core temperature values are determined, thermal gradients and heat flux units at each Gaussian integration points within each element are calculated according to the Eq. (12) [5]:

$$\begin{Bmatrix} i_x \\ i_y \\ i_z \end{Bmatrix} = [B]\{T\} \tag{12}$$

The velocity of the flow unit at each Gaussian integration point is calculated from Eq. (13) [5]:

$$\begin{Bmatrix} \nu_x \\ \nu_y \\ \nu_z \end{Bmatrix} = [C][B][T] \tag{13}$$

In the realized model, the thermal conductivity at each Gaussian integration point is stored in a certain array for the subsequent formation of finite element equations. The same thermal conductivity values are used to calculate the heat flux unit [5].

It is possible to account for the amount of heat flow in any direction. This number can be calculated from the node temperatures and the coefficients of the global equation of the finite element. The equation of the heat flux in the matrix form will be written in the form [5]:

$$[K]\{T\} + [M]\frac{\Delta T}{\Delta t} = Q \tag{14}$$

Global sets of finite equations for one element are as follows:

$$\begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} & c_{17} & c_{18} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} & c_{27} & c_{28} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36} & c_{37} & c_{38} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46} & c_{47} & c_{48} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56} & c_{57} & c_{58} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66} & c_{67} & c_{68} \\ c_{71} & c_{72} & c_{73} & c_{74} & c_{75} & c_{76} & c_{77} & c_{78} \\ c_{81} & c_{82} & c_{83} & c_{84} & c_{85} & c_{86} & c_{87} & c_{88} \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \end{Bmatrix} = \begin{Bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \\ Q_6 \\ Q_7 \\ Q_8 \end{Bmatrix} \quad (15)$$

From the Eq. (14) of heat flux, the total flux of temperature variation between the two nodes is:

$$Q = kA\frac{\Delta T}{l} \quad (16)$$

The coefficients C in Eq. (15) are represented by "kA/l" in Eq. (16). Therefore, the flow from node i to node j:

$$Q_{ij} = C_{ij}\left(T_i - T_j\right) \quad (17)$$

3 The main part

The method allows to determine the ground bearing capacity class for pile-trestle type piers in conditions of perfmafrost subfoundation. When calculating the bearing capacity, the initial equation of limiting states "on the average pressure" is used [3]:

$$\sum N_п + \sum N_к = m\gamma_n RA \quad (18)$$

To determine the ground bearing capacity of the bored precast piles the Eq. (19) is used [4]

$$F_u = \gamma_t \gamma_c \left(RA + \sum_{i=1}^{n} R_{af,i} A_{af,i} \right) \quad (19)$$

In such case, the permissible temporary load is calculated by the formula

$$k = \frac{mn_{св}\frac{F_u}{\gamma_n} - \sum_{i=1}^{n} N_{n,i}}{\varepsilon_k \gamma_{fk} \sum \Omega_k^N} \quad (20)$$

In accordance with [4], the average annual temperature is determined by the following formula

$$T_0 = \frac{1}{t_y}\left[\left(T_{f,m} - T_{bf}\right) t_{f,m} + L_v d_{th,n} \left(\frac{d_{th,n}}{2\lambda_f} + R_s \right) \right] + T_{bf} \quad (21)$$

4 Discussion and conclusion

To compare the above methods we plotted several graphs of the average annual soil temperature, the bearing capacity of foundations for soil and the bearing capacity class of piers in accordance with the settlements climatic data, Figure 1 and Figure 2. Based on the comparison, it was found that the method using numerical models corresponds to higher values (up to fifteen percent) of both the class of supports and other characteristics.

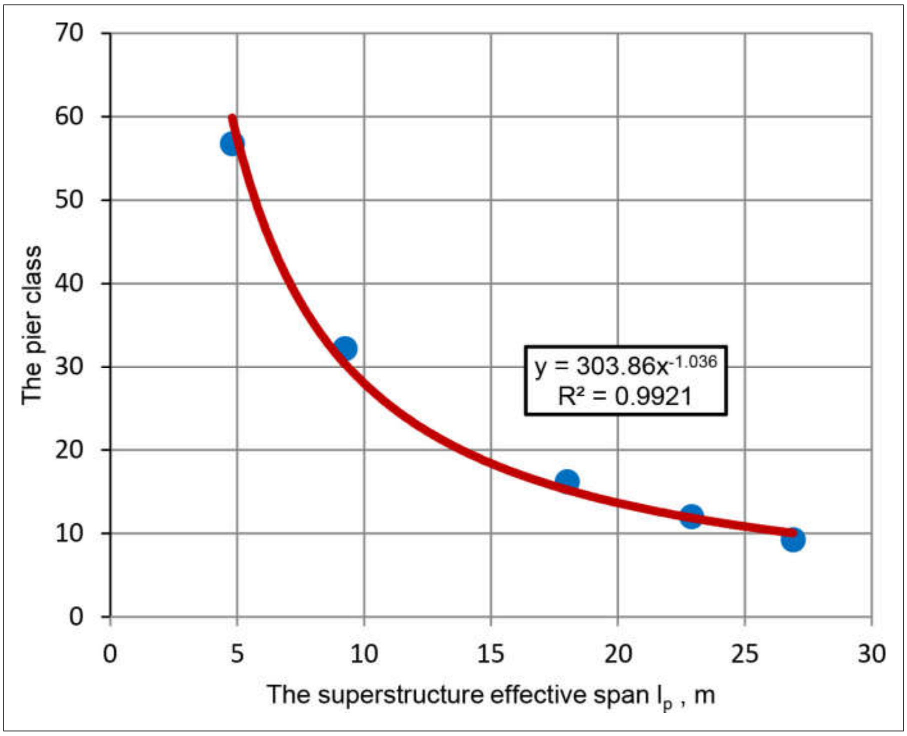

Figure 1 The dependence between the superstructure effective span and the pier class

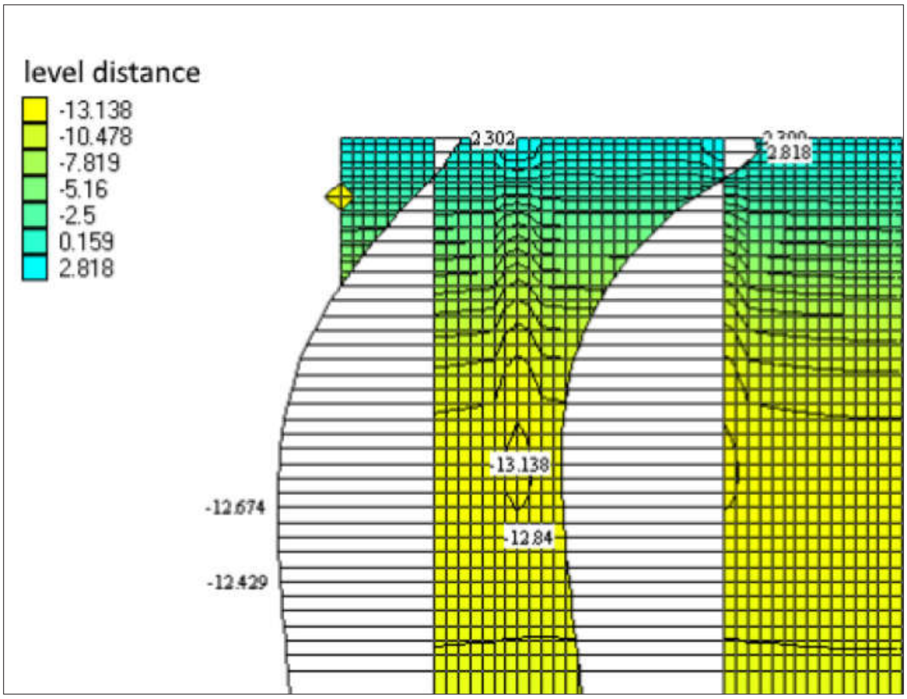

Figure 2 Ust'-Nera, the subfoundation temperature field in September

Thus, numerical methods describe the thermophysical processes in the interaction of foundations and sudfoundation frozen soils more accurately, which in turn makes it possible to obtain higher reliability measures of both structural units and the entire structure as a whole.

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