Applied Mathematics, Modeling and Computer Simulation
C.-H. Chen et al. (Eds.)

doi:10.3233/ATDE231047

Computer Modelling of Thermal Interaction in the Pile Foundation System of a Railway Bridge Support Structure in Permafrost

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Abstract. A new model and computer program have been developed to describe the propagation of non-stationary thermal fields in frozen soils with complex lithology for pile foundations of capital construction projects. The results obtained were used to predict changes in the dynamics of the bearing capacity of soil for the emergency support structure of a railway bridge in the permafrost zone. This support structure consists of 12 large-diameter piles, for which solar radiation is also considered for the piles located on the southern part of the support structure, which makes it possible to observe the effect of a thermal bridge, when during the summer season the accumulated heat spreads deeper and faster into the pile than through the ground due to higher thermal conductivity of the pile concrete. In the approach the prehistory of the thermal processes in the soil foundation is essential for the bearing capacity estimation. The results of numerical calculations are presented.

Keywords. Pile foundation, permafrost, soil bearing capacity, climate change, mathematical modelling

1. Introduction

In the permafrost zone the one of the basic principles of construction of most residential buildings and capital structures is related to the needs preserving the frozen state of the foundation soils. The tendencies of air temperature warming and increasing anthropogenic impact on the environment result the changes in features of permafrost, the boundaries, the firmness, and the durability. Last two decades these processes especially activated in the Northern Hemisphere and makes up about 25% of the Earth's surface [1]. These changes are especially relevant in areas where pile foundations of residential buildings, railway bridge supports, and other engineering structures are used. A number of serious accidents are caused by the permafrost degradation in the northern regions [2-5]. Therefore, the temperature monitoring and predicting the changes in the permafrost that affect the bearing properties of foundation soils under such capital structures is an urgent problem. The basic parameter which effect on the permafrost is

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the temperature. To solve this problem of the monitoring there used the methods of computer modeling of three-dimensional non-stationary thermal fields in the foundations of structures in combination with data from measuring soil temperatures in thermometric wells [6,7]. When modeling thermal fields in the soil that influence changes in the bearing capacity of the soil, it is necessary to consider climate changes and the influence of technogenic influences on the pile foundation.

The operation of railway lines in the permafrost zone is associated with certain safety requirements. For example, railway bridge supports are influenced by climatic and dynamic loads, which must be considered when operating railway tracks in such conditions. The paper considers a specific railway bridge support located in the Yamalo-Nenets Autonomous Okrug (Russia), for which long-term observations have shown that global warming has continued since the late 1970s at a rate of 2.4-2.8°C per 50 years [8]. Observations of this support showed the subsidence by 15 mm over 6 months, which could lead to an accident on this section of the railway line. This paper is devoted to thermal engineering calculations for modelling non-stationary temperature fields and calculating the load-bearing capacities of piles around this railway support. The developed approach and software can be applied to other supports of railway bridges located in the permafrost zone.

2. Statement of the Problem and Mathematical Model

2.1. Object of study

A metal bridge crossing of a railway line with an emergency railway support is considered (figure 1). The railway support is a group of 12 piles with a diameter of 1024 mm, located in three rows at 1.6–1.5 m from each other and united at the top by a reinforced concrete grillage.

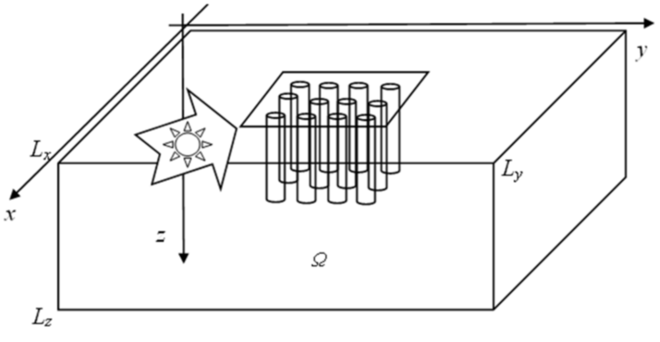


Figure 1. Railway Bridge Support Structure

2.2. Mathematical model

To model thermal fields in the permafrost zone during the operation of various technical systems, various technical systems, climatic parameters and physical factors should be considered. As the natural climatic factors may be considered seasonal changes in air temperature and solar radiation, cyclic thawing and freezing of the soil during the seasons, snow cover, etc. The physical factors include the different thermophysical parameters of soils.

Let at the initial moment t_0 the soil occupies a given parallelepiped Ω, containing piles of railway bridge support and has the temperature $T_0(x,y,z)$. The foundation of the bridge support is 12 metal pipes with a diameter of 1024 mm, filled with reinforced concrete. Let consider a three-dimensional computational domain in which the axes x and y located parallel to the ground surface, and the z axis is directed downward (figure 1). In the center of the computational domain Ω in the plane $\{x,y\}$ there is a grillage of a railway support. We will use for modeling the processes of heat propagation in frozen soil the following equation in the region Ω

$$\rho(c_v(T) + k\delta(T - T^*))\frac{\partial T}{\partial t} = div(\lambda(T)\, grad\, T) \tag{1}$$

with the initial condition

$$T(t_0, x, y, z) = T_0(x, y, z). \tag{2}$$

Here, $\rho=\rho(x,y,z)$ is the density [kg/m^3], $T^*=T^*(x,y,z)$ is the temperature of the phase transition, $c_v(T)=\begin{cases} c_1(x,y,z), \text{ for } T < T^* \\ c_2(x,y,z), \text{ for } T > T^* \end{cases}$ is the specific heat capacity [J/(kgK)], $\lambda(T)=\begin{cases} \lambda_1(x,y,z), \text{ for } T < T^* \\ \lambda_2(x,y,z), \text{ for } T > T^* \end{cases}$ is the thermal conductivity coefficient [W/(mK)], $k=k(x,y,z)$ is the specific heat of the phase transition, and δ is the Dirac δ-function.

Applicability of this equation for solving such problems is justified in [9]. The main zone of formation of natural thermal fields is on the soil surface. As a boundary condition at $z=0$, the equation of balance of flows bringing and taking away energy is used, taking into account the main climatic factors, namely [6,7]

$$\alpha q + b(T_{air} - T|_{z=0}) = \varepsilon\sigma\left(T^4 - T_{air}^4\right) + \lambda \frac{\partial T}{\partial z}\Big|_{z=0} \tag{3}$$

Here $T_{air}=T_{air}(t,x,y)$ denotes the air temperature at time t in the surface layer at point $(x,y)\in \Omega$. T_{air} changes in accordance with the annual temperature cycle and changes 4 times a day in accordance with data from the Novy Urengoy weather station, taking into account the warming trend, which in the report is 0,04°C per year. In the winter in $T_{air}(t,x,y)$ it is also taken into account a snow cover. $\sigma = 5{,}67\cdot 10^{-8}$Вт/(м^{2}К^4) is the Stefan-Boltzmann constant, $b=b(t,x,y)$ and $\varepsilon=\varepsilon(t,x,y)$ are the heat transfer and the emissivity coefficients, respectively. Heat transfer and emissivity coefficients depend on the type and condition of the soil surface. The term αq(t) corresponds to the solar energy, where $\alpha=\alpha(t,x,y)$ is the part of energy spent on heating the soil. This term, in general, depends on the date and time in the day circle, the transparency of the atmosphere and the latitude of the area. Standard boundary conditions are used at the lateral boundaries of the computational domain [7].

As the starting point t_0 for computer modeling we take February 1983, when the first temperature data were obtained in the thermometric well $T^{(1)}$. Let us denote the surface of the thermometric well $T^{(1)}$ by $\partial T^{(1)}$, on which the measured temperature $T(t_0, z)^{(1)}$ is set, depending on the soil temperature. In this case, when computer modelling should also consider the following condition:

$$T|_{\partial T^{(i)}} = T(t_0, z)^{(1)} \tag{4}$$

3. Computer modelling and results of numerical calculations

To solve problem (1) - (4) using the ideas of paper [7] in a three-dimensional computational domain, it is used the finite difference method with an rectangular mesh, condensing according to a certain law near the soil surface and the surfaces of the piles. An implicit central-difference three-point scheme for splitting in spatial variables is used. The system of difference linear algebraic equations has a tridiagonal form and solved by the sweep method. Calibration of the developed software product was carried out based on data in thermometric wells starting in February 1983. During the modelling, an annual climate warming trend was set as 0,04°C. Comparison of data in a thermometric well in 2022 and 2023 showed a good agreement between the calculated temperatures and temperature monitoring data (figure 2).

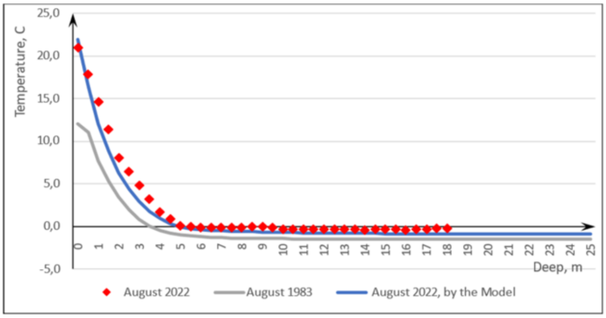
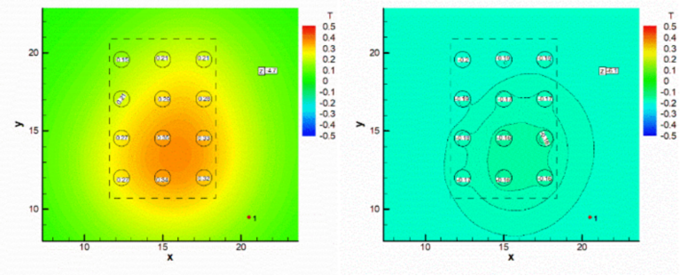


Figure 2. Comparison of well temperatures in August 2022

Thus, the studies showed that the calibration of the developed software was carried out successfully, which means that further calculations are justified to predict the dynamics of changes in the temperature regimes of the soils surrounding the bridge support.

Let us present calculations of thermal fields around the bridge support at different depths (figure 3).



(a) at the deep of 4,7 m (b) at the deep of 6,1 m

Figure 3. Temperature fields in July 2023

Analysis of the images of figures 3(a) and 3(b) shows that the southern part of the railway support warms up more than the northern part. The bearing capacity of the piles was determined using the Building Code [10]. An analysis of the temperatures on the surfaces of the piles showed that the highest temperature on the surface has the pile 1 in the left bottom corner (figure 1), which has the minimum bearing capacity. Figure 4 shows the change in the bearing capacity of the pile 1 from 1983 to 2033. The peaks correspond to the most frozen state of soil in March.

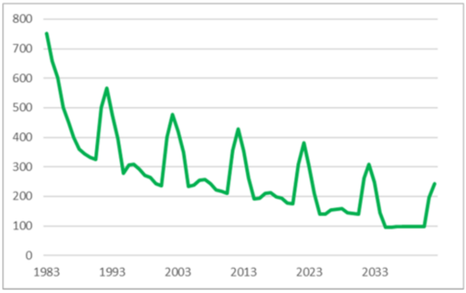


Figure 4. The bearing capacity [tf] of the pile 1 during the simulated period from 1983 to 2033 years.

4. Conclusion

A new mathematical model has been constructed to find non-stationary temperature fields in the soil around the bridge support piles, taking into account temperature monitoring data in February 1983, August 2022 and February 2023. The model also considers changing air temperature with a time step of 4 hours, soil lithology, solar radiation, and the location of the North-South support grillage. Taking into account the setting of the climate warming trend equal to 0.04°C, the developed software was calibrated, which made it possible, starting thermal calculations in February 1983, to obtain a good match with temperature data in wells in August 2022 and February 2023. During thermal engineering calculations, temperatures on the surface of 12 piles were obtained and their load-bearing capacities were calculated, both for 2023, and a forecast was given for changes in these dynamics until 2033.

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