

PERMAFROST ENGINEERING

FORECAST OF PILE FOUNDATION STABILITY BASED ON THE RESULTS OF TEMPERATURE OBSERVATIONS IN A NEARBY BOREHOLE

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The possibilities of using the results of permafrost temperature measurements for a short-term forecast of permafrost temperature regime by the extrapolation method and assessment of the stability of the pile foundation on the basis of this forecast are considered. The soil temperature has been monitored over the entire depth of the pile foundation, including one temperature sensor located under the lower end of the pile. The processing of the results of temperature measurements has been carried out according to the outlined methodology using three computer programs, links to which on the Internet are given in this article.

Keywords: *temperatures observations, permafrost soil, forecast, stability, processing technique.*

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INTRODUCTION

The stability of foundations on permafrost is known to be assessed at the design stage based on the permafrost temperature forecast, which is carried out using an analytical or numerical solution to the problem of thermal conductivity with phase transitions of water in the soil (Stefan's problem). The accuracy of solving such a problem depends on the accuracy of setting boundary conditions, which include the thermal impact of the environment and constructions on the foundation soil. Unfortunately, there are many factors in analytical and numerical solutions that are not adequately taken into account, such as the thermal resistances of snow and vegetation and the thermal effect of groundwater. This leads to design errors that can be detected using geotechnical monitoring. One of the main tasks of geotechnical monitoring is to monitor the evolution of the temperature field of the permafrost at the base of constructions. To prevent accidents, it is necessary to know the predicted values of the permafrost soil temperature, which can be obtained by extrapolating the past and present temperature conditions of the permafrost soil to the future. According to the authors, this approach is more efficient than calibrating mathematical models for their use for predictive purposes. As is known, the Stefan problem has no inverse solution, i.e., its solution does not allow us to obtain initial and boundary conditions. Therefore, a direct solution is used for calibration, in which initial and boundary conditions are intuitively selected in order to obtain an adequate result.

Thus, the first problem considered in this article is the development of a sufficiently accurate method for extrapolating permafrost temperature fields over time, that is, to find an adequate extrapolation function and establish the optimal lead (forecast) period.

The second problem is the mathematical processing of the predicted permafrost temperature field in order to obtain calculated parameters for assessing the stability of the pile foundation. It includes calculating the average temperature of the permafrost near the side surface of the pile and under its lower end, as well as the thickness of the thawed soil layer above the permafrost and the seasonal freezing layer.

Finally, the third problem is to calculate the stability of the pile foundation as a result of the impact of the payload and frost heave forces. Safety factors characterizing (a) the impact of the payload (the ratio of the pile's bearing capacity to the payload) and (b) frost heave forces (the ratio of the forces preventing the pile from being heaved out to the frost heave forces) are also calculated.

Extrapolation of temperature observations over time

Predictive calculations of permafrost temperature fields based on the actual ground temperature constitute a problem of extrapolating a discrete set of measurement moments over time. In this case, the inverse Stefan problem arises, which, as noted above, is mathematically incorrect and does not have an unambiguous solution. The way out of this situation is a compromise approach, in which the physical nature of the problem serves as the basis for finding a class of

support functions that make it possible to find the best extrapolation function by relatively simple calculations. To implement it, the authors used an approximate method for calculating temperature fields in the foundations of constructions, called the equivalent temperature method [Khrustalev, 1971]. The idea of the method is to reduce Stefan's three-dimensional problem to a set of one-dimensional problems. Omitting the details, which can be found in the cited monograph, let us write the dependence of temperature (T) on time (τ):

$$T = cE(\tau) + d, \quad (1)$$

$$E(\tau) = 1 - \operatorname{erf}\left(\frac{y}{2\sqrt{a\tau}}\right), \quad (2)$$

where c, d are unknown parameters associated with the values of the equivalent and initial temperature, °C; y is the depth of the calculation point, m; a is the thermal diffusivity of the soil, $\text{m}^2/\text{°C}$; and $\operatorname{erf}(u)$ is the integral of probabilities, a tabulated function, dimensionless.

For unknown parameters, there are soil temperature values measured at many points at certain points in time and forming a system of equations:

$$c_i E_{ij} + d_i = T_{ij}, i = 1, 2, \dots, n, j = 1, 2, \dots, m, \quad (3)$$

where n is the number of ground temperature measurement points in the borehole; m is the number of ground temperature measurements over time, separated by a period equal to a multiple of the number of years; E_{ij} is the value of function (2) at the point y_i at the τ_j .

Measured soil temperature values (in the area of thermal influence of the construction) are distorted by measurement errors and human-made and natural random deviations. Therefore, for $m > 2$, the system of equations (3) is inconsistent and only yields approximate solutions. However, if we take into account the two most recent temperature measurements for unknown parameters c and d , this system of equations has a rigorous analytical solution, namely:

$$\begin{cases} c_i E_{i,m-1} + d_i = T_{i,m-1} \\ c_i E_{i,m} + d_i = T_{i,m} \end{cases}, \quad (4)$$

$$c_i = (T_{i,j} - T_{i,m-1}) / (E_{i,j} - E_{i,m-1}); \quad (5)$$

$$d_i = T_{i,m} - c_i E_{i,m}. \quad (6)$$

Substituting (5) and (6) into (1), we obtain the desired extrapolation function:

$$T_{i,k} = c_i E_{i,k} + d_i, k > m. \quad (7)$$

Calculation using formula (7) can be performed automatically. For this purpose, the authors have developed a computer program (macro A, see Supplementary materials).

Determination of design parameters for assessing the stability of a pile foundation

The predicted values of the soil temperature in the control borehole are determined as follows.

First, the number of the sensor (measured from the soil surface), where a positive temperature is detected is set to $n1$. Then the number of the last sensor located above sensor $n1$ and having a negative temperature is set to $n2$. Then, two important parameters are obtained by interpolation – the depth of soil thawing H at the time of the soil temperature forecast and the depth of seasonal soil freezing D_f :

$$H = Y_{n1+1} - (Y_{n1+1} - Y_{n1}) \cdot (T_{n1} - T_{bf}) / (T_{n1} - T_{n1+1}),$$

$$D_f = Y_{n2} + (Y_{n2+1} - Y_{n2}) \cdot (T_{bf} - T_{n2}) / (T_{n2+1} - T_{n2}),$$

where Y_i is the depth of the i -th temperature sensor, m; T_i is the soil temperature indicated by the i -th temperature sensor; T_{bf} is the freezing–thawing temperature of the soil, °C.

Next, the average temperature of the permafrost (T_e) is calculated using data from sensors located in the depth range from H to L (depth of immersion of the pile in the soil, m), and the temperature near the lower end of the pile (T_z) at the time of the forecast is calculated by interpolation:

$$T_z = (L - Y_{n1}) \cdot (T_{n1+1} - T_{n1}) / (Y_{n1+1} - Y_{n1}) + T_{n1}.$$

The calculation of these parameters can be performed in a computer program developed by the authors (macro B, Supplementary materials).

Calculation of the stability of the pile foundation based on the predicted temperature values

Calculation of the stability of a pile foundation includes checking two limiting conditions – bearing capacity and heaving.

Let's consider them sequentially.

Verification of the bearing capacity limits. In this case, monitoring the stability of the pile foundation is reduced to checking the value of the bearing capacity safety factor (k_u), which should always be greater than one during the foundation operation period, that is:

$$k_u = F_u / (F_v + F_g) > 1,$$

where F_u is the bearing capacity of the pile, kN; F_v is the payload on the pile, kN; F_g is the friction force of the thawed soil against the side surface of the pile, kN. In addition:

$$F_u = F_{u,T} + F_{u,b},$$

$$F_{u,T} = \gamma_c R S_p,$$

$$F_{u,b} = \gamma_c \gamma_{ca} R_{af} u_p (L - H),$$

$$F_g = 0.8 \gamma_{cf} f_c u_p (H - D_f),$$

where $F_{u,T}$ and $F_{u,b}$ are the bearing capacities of the lower end and the lateral surface of the pile, respectively, kN; γ_c is the coefficient of working conditions taken according to Table 7.2 [SP 25.13330.2020], dimensionless; γ_{ca} is the coefficient taking into account the pile material, dimensionless and taken equal to 1 for concrete, 0.7 for steel, and 0.9 for wood; R is the design pressure on the frozen soil under the lower end of the pile, kPa; s_p is the area of the lower end of the pile, m²; R_{af} is the design resistance of the frozen soil or soil mortar to shear on the lateral freezing surface within the part of the pile located in the frozen soil, kPa; u_p is the perimeter of the pile, m; L is the depth of pile penetration into the ground, m; and H is the thickness of the thawed layer above the permafrost table, m. Parameters R and R_{af} are determined according to the data given in Tables B1 and B3 of Supplementary materials [SP 25.13330.2020] depending on the calculated values of the soil temperature near the lower end of the pile T_z and its lateral surface T_e ; γ_{cf} is the coefficient of soil working conditions on the lateral surface of the pile determined according to Table 7.4 [SP 24.13330.2021] depending on the method of the pile driving, dimensionless; f_c is the calculated resistance of thawed soil along the lateral surface of the pile taken according to Table 7.3 [SP 24.13330.2021], kPa; D_f is the depth of seasonal soil freezing, m.

Verification of the heaving limit conditions. In this case, stability monitoring of the pile foundation is reduced to checking the value of the heaving safety factor k_f :

$$k_f = F_y / F_f > 1,$$

$$F_y = F_v + F_g + F_{u,b},$$

$$F_f = \gamma_{ca} \gamma_c \tau_{fh} u_p D_f,$$

where F_y and F_f are the force keeping the pile from heaving (temperature-dependent) and the heaving force, respectively, kN; τ_{fh} is the specific tangential heaving force taken according to Table 7.8 [SP 25.13330.2020], kPa.

A computer program (macro C, see Supplementary materials) was compiled to calculate the stability forecast of the pile foundation in automatic mode.

It should be noted that the described method, like most of the methods for analytical calculation of temperature fields and thawing “bowls” at the base of constructions, assumes that the soil is homogeneous. In the case of layered soil, averaged soil characteristics are used in the calculation. Averaging is performed within the averaging depth using formula for the soil thermal conductivity and formula for averaging the remaining characteristics of the frozen soil. The depth of the location of the last calculated tem-

perature sensor in the control borehole is taken as the averaging depth:

$$\lambda = \sum_{i=1}^n h_i / \sum_{i=1}^n \frac{1}{\lambda_i} \cdot h_i,$$

$$A = \sum_{i=1}^n A_i \cdot h_i / \sum_{i=1}^n h_i,$$

where λ_i , A_i are the numerical values of the soil characteristics of the i -th layer; h_i is the thickness of the i -th layer; n is the number of i -th layers within the depth of averaging.

Obtaining data for verification of the extrapolation method and compilation of an example calculation

Comparison of the forecast results with the data from field observations is replaced by a conditional comparison with the data of mathematical modeling of the permafrost temperature field at the base of the support of an aboveground gas pipeline located at a distance of 2 m from the building, since modeling allows us to obtain a fairly accurate picture of the soil temperature field under the specific conditions.

Mathematical modeling based on the solution of Stefan's problem was implemented in the WARM program [Emelyanov et al., 1994]. The algorithm of this program includes the finite difference method using the balance method and the enthalpy formulation of the problem [Ershov, 1999].

Problem statement. A two-dimensional model area of 24 × 24 m divided into blocks in horizontal and vertical directions with a spacing of 1 m is considered. On the right side of the model area (0 to 6 m), there is a building (half of a building). A 10-m-long support of the aboveground gas pipeline is found 8 m from the left boundary, and a 10.5-m-deep tem-

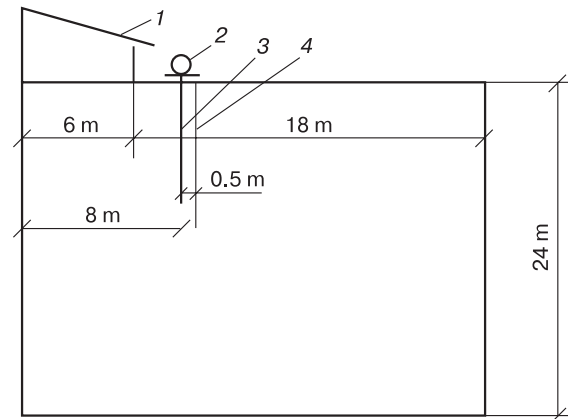


Fig. 1. Calculation scheme of the model (two-dimensional model).

1 – building (half), 2 – aboveground gas pipeline, 3 – aboveground gas pipeline support, 4 – temperature borehole. The model area is split into horizontal and vertical blocks with a spacing of 1 m.

Table 1. Boundary condition of the 3rd type outside the building

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
T_{air}	-42.0	-35.6	-22.0	-6.8	6.2	15.6	18.8	14.9	6.1	-7.9	-28.2	-39.5
α	0.66	0.66	0.62	1.14	3.63	3.60	3.51	3.44	3.37	2.13	0.94	0.81

Note: T_{air} – atmospheric air temperature, °C; α – coefficient of heat exchange between the ground surface and the atmosphere, $\text{W}/(\text{m}^2 \cdot ^\circ\text{C})$.

perature borehole is 8.5 m away from the left side of the model area and 0.5 m from the support of the gas pipeline with a depth of 10.5 m. The design of the computational model area is shown in Fig. 1.

Boundary conditions. Boundary conditions of the second type with zero heat flow were set at the lower and lateral boundaries of the model area. At the upper boundary, first-type (under the building) and third-type (outside the building's contour) boundary conditions were set. Thus, a constant temperature of 20°C was set at the boundary under the building (from 0 to 6 m). Outside the building (from 6 to 24 m), the temperature of atmospheric air and the heat exchange coefficient between the surface and atmospheric air were set (Table 1).

The air temperature shown in Table 1 was adjusted for global warming from the start of the modeling in the form of a linear temperature trend equal to 0.05°C/yr.

Initial conditions. The initial constant temperature of permafrost equal to -3.0°C was taken for the entire model area.

Soil characteristics. The soil was a sandy loam with constant properties throughout the calculation area. Thermal conductivity was 1.28 $\text{W}/(\text{m} \cdot ^\circ\text{C})$ for the thawed soil and 1.65 $\text{W}/(\text{m} \cdot ^\circ\text{C})$ for the frozen soil; heat capacity was 599 $\text{W} \cdot \text{h}/(\text{m}^3 \cdot ^\circ\text{C})$ and 458 $\text{W} \cdot \text{h}/(\text{m}^3 \cdot ^\circ\text{C})$, respectively. The latent heat of phase transition was 25 250 $\text{W} \cdot \text{h}/\text{m}^3$, and the temperature of the beginning of the phase transition of water was -0.1°C.

Gas pipeline support. The support consisted of one steel pile with an outer diameter of 0.3 m. The pile was driven into the permafrost soil to a depth of 10 m. The vertical load on the top end of the pile was 200 kN.

Temperature control borehole. The temperature borehole was located 2.5 m from the building and 0.5 m from the gas pipeline support. Temperature sensors were installed at depths from 0.5 to 10.5 m with 1-m spacings.

The simulation results – temperature values at the loci of temperature measurement sensors (8.5 m from the left edge of the model area to a depth of 10.5 m) after 10, 11, ... 15 years from the start of the simulation are given in Table 2.

Verification of the extrapolation method for temperature forecasting

Data on model soil temperatures calculated by the extrapolation method with a help of macro A (see Supplementary materials) and by the numerical modeling based on the results of field observations and the WARM program [Emelyanov *et al.*, 1994] are given in Table 3. From the presented material, it is seen that the forecast error (according to macro A) within a 1-year-lead time does not exceed 0.2°C. However, with an increase in the lead time, it increases almost linearly. Thus, at the lead time of 2 years, the error exceeds 0.3°C and at the lead time of 4 years, it approaches 0.6°C. Therefore, for geotechnical monitoring, a 1-year-long lead time is preferable, which allows for a satisfactory match between mathematical modeling data (WARM program) and the extrapolation forecast method (macro A, see Supplementary materials).

Example of a pile foundation stability prediction

A stability forecast was made for the gas pipeline support (Fig. 1). To reduce the length of the paper, the forecast was first made for only one year (1992). The forecast for the subsequent years was carried out similarly.

The initial parameters were the data specified in the formulation of the temperature field modeling problem, as well as the temperature fields themselves obtained during numerical modeling using the WARM program (Table 2). The calculation was performed sequentially using macros A, B, and C (see Supplementary materials). The input parameters of the subsequent macro were the output parameters of the previous macro. The results of predicting the stability of the pile foundation are given in Table 4.

From the analysis of the data in Table 4, it follows that the pile support in all months of 1992 has safety factors greater than one and, therefore, remains stable. Moreover, the observer comes to this conclusion a year earlier, i.e. in 1991. This is very important, because had the outcome been different, a year remains in reserve to correct the situation (e.g., via artificial cooling of the support base).

Table 2. **Results of numerical simulation of the soil temperature regime at the loci of temperature sensors using the WARM program**

Y, m	Ground temperature by month, °C											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	2	3	4	5	6	7	8	9	10	11	12	13
<i>1990</i>												
0.5	-9.03	-9.72	-8.05	-6.1	-2.33	-0.1	2.58	10.31	8.66	4.23	-0.1	-0.1
1.5	-0.1	-0.1	-0.1	-3.1	-1.76	-0.28	-0.1	-0.1	3.17	3.36	1.44	0.84
2.5	0.66	0.43	0.38	-0.1	-0.1	-0.1	-0.1	-0.1	-0.04	2.24	1.6	1.15
3.5	0.62	0.47	0.42	-0.02	-0.1	-0.1	-0.1	0.34	0.51	1.22	1.09	1.05
4.5	-0.10	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.63
5.5	-0.10	-0.1	-0.1	-0.1	-0.1	-0.24	-0.29	-0.21	-0.12	-0.1	-0.1	-0.1
6.5	-0.32	-0.31	-0.3	-0.34	-0.42	-0.49	-0.53	-0.48	-0.41	-0.37	-0.34	-0.32
7.5	-0.51	-0.49	-0.47	-0.5	-0.58	-0.65	-0.69	-0.67	-0.62	-0.58	-0.54	-0.51
8.5	-0.69	-0.66	-0.64	-0.64	-0.69	-0.76	-0.81	-0.81	-0.78	-0.74	-0.71	-0.67
9.5	-0.86	-0.83	-0.8	-0.79	-0.81	-0.86	-0.91	-0.93	-0.91	-0.88	-0.85	-0.82
10.5	-1.01	-0.98	-0.95	-0.93	-0.94	-0.97	-1.0	-1.02	-1.02	-1.01	-0.98	-0.95
<i>1991</i>												
0.5	-8.84	-9.72	-7.99	-5.93	-2.24	-0.10	2.89	10.37	8.91	4.37	-0.10	-0.10
1.5	-0.1	-0.10	-0.10	-2.91	-1.68	-0.27	-0.10	-0.10	3.92	3.68	1.57	0.90
2.5	0.77	0.52	0.46	-0.10	-0.10	-0.10	-0.10	-0.10	2.00	2.51	1.81	1.26
3.5	0.88	0.70	0.64	0.45	0.0	-0.01	0.21	0.54	1.23	1.65	1.49	1.18
4.5	0.58	0.50	0.46	0.34	0.06	-0.03	0.13	0.36	0.66	0.89	0.88	0.77
5.5	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
6.5	-0.27	-0.14	-0.11	-0.13	-0.20	-0.27	-0.27	-0.23	-0.17	-0.12	-0.10	-0.10
7.5	-0.47	-0.36	-0.32	-0.32	-0.38	-0.44	-0.46	-0.44	-0.40	-0.36	-0.33	-0.31
8.5	-0.64	-0.56	-0.52	-0.49	-0.52	-0.58	-0.61	-0.61	-0.58	-0.55	-0.52	-0.49
9.5	-0.79	-0.74	-0.70	-0.66	-0.67	-0.70	-0.74	-0.75	-0.74	-0.71	-0.68	-0.66
10.5	-0.92	-0.89	-0.85	-0.81	-0.80	-0.82	-0.85	-0.86	-0.86	-0.85	-0.82	-0.8
<i>1992</i>												
0.5	-8.64	-9.72	-7.87	-5.87	-2.17	-0.10	3.20	10.43	9.14	4.50	-0.10	-0.10
1.5	-0.10	-0.10	-0.10	-2.83	-1.61	-0.24	-0.10	-0.10	4.32	3.93	1.64	0.94
2.5	0.83	0.55	0.48	-0.10	-0.10	-0.10	-0.10	0.98	2.30	2.65	1.91	1.33
3.5	0.97	0.77	0.69	0.50	0.45	0.22	0.31	0.88	1.45	1.81	1.63	1.32
4.5	0.67	0.57	0.52	0.46	0.36	0.19	0.23	0.56	0.94	1.17	1.18	1.050
5.5	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	0.21	0.45	0.59	0.63	0.60
6.5	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
7.5	-0.30	-0.29	-0.28	-0.29	-0.32	-0.36	-0.37	-0.37	-0.34	-0.32	-0.30	-0.29
8.5	-0.47	-0.45	-0.43	-0.43	-0.46	-0.50	-0.53	-0.54	-0.52	-0.49	-0.47	-0.45
9.5	-0.63	-0.60	-0.58	-0.57	-0.58	-0.62	-0.65	-0.66	-0.65	-0.63	-0.61	-0.59
10.5	-0.78	-0.74	-0.72	-0.70	-0.70	-0.72	-0.74	-0.76	-0.76	-0.75	-0.73	-0.71
<i>1993</i>												
0.5	-8.50	-9.71	-7.86	-5.77	-2.07	-0.10	3.49	10.5	9.34	4.63	-0.10	-0.10
1.5	-0.10	-0.10	-0.10	-2.76	-1.54	-0.22	-0.10	-0.10	4.61	4.14	1.69	0.96
2.5	0.89	0.60	0.53	-0.10	-0.10	-0.10	0.57	1.15	2.51	2.76	1.97	1.37
3.5	1.10	0.87	0.79	0.60	0.53	0.51	0.70	1.11	1.59	1.89	1.70	1.37
4.5	0.93	0.81	0.74	0.67	0.60	0.57	0.61	0.82	1.04	1.25	1.24	1.11
5.5	0.55	0.49	0.45	0.42	0.33	0.29	0.31	0.41	0.54	0.66	0.69	0.66
6.5	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.1	-0.10	-0.10	-0.10	-0.10
7.5	-0.28	-0.27	-0.26	-0.27	-0.30	-0.33	-0.35	-0.25	-0.20	-0.16	-0.13	-0.11
8.5	-0.43	-0.41	-0.40	-0.40	-0.42	-0.47	-0.49	-0.43	-0.40	-0.36	-0.33	-0.30
9.5	-0.57	-0.55	-0.53	-0.52	-0.53	-0.57	-0.59	-0.58	-0.55	-0.53	-0.50	-0.47
10.5	-0.69	-0.67	-0.66	-0.64	-0.64	-0.66	-0.68	-0.69	-0.67	-0.66	-0.63	-0.61

End of Table 2

1	2	3	4	5	6	7	8	9	10	11	12	13
1994												
0.5	-8.38	-9.71	-7.80	-5.69	-1.98	-0.10	3.73	10.55	9.44	4.71	-0.10	-0.10
1.5	-0.10	-0.10	-0.10	-2.71	-1.43	-0.21	-0.10	-0.10	4.75	4.24	1.72	0.98
2.5	0.92	0.62	0.55	-0.10	-0.10	-0.09	0.70	1.19	2.62	2.84	2.02	1.41
3.5	1.14	0.91	0.82	0.63	0.56	0.55	0.81	1.17	1.68	1.98	1.78	1.44
4.5	0.98	0.86	0.79	0.72	0.66	0.63	0.70	0.88	1.15	1.36	1.37	1.23
5.5	0.60	0.55	0.51	0.48	0.45	0.38	0.39	0.49	0.74	0.88	0.93	0.89
6.5	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	0.02	0.34	0.42	0.47	0.48
7.5	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.14	-0.10	-0.10	-0.10	-0.10
8.5	-0.28	-0.27	-0.26	-0.26	-0.27	-0.29	-0.31	-0.33	-0.30	-0.29	-0.28	-0.27
9.5	-0.43	-0.42	-0.40	-0.39	-0.40	-0.42	-0.44	-0.46	-0.45	-0.44	-0.42	-0.41
10.5	-0.57	-0.55	-0.54	-0.52	-0.52	-0.53	-0.55	-0.57	-0.57	-0.56	-0.55	-0.53
1995												
0.5	-8.27	-9.70	-7.77	-5.62	-1.94	-0.10	3.98	10.6	9.53	4.79	-0.10	-0.1
1.5	-0.10	-0.10	-0.10	-2.65	-1.37	-0.12	-0.10	-0.10	4.86	4.34	1.76	1.00
2.5	0.96	0.65	0.57	-0.10	-0.10	0.31	0.76	1.22	2.71	2.90	2.06	1.44
3.5	1.21	0.98	0.88	0.70	0.61	0.68	0.90	1.24	1.76	2.05	1.84	1.49
4.5	1.10	0.97	0.89	0.82	0.75	0.74	0.82	1.00	1.23	1.43	1.43	1.29
5.5	0.83	0.77	0.72	0.68	0.63	0.61	0.62	0.70	0.81	0.93	0.98	0.94
6.5	0.46	0.43	0.41	0.39	0.34	0.30	0.30	0.34	0.40	0.47	0.51	0.51
7.5	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
8.5	-0.26	-0.25	-0.24	-0.24	-0.25	-0.28	-0.29	-0.29	-0.29	-0.28	-0.27	-0.26
9.5	-0.39	-0.37	-0.36	-0.36	-0.37	-0.39	-0.41	-0.42	-0.41	-0.4	-0.39	-0.38
10.5	-0.51	-0.49	-0.48	-0.47	-0.47	-0.48	-0.50	-0.51	-0.51	-0.51	-0.50	-0.49

Note: Y is the depth of the temperature sensor, m.

Table 3. Error of forecasting the ground temperature by the extrapolation method

Lead time	1 year			2 years			3 years			4 years		
	October 1, 1992			October 1, 1993			October 1, 1994			October 1, 1995		
Y, m	T_{mod}	T_{pr}	$T_{\text{mod}} - T_{\text{pr}}$	T_{mod}	T_{pr}	$T_{\text{mod}} - T_{\text{pr}}$	T_{mod}	T_{pr}	$T_{\text{mod}} - T_{\text{pr}}$	T_{mod}	T_{pr}	$T_{\text{mod}} - T_{\text{pr}}$
0.5	4.50	4.49	0.01	4.63	4.60	0.03	4.71	4.70	0.01	4.79	4.79	0.00
1.5	3.93	3.96	-0.03	4.14	4.21	-0.07	4.24	4.44	-0.20	4.34	4.64	-0.30
2.5	2.65	2.75	-0.10	2.76	2.96	-0.20	2.84	3.15	-0.31	2.90	3.32	-0.42
3.5	1.81	2.03	-0.22	1.89	2.37	-0.48	1.98	2.67	-0.69	2.05	2.95	-0.90
4.5	1.17	1.76	-0.59	1.25	2.54	-1.29	1.36	3.24	-1.88	1.43	3.87	-2.44
5.5	0.59	-0.10	0.69	0.66	-0.10	0.76	0.88	-0.10	0.98	0.93	-0.10	1.03
6.5	-0.10	0.10	-0.20	-0.10	0.30	-0.40	0.42	0.47	-0.05	0.47	0.63	-0.16
7.5	-0.32	-0.17	-0.15	-0.16	0.01	-0.17	-0.10	0.16	-0.26	-0.10	0.30	-0.40
8.5	-0.49	-0.38	-0.11	-0.36	-0.23	-0.13	-0.29	-0.10	-0.19	-0.28	0.02	-0.30
9.5	-0.63	-0.56	-0.07	-0.53	-0.43	-0.10	-0.44	-0.31	-0.13	-0.40	-0.20	-0.20
10.5	-0.75	-0.71	-0.04	-0.66	-0.58	-0.08	-0.56	-0.47	-0.09	-0.51	-0.37	-0.14
Average	-	-	0.20	-	-	0.34	-	-	0.44	-	-	0.57

Note: Y is the depth of the temperature sensor, m; T_{mod} and T_{pr} are model ground temperature based on field observations (WARM) and predicted ground temperature (macro A, Supplementary materials), respectively, °C; $T_{\text{mod}} - T_{\text{pr}}$ is the error of the prediction, °C (absolute units).

Table 4. The results of forecasting the stability of the pile foundation

January						July					
F_v	200	F_u	276.07	K_u	1.38	F_v	200	F_u	340.68	K_u	1.70
F_y	326.78	F_f	145.14	K_f	2.25	F_y	326.78	F_f	0	K_f	∞
February						August					
F_v	200	F_u	285.54	K_u	1.43	F_v	200	F_u	354.28	K_u	1.77
F_y	326.78	F_f	145.14	K_f	2.25	F_y	326.78	F_f	0	K_f	∞
March						September					
F_v	200	F_u	287.31	K_u	1.44	F_v	200	F_u	346.65	K_u	1.73
F_y	326.78	F_f	145.14	K_f	2.25	F_y	326.78	F_f	0	K_f	∞
April						October					
F_v	200	F_u	298.46	K_u	1.49	F_v	200	F_u	336.94	K_u	1.68
F_y	326.78	F_f	178.13	K_f	1.83	F_y	326.78	F_f	0	K_f	∞
May						November					
F_v	200	F_u	308.20	K_u	1.54	F_v	200	F_u	272.89	K_u	1.36
F_y	326.78	F_f	178.13	K_f	1.83	F_y	326.78	F_f	85.77	K_f	3.81
June						December					
F_v	200	F_u	329.11	K_u	1.65	F_v	200	F_u	264.88	K_u	1.32
F_y	326.78	F_f	85.77	K_f	3.81	F_y	326.78	F_f	85.77	K_f	3.81

Note: F_u , F_y , F_f are the bearing capacity of the pile, the force holding the pile from being heaved out, and the heave force, respectively, kN; F_v is the payload on the top of the pile, kN; and K_u , K_f are the coefficients of the reserve in terms of bearing capacity and frost heave, respectively, dimensionless.

CONCLUSIONS

The methodology for processing permafrost temperature monitoring data described in this paper is a rapid method that does not require a large amount of initial data, which is difficult to obtain using software packages for solving the Stefan problem with their calibration based on field observations. In this regard, the proposed method is of great importance for the operational control of permafrost temperature conditions. It enables early warning of structure failures and the adoption of management decisions to prevent them. This suggests the need to incorporate the proposed rapid method into geotechnical monitoring in the permafrost zone.

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References

- Emelyanov N.V., Pustovoit G.P., Khrustalev L.N., Yakovlev S.V., 1994. *Program for Calculating Thermal Interaction of Engineering Structures with Permafrost Soils* "WARM". Certificate No. 940281. RosAPO, 1 p. (in Russian)
- Ershov E.D. (Ed.), 1999. *Fundamentals of Geocryology*. Vol. 5. Moscow, Moscow Univ. Press, 526 p. (in Russian)
- Khrustalev L.N., 1971. *Temperature Regime of Permafrost Soils in Built-Up Areas*. Moscow, Nauka, 168 p. (in Russian)
- SP 24.13330.2021. *SNiP 2.02.03-85. Pile Foundations*. Moscow, Ministry of Construction of Russia, 113 p. (in Russian)
- SP 25.13330.2020. *Basements and Foundations on Permafrost Soils*. Moscow, Ministry of Construction of Russia, 136 p. (in Russian)
- URL: <https://disk.yandex.ru/i/pE3IAHgw31G5Lw>
- URL: <https://disk.yandex.ru/i/W0r5Z2i9guBQLA>
- URL: <https://disk.yandex.ru/i/Au9FRimdtks9uQ>

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SUPPLEMENTARY MATERIALS

The computer programs (macros) offered to the reader's attention are written in Visual Basic Application language using the Excel 2007 platform (VBA Excel). To view them in the Excel worksheet corresponding to the selected macro, click the "Developer" button on the command line and then the "Visual Basic" button. The programs are ready for practical use, for which the user must perform two very simple operations: fill in the yellow field on the Excel worksheet with input (source) data and click the "Run" button at the top of the worksheet. The calculation result will be displayed in the gray field on this worksheet.

Access to the programs is provided via the following links:
macro A – <https://disk.yandex.ru/i/pE3IAHgw31G5Lw>
macro B – <https://disk.yandex.ru/i/W0r5Z2i9guBQLA>
macro C – <https://disk.yandex.ru/i/Au9FRimdtks9uQ>