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GEOCRYOLOGICAL MONITORING AND FORECAST

EMERGENCY FORECAST BASED ON PERMAFROST TEMPERATURE MONITORING DATA NEAR AN UNDERGROUND OIL PIPELINE

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Permafrost temperature monitoring near underground oil pipelines makes it possible to estimate permafrost thawing depth under structures and predict changes in the soil temperature over time and the time of emergency, in case the latter one will occur in the future. Permafrost temperature monitoring is carried out in close proximity to the oil pipeline and at depths below the bottom of the layer of seasonal temperature fluctuations. The results of monitoring are processed according to the methodology described in the article.

Keywords: *permafrost, oil pipeline, thawing depth, temperature monitoring, forecast, time of emergency.*

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INTRODUCTION

Any engineering structure on permafrost interacts with the frozen soil base during the entire period of operation. This interaction often leads to negative consequences, so it is necessary to be able to manage, control, and predict it. These actions are known as geotechnical monitoring. The latter is especially important for those structures, where accidents lead to unpredictable environmental consequences; in particular, for oil pipelines. An oil pipeline accident often leads to an oil spill, which is associated with significant damage to the natural environment and even with the withdrawal of vast territories from economic use.

An essential part of geotechnical monitoring is monitoring of permafrost temperature. Temperature monitoring along the main underground oil pipelines is carried out both at potentially dangerous sections equipped before or during the pipeline laying, and selectively on certain sections, where safety concerns appear during pipeline operation. Temperature sensors can be located in the soil directly under the pipeline and in wells in the immediate vicinity of the pipeline. In 2010–2012, JSC "Transneft" together with the Bauman Moscow State Technical University developed and implemented a system for multiple monitoring of geological processes at the experimental sections of the pipeline laying, including technical diagnostics of the pipeline, monitoring of the planned altitudinal position of the pipeline, and parameters characterizing the hydrogeological conditions of the pipeline laying. This system allows one to control the following parameters: the change in the position of the pipeline, the groundwater level, the distribution of soil temperature, the displacement of soil on slopes, and its acceleration under seismic influences [*Lisin, Alexandrov, 2013*]. The control is carried out in an automatic mode with the transmission of information by radio to the information processing center, whose main functions are diagnostics of the monitoring system and display of warning messages about exceeding the threshold values or remaining reserves up to the threshold values of the monitored parameters on the display screen. Thus, the system allows us to constantly monitor the temperature of the oil pipeline and the surrounding soil. This is a sophisticated state-of-the art system, which has not yet become widespread.

In the permafrost area, one of the main tasks of monitoring is to control the development of permafrost thawing around underground oil pipelines. This control is carried out at experimental sites and allows one not only to identify extreme thawing values that endanger the integrity of the pipeline in real time but also to forecast them for the future, which is of special importance. For this purpose, calibrated mathematical models of thawing zone are used; these models are defined in the Company's regulatory documents.

Calibration is commonly referred to as changing the structure and composition of a mathematical model in such a way that the edited model is adequate "to nature" for each of the parameters set in the model. Calibration is carried out on the basis of solving the inverse problem of thermal conductivity with phase transition of soil moisture (the so-called Stefan problem). This involves an additional problem related to the fact that the inverse problem of thermal conductivity (restoration of the initial and boundary conditions from the temperatures at certain moments of time) is mathematically incorrect and has no unambiguous solution. Therefore, a direct problem solution is used for calibration, in which the initial and boundary conditions are changed blindly in hope to obtain a result adequate "to nature." This is a long and unpromising way. Today, this process can be significantly simplified by replacing the three-dimensional Stefan problem with a sum of one-dimensional problems, the number of which is determined by the number of calculation points [*Khrustalev, 1971*].

As known, a mathematical model consists of two parts that can be referred to as the core and the shell. By the core, we will understand the numerical solutions of the Stefan problem; by the shell, we will understand the initial data necessary for this. Core can be different (for example, numerical solutions of the Stefan problem by the finite difference method using explicit and implicit schemes and the finite element method) and the calculation result with the same source data will always be the same, because the difference in modeling results is determined only by the difference in shells, i.e. by the source data. Therefore, calibration of a mathematical model is an adjustment of the initial data to obtain the desired result. It does not matter, which core the model contains. Moreover, under certain conditions, the core may be not numerical, but analytical. Based on these considerations, a fast calibration method was developed for a mathematical model of the interaction of an underground pipeline with host frozen soils [*Gunar et al., 2021*], which made it possible to significantly simplify the calibration method and to obtain a reliable tool for predicting permafrost thawing zone around an underground water pipeline or oil pipeline. However, this method is not free from shortcomings. Thus, to use a mathematical model, it is necessary to set the boundary and initial conditions, as well as thermophysical properties of soils, which is not always possible, because some of the information is lost over time. In this regard, the technique described below has clear advantages, in particular, the possibility of using it for unequipped sites.

FORECASTING TECHNIQUE

For unequipped sites that are discussed below, direct control over the development of thawing is impossible, because borehole drilling near the oil pipeline is strictly prohibited. However, by drilling a borehole at a minimum distance from the pipeline, which is determined by safety requirements (at a distance of 0.5–1.5 m from the element of the pipe) and measuring the temperature of frozen soil in this borehole, it is possible to estimate the depth of permafrost under the center of the pipeline at the moment. The soil temperature o should be measured no higher than the bottom of the layer of annual temperature fluctuations. This will allow us to take the current temperature values as the mean annual values and to determine the soil thawing depth from them. This is the first problem, the solution of which is considered in this article.

If such temperature measurements are carried out regularly, a temporary sample of temperatures will be obtained, which can then be extrapolated over time to obtain a forecast temperature for a given period (forecast period). Only one difficulty is faced here: the choice of extrapolation function. This is the second problem considered in this article.

Having predicted temperatures and using solution of the first problem, it is possible to calculate the depth of permafrost thawing under the pipeline for the forecast period.

It remains only to clarify whether the soil subsidence, at this depth of thawing, will cause an oil pipeline accident and, if so, when this accident will occur. This is the third problem to be discussed in this paper.

Calculation of the depth of permafrost thawing under an underground oil pipeline based on the results of temperature measurements in a closely located borehole

The calculations are based on the idea of a quasistationary ground temperature field (mean annual temperatures) in the area adjacent to the pipeline, which is formed during the development of permafrost thawing around the pipeline. Its analytical description can be found, for example, in the monograph [*Porkhaev, 1970*]. Knowing the mean annual ground temperature at certain points of this field, it is possible to judge the thawing depth under the pipeline. To do this, it is necessary to solve a system of transcendental equations with two unknowns: the depth of permafrost thawing under the central part of the pipeline as measured from the ground surface (h) and the soil temperature at the depth of zero annual heat turnover, which existed in natural conditions before the beginning of the pipeline operation (T_0).

Let us write down this system for two observation points (x, y_i) and (x, y_{i+k}), which are located in a test borehole near an oil pipeline (from 0.5 to 2.0 m):

$$\begin{cases} T(x,y_i) - T_{bf} = (T_0 - T_{bf}) \dfrac{f(0,h) - f(x,y_i)}{f(0,h)}, \\ T(x,y_{i+k}) - T_{bf} = (T_0 - T_{bf}) \dfrac{f(0,h) - f(x,y_{i+k})}{f(0,h)}, \end{cases} \tag{1}$$

where x is the distance from the observation borehole to the axis of the oil pipeline, m; y_i, y_{i+k} are the depths of the temperature sensors in the observation borehole, m; $T(x, y_i)$, $T(x, y_{i+k})$ are subzero mean annual ground temperatures at two observation points, °C; T_0 is the ground temperature at the depth of zero annual heat turnover under natural conditions before the start of the pipeline operation, °C; T_{bf} is the temperature of the beginning of soil freezing, °C; and h is the depth of permafrost thawing under the middle of the pipeline measured from the soil surface, m.

The coordinate function is determined by the formula

$$f(x,y) = \frac{1}{2A_p} \ln \frac{x^2 + \left(y + \sqrt{h_p^2 - r_{ins}^2}\right)^2}{x^2 + \left(y - \sqrt{h_p^2 - r_{ins}^2}\right)^2},$$

$$A_p = \ln\left(\frac{h_p}{r_{ins}} + \sqrt{\frac{h_p^2}{r_{ins}^2} - 1}\right),$$

where x, y are the coordinates of the point, m; h_p is the distance from the soil surface to the center of the underground oil pipeline, m; and r_{ins} is the radius of the oil pipeline with circular thermal insulation along its external generating line, m.

The solution of Eq. (1) is carried out by the iteration method. As a result, an array of data is formed equal to the number of combinations (by two) of temperature measurements at depth points (according to the number of unknowns in Eq. (1)). Naturally, the average value of this array should be taken for the calculation. To facilitate calculations, the authors have developed a computer program (macro 1, see Appendix).

Permafrost temperature forecast based on initial observations in the monitoring borehole

Predictive calculations of temperature fields based on actual soil temperatures constitute the problem of extrapolating the actual temperatures specified on a discrete set of measurement moments in time. In this case, the so-called inverse problem of thermal conductivity arises. As noted above, this problem is mathematically incorrect and does not have a precise analytical solution.

A compromise approach, in which the physical essence of the problem serves as the basis for finding a class of support functions that allow finding the best extrapolation function by relatively simple calculations, seems to be reasonable.

To implement this, the authors used an approximate method for calculating temperature fields in the construction basements, which was developed in 1971 and called the equivalent temperature method [*Khrustalev, 1971*]. Its idea is to reduce the three-dimensional problem of thermal conductivity to a set of one-dimensional problems (according to the number of calculated points). Omitting the details that can be found in [*Khrustalev, 1971*], we can express the dependence of temperature (T) on time (τ) in the form:

$$T(\tau) = aE(\tau) + b,$$

$$E(\tau) = 1 - \operatorname{erf}\left(\frac{y}{2\sqrt{(\lambda_f / C_f)\tau}}\right), \qquad (2)$$

where a and b are unknown parameters associated with equivalent and initial temperatures; y is the depth of the calculated point; C_f is the volumetric heat capacity of frozen soil, W·h/(m^3·°C); λ_f is the thermal conductivity coefficient of frozen soil, W/(m·°C); erf is the probability integral, tabulated function.

To determine unknown parameters, we have the values of soil temperature T_i, measured at certain moments of time τ_i and constituting a system of equations:

$$a_i E_{i,j} + b_i = T_{i,j}, \quad i = 1, 2, ..., n, \quad j = 1, 2, ..., m,$$

where n is the number of temperature measurement points in the borehole; m is the number of temperature measurements in time, separated by a period of a number of years; $E_{i,j}$ is the value of the function (2) at point (x, y_i) in time τ_j.

Thus, for each i-th point we have a set of m equations. Grouping them into pairs, we get $m/2$ systems of equations equal to the number of combinations of elements of this set by two ($m/2$), of the following form:

$$\begin{cases} a_i E_{i,j} + b_i = T_{i,j}, \\ a_i E_{i,j+k} + b_i = T_{i,j+k}. \end{cases} \qquad (3)$$

Having solved the system of Eqs. (3), we will obtain the values a_i and b_i. There will be $m/2$ of such values according to the number of equations. It is natural to take their average value as a_i^{av}, b_i^{av} for calculation. After that, we will get an extrapolation formula in time for each depth at which the temperature was measured:

$$T(x, y_i, \tau) = a_i^{av}\left(1 - \operatorname{erf}\frac{y_i}{2\sqrt{(\lambda_f / C_f)\tau}}\right) + b_i^{av}, \qquad (4)$$

where $T(x, y_i, \tau)$ is the predicted temperature at point (x, y_i) at the moment τ, °C; τ is the forecast period counted from the start of operation of the pipeline, years.

The duration of observations is determined by the forecast period. Usually, when extrapolating, the ratio of the forecast period to the observation period is 1:3, if linear polynomials are used as an extrapolation function. In our case, the extrapolation function is found from an approximate analytical solution of a physical problem, to which this restriction does not apply. The calculations below show that it can be equal to 2:1.

To facilitate calculations according to Eq. (4), the authors have developed a computer program (macro 2, Appendix).

Calculation of the emergency subsidence of underground oil pipeline and the critical depth of permafrost thawing under its central part

The calculation of the maximum subsidence is carried out according to the methodology described in the monograph [*Tartakovsky, 1976*]. This calculation consists in checking four limiting conditions for a given subsidence. A subsidence is considered an emergency if one or several conditions are violated. The limiting conditions are given below.

1. Pipe strength condition:

$$\lim 1 = \frac{1}{\gamma_n} \cdot \frac{\sigma_{tem}}{|\sigma_{\lim N}|} \geq 1,$$

where $\sigma_{\lim N}$ is the total longitudinal strain in the pipe, Pa; γ_n is a dimensionless reliability coefficient taken from 1.0 to 1.1 according to [*SNiP 2.05.06-85*, 2005*]; σ_{tem} is the temporal steel strength, Pa according to [*GOST TU 14-3-1344-85, 1985*]. The total longitudinal strain is equal to

$$\sigma_{\lim N} = 0.3\sigma_{cir} + \sigma_T + \sigma_s,$$

where σ_{cir} is the circular strain caused by the internal pressure in the pipe, Pa; σ_T, σ_s are the longitudinal strains in the pipe from temperature changes and elastic bending of the pipeline during its subsidence, respectively, Pa. Their values are determined by the following formulas:

$$\sigma_{cir} = 1.15 \frac{p_p d_{p,in}}{2\delta_p},$$

$$\sigma_T = E_{st} \alpha_T \Delta T,$$

$$\sigma_s = 3 \cdot 10^5 \psi_p \sqrt{\frac{q_{ent} s}{\beta_1 d_p \delta_p}},$$

where p_p is the internal pressure in the pipe, Pa; $d_{p,in}$ is the inner diameter of the pipe, m; δ_p is the wall thickness of the pipe, m; E_{st} is the modulus of elasticity of steel, $2 \cdot 10^{11}$ Pa; α_T is the coefficient of linear expansion of steel, $1.2 \cdot 10^{-5}$ 1/°C; ΔT is the difference between maximum and minimum pipe wall temperatures during the entire time of operation of the pipeline; it is assumed to be 40°C for underground pipelines; d_p is the outer diameter of the pipe, m; s is the subsidence of the pipeline during permafrost thawing, m; ψ_p, β_1 are dimensionless coefficients determining the operation of the pipe on an elastic base during bending and depending on the length of the section (L_{sp}, m) of the pipeline subjected to bending; and q_{ent} is the total weight loading on 1 m of the pipe, N/m.

The length of the pipeline section subjected to bending during its subsidence is determined by the fitting according to the formulas:

$$L_{sp} = \sqrt[4]{\frac{384 E_{st} I_p s}{\beta_1 q_{ent}}},$$

$$\beta_1 = 1 + 6w + 16w^2,$$

$$w = \frac{14\,389 d_p}{L_{sp} \sqrt[3]{\left(k_b L_{sp} d_p\right)/\delta_p}},$$

$$\psi_p = \frac{10 + 15w + 6w^2}{10(1+2w)},$$

where I_p is the equatorial moment of inertia of the pipe section: $I_p = \pi\left(d_p^4 - d_{p,in}^4\right)/64$; k_b is the coefficient of the bed, N/m^3; w is the auxiliary design parameter; q_{ent} is the total weight load per 1 m of pipe, N/m. The total weight load is equal to

$$q_{ent} = 1.1\left(q_p + q_{ins} + q_{pr} + q_{ba} + q_{soil}\right),$$

where q_p, q_{ins}, q_{pr}, q_{ba}, q_{soil} are the weights of 1 m of the pipe, insulation, product, ballast, and soil lying on the pipe, N/m. The values are determined by the following formulas:

$$q_p = \frac{\pi}{4} \rho_{st} g \left(d_p^2 - d_{p,in}^2\right),$$

$$q_{ins} = \frac{\pi}{4} \rho_{ins} g \left(d_{ins}^2 - d_p^2\right),$$

$$q_{pr} = \frac{\pi}{4} \rho_{pr} g d_{p,in}^2,$$

$$q_{soil} = 0.88 g \rho_{th} d_{ins} h_p,$$

$$q_{ba} = \frac{\rho_{ba}}{\rho_{ba} - \rho_w} q_{ba,w},$$

$$q_{ba,w} = 1.05 g \rho_w \frac{\pi d_{ins}^2}{4} - 0.95\left(q_p + q_{ins}\right) - q_{soil,w},$$

$$q_{soil,w} = \frac{\rho_s - \rho_w}{\rho_s \left(1 + w_{tot}\right)} q_{soil},$$

where ρ_{st}, ρ_{ins}, ρ_{pr}, ρ_{th}, ρ_{ba}, ρ_w, ρ_s are the densities of steel, thermal insulation, transported liquid, thawed soil, ballast, water, soil particles, kg/m^3; w_{tot} is the total moisture content of frozen soil, decimal fraction; d_{ins} is the outer diameter of the pipeline with circular thermal insulation, m; h_p is the distance from the soil surface to the center of the underground pipeline, m; and g is the acceleration of gravity, 9.81 m/s^2.

The bed coefficient is determined by the formula

$$k_b = 0.523 E/d_p,$$

where E is the modulus of deformation of thawed soil, Pa.

2. The condition of stability of the pipe in the longitudinal direction:

$$\lim 2 = \frac{N_{\lim}}{(0.2\sigma_{cir} + \sigma_T) F_p} \geq 1,$$

where $F_p = (\pi/4)\left(d_p^2 - d_{p,in}^2\right)$; $N_{\lim}$ are the maximum compressive forces that can be perceived by the pipe without losing its stability in the longitudinal direction, N. The formulas by which these values are determined:

$$N_{\lim} = \min \begin{cases} 4.09\sqrt[11]{p_0^2 q_H^4 F_p^2 E_{st}^5 I_p^3}, \\ 2\sqrt{k_b d_p E_{st} I_p}, \end{cases}$$

$$p_0 = \pi d_p (p_1 \mathrm{tg}\,\varphi + c),$$

$$p_1 = \frac{1.6 g \rho_{th} h_p d_p \left[1 + \mathrm{tg}^2\left((\pi/4) - 0.5\varphi\right)\right] + q_1}{\pi d_p},$$

$$q_1 = 0.95\left(q_p + q_{ins} + q_{ba}\right),$$

$$q_H = q_1 + 0.8 g \rho_{th} d_p \left(h_p - \frac{\pi d_p}{8}\right),$$

where φ is the angle of internal friction of thawed soil, rad; c is the traction of thawed soil, Pa. The remaining values are given above.

3–4. Conditions for the absence of elastic deformations in the pipe:

$$\lim 3 = \frac{1}{\gamma_n} \frac{\sigma_{fl}}{|\sigma_{\lim N}|} \geq 1,$$

$$\lim 4 = \frac{1}{\gamma_n} \frac{\sigma_{fl}}{|\sigma_{cir}|} \geq 1,$$

where σ_{fl} is the flow stress of steel, Pa.

The algorithm to determine emergency subsidence (s_u) implies multiple checking of limit conditions by setting the subsidence of the pipeline and increasing it every time until a violation of at least one of the limiting conditions. The pipeline subsidence corresponding to this event is considered an emergency. Knowing s_u, it is easy to calculate the critical depth of thawing, H_{cr}, under the pipeline . The calculation is carried out according to the formula

$$H_{cr} = \frac{s_u}{\delta} + h_p + \frac{d_{ins}}{2},$$

where s_u is the value of the emergency subsidence, m; δ it the relative subsidence during permafrost thawing, fraction of a unity.

The value of δ depends on the ice content of the soil, g_i, and is determined in laboratory from samples taken from the control borehole, or according to the table, as a function of g_i [*STO Gazprom..., 2008*]. In turn, g_i is calculated by the formula $g_i = \rho_{d,f}(w_{tot} - w_w)$, where w_{tot} is the total soil moisture; is the moisture due to unfrozen water; $\rho_{d,f}$ is the density of dry frozen soil, kg/m^3.To facilitate the calculations of s_u and H_{cr}, the authors have developed a computer program (macro 3, see Appendix).

In conclusion, we have to note two important circumstances:

(1) The technique is developed only for permafrost without residual thaw layer (permafrost table merging with the active layer).

(2) The technique, as well as the vast majority of methods for the analytical calculation of bowls and halos of thawing at the basements of constructions, is based on the fact that the soils are homogeneous. In the case of layered soil, the averaged soil characteristics are taken into account. The calculations are carried out within the depth of the averaging to average the coefficients of the thermal conductivity of the soil and other characteristics according to the following formulas:

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

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

where λ_i, A_i are the numerical values of the ground 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. The depth of the location of the deepest temperature sensor in the control borehole is taken as the averaging depth.

VERIFICATION OF THE METHODOLOGY

Comparison of the calculated data with experimental observations in our case will be conventional, because everything concerning the state of existing oil pipelines is a closed information. To complete the task, we will replace the actual data of the results of mathematical modeling using the QFrost software [*Pesotsky, 2016*]. We accept a two-dimensional model, with the computational domain size of 48 × 48 m (Fig. 1).

The designed dimensions of the pipeline are as follows: the radius along the outer circular insulation r_{ins} = 0.75 m, the distance from the earth surface to the center of the pipeline h_p = 1.75 m. The climatic characteristics are taken from data of the Amga weather station (30-yr-long period) in the Republic of Sakha (Yakutia). Let us formulate the boundary conditions of the third kind at the upper boundary of the computational domain (Table 1). On the surface of the circular insulation of the oil pipeline, we assume a boundary condition of the first kind: T_p = 20°C (T_p is the temperature on the surface of the circular insulation of the pipeline); for other boundaries, a boundary condition of the second kind with zero heat

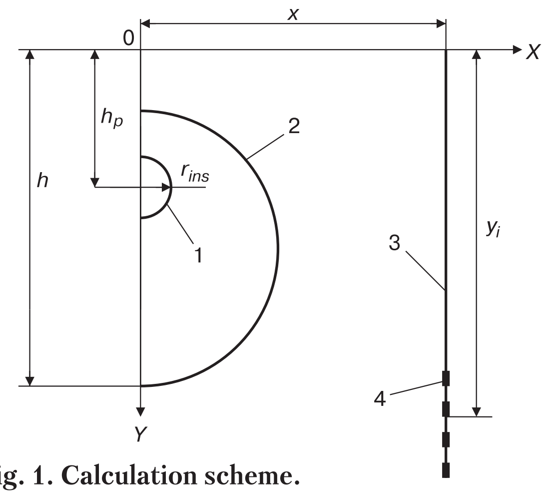

Fig. 1. Calculation scheme.

1 – oil pipeline; 2 – permafrost thawing boundary around the pipeline; 3 – control borehole; 4 – temperature sensor; r_{ins} – radius for the outer boundary of circular insulation; h_p – distance from the ground surface to the center of the pipeline; h – thawing depth under the pipeline; y_i – distance from the earth surface to the temperature sensor (measuring point).

Table 1. **Boundary conditions of the 3rd kind on the ground surface**

Month	T, °C	α, W/(m²·°C)	Month	T, °C	α, W/(m²·°C)
I	–42.0	0.75	VII	18.8	4.2
II	–35.6	0.68	VIII	14.9	4.2
III	–22.0	0.69	IX	6.1	4.2
IV	–6.8	1.31	X	–7.9	2.84
V	6.2	4.2	XI	–28.2	1.09
VI	15.6	4.2	XII	–39.5	0.95

Note: T is the mean monthly air temperature; α is the heat exchange coefficient at the soil surface.

flow is taken. The soil containing the oil pipeline is represented by loam with the following characteristics: thermal conductivity in thawed and frozen state (W/(m·°C)): λ_{th} = 1.33, λ_f = 1.51; volumetric heat capacity in thawed and frozen state (W·h/(m³·°C)): C_{th} = 777, C_f = 592; density of frozen soil in the dry state $\rho_{d,f}$ = 1600 kg/m³; the total moisture content of the frozen soil w_{tot} = 0.2; and the amount of unfrozen water w_w = 0.05.

October 1 was taken as the starting date of the simulation. To establish the temperature distribution curve by the depth, a preliminary solution of the linear problem was carried out using the QFrost software.

The depth of the computational domain is assumed to be 48 m. At the upper boundary of the computational domain, a boundary condition of the 3rd kind is set according to Table 1. At the lower and lateral boundaries, the 2nd kind condition is set: the value of the heat flow is taken equal to zero. Modeling was carried out until the establishment of a quasistationary state of the temperature regime of soils. The results of simulation are shown in Table 2.

Using macro 1 (see Appendix), we recalculate the modeling data on soil temperature into the depths of thawing and compare them with the depths obtained as a result of modeling using the QFrost software (Fig. 2).

As one can see, the coincidence is not perfect, but it is quite acceptable. Thus, according to this test, our first "temperature–depth" technique is valid.

Using macro 2 (see Appendix), we make a forecast of changes in soil temperature to a depth of 20, 25 m and evaluate it based on the results of modeling. Doing this, we formulate two problems:

(1) For the observation period, we take the period from the 1st to the 5th year (Table 2), for the decadal forecast period.

(2) For the observation period, we take the period from the 1st to the 10th year (Table 2) for the forecast period of three decades.

The results of corresponding calculations are given in Tables 3 and 4.

Table 2. **Changes in the depth of permafrost thawing and soil temperatures under the central part of the pipeline and the temperature of the soil**

Time, years	Depth of thawing, m	Temperature* according to modeling data at a depth (m)					
		15.25	16.25	17.25	18.25	19.25	20.25
0	0	4.82	4.80	4.78	4.77	4.76	4.75
1	5.66	4.60	4.65	4.68	4.70	4.72	4.73
2	6.74	4.15	4.27	4.37	4.45	4.51	4.57
3	7.50	3.75	3.91	4.04	4.16	4.26	4.34
4	8.02	3.45	3.60	3.76	3.90	4.02	4.12
5	8.51	3.15	3.35	3.52	3.67	3.80	3.92
10	10.1	2.32	2.54	2.74	2.92	3.08	3.23
30	13.0	1.15	1.38	1.58	1.77	1.94	2.10

*Temperature of the soil at a distance of 4.25 m from the pipeline axis.

It is difficult to judge the reliability of the proposed method (observed temperature – predicted temperature) only from data in Tables 3 and 4. Therefore, using macro 1 (Appendix), we recalculate the predicted ground temperatures indicated in Tables 3 and 4 into the predicted thawing depths and compare them with the depths obtained as a result of modeling (Table 5).

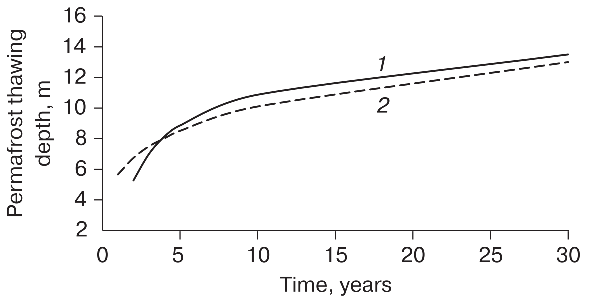

Fig. 2. Dependence of permafrost thawing depth under the oil pipeline on time.

1 – the results of mathematical modeling; *2* – the results of calculation of permafrost temperature at a distance of 4.25 m from the pipeline axis.

Table 3. **Forecast of permafrost temperature as based on the results of modeling for 10 years**

Depth, m	Temperature, °C	
	forecast	modeling data
15.25	–2.84	–2.32
16.25	–2.92	–2.54
17.25	–3.08	–2.74
18.25	–3.17	–2.92
19.25	–3.26	–3.08
20.25	–3.67	–3.23

Table 4. **Forecast of permafrost temperature as based on the results of modeling for 30 years**

Depth, m	Temperature, °C	
	forecast	modeling data
15.25	–1.73	–1.15
16.25	–1.88	–1.38
17.25	–2.10	–1.58
18.25	–2.22	–1.77
19.25	–2.33	–1.94
20.25	–2.95	–2.10

Table 5. **Forecast of permafrost thawing depth under the central part of the pipeline as based on the forecast temperature**

Time, years		Depth of permafrost thawing, m		Forecast error, %
observations	forecast	forecast	modeling data	
5	10	9.13	10.1	9.6
10	30	12.39	13.0	4.7

Table 5 presents generalized data. They indicate that the proposed methodology "Prediction of the depth of permafrost thawing under an underground oil pipeline based on the results of observations of soil temperature in a closely located borehole" gives satisfactory results.

Example of calculating the possibility of an oil pipeline emergency

Let us summarize the above statements. For this, we will consider a problem covering all aspects of the proposed methodology: we will estimate the time of occurrence (non-occurrence) of an oil pipeline emergency from the results of initial observations of soil temperature in a borehole located close to the oil pipeline. The sequence of actions is as follows.

Conditionally, the results of mathematical modeling for the first 10 years (Table 2) are taken as initial observations in a borehole located at a distance of 4.25 m from the axis of the pipeline. Using this spatio-temporal sampling of temperatures, we determine the forecast temperature fields for the periods of 15, 20, 25 and 30 years. Further, using the obtained temperature fields, we find the depth of permafrost thawing under the central part of the pipeline, which we then compare with the critical depth of thawing and determine the time when the predicted thawing depth will reach the critical level. The soil characteristics are assumed to be equal to the soil characteristics used in in mathematical modeling.

Sequentially using macros 2, 1, and 3 (see Appendix), we obtain data that allow us to draw graphs (Fig. 3).

As can be seen, before the end of the pipeline operation period, the critical depth is greater than the predicted depth, which indicates the absence of an emergency situation because of permafrost thawing.

Thus, only on the basis of initial observations of the soil temperature, the authors came to the conclusion about the oil pipeline basement safety.

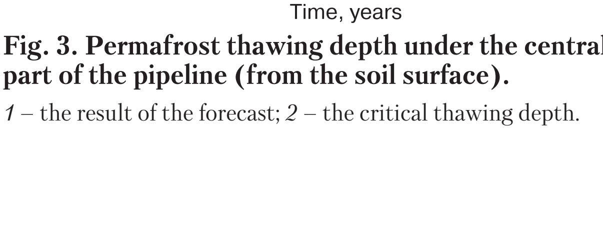

Fig. 3. Permafrost thawing depth under the central part of the pipeline (from the soil surface).

1 – the result of the forecast; *2* – the critical thawing depth.

CONCLUSIONS

1. The proposed methodology for predicting the emergency situation of an underground oil pipeline based on the results of observations of the ground temperature in a nearby borehole is simple to use; it can be applied to sections of an oil pipeline within permafrost areas without a comprehensive system of permafrost temperature monitoring.

2. The technique is applicable only in permafrost areas without a residual thaw layer.

3. The application of this technique allows one to judge the reliability or unreliability of the oil pipeline basement from temperature observations in a borehole drilled at a safe distance (0.5–1.5 m) from an underground oil pipeline.

The data presented in this article indicate that this technique ensures quite satisfactory results and can be recommended for practical use.

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Appendix. – https://yadi.sk/d/xva4hnsryVklgA

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APPENDIX

The computer programs (macros) offered to the reader are written in the Visual Basic language using the Excel 2007 platform (VBA Excel). To view them, you should press the "Developer" key on the Excel sheet corresponding to the selected macro in the command line and then the "Visual Basic" key. The programs are ready for practical use, for which the user must perform only two simple operations: fill in the yellow field on the Excel sheet with their source data and make one mouse click on the "Start" button placed at the top of the sheet. The result of the calculation can be read on the gray field of this sheet.

Access to the programs is provided through URL: https://yadi.sk/d/xva4hnsryVklgA