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THE STOCHASTIC PROGNOSIS OF SOIL CONDITION UNDER THE OBJECTS BUILT IN THE PERMAFROST[*]

ABSTRACT. The study contains the calculation of soil conditions under the oil tank installed at the Varandeyskoye oil field cooled by slightly inclined heat stabilizers produced by OJSC Fundamentproekt. It is generated forty seven scenarios of these conditions development over an eight-year period on the basis of Monte-Carlo method and the distribution of meteorological characteristics which average the archive data from Varandey meteorological station. It is demonstrated that soil temperatures for different scenarios vary considerably, which raises doubts about reliability of a typical one-scenario forecast. Therefore, it is suggested the stochastic approach to calculate the worst forecast which should be taken into consideration at the design stage of the project.

KEY WORDS. Thermostabilizer, tank, oil, foundation, simulation.

The natural resources of the northern and eastern parts of Russia become even more important, and the state economic and social programmes require active development of the vast underpopulated areas to the east of the Urals along the other back-country territories. This sets a number of tasks which partly deal with engineering construction on permafrost in the regions with highly adverse climate [1].

The permafrost regions of Russia make up 65% of its territory, so developing construction technologies effective in the specific conditions of these regions is of great importance [2]. To decrease costs of oil production and transportation it is viable to build oil tanks of high capacity (10,000–100,000 m^3) close to the producing oil fields.

This research contains calculation and stochastic prognosis of temperature fields under the oil storage tank with the loading capacity of 50,000 m^3 (vertical stock tank 50,000) with the system of slightly inclined heat stabilizers produced by Fundamentproekt Federal State Unitary Enterprise and installed at the Varandeyskoye oil field [3, 4].

The oil storage tank at the field is a cylinder with the internal diameter of $d_{ex} = 60.70\ m$ and the outer diameter of $d_{outer} = 66.07\ m$. The space between the internal and external walls of the tank contains air to prevent sideways thermal fluxes. The oil temperature in the tank is 45°C. The tank rests on a layer of fill-up soil, its depth being $l_1 = 0.60\ m$ and the heat conductivity coefficient $\lambda_1 = 0.95\ \frac{W}{m \cdot {}^\circ C}$. Under this layer

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there is a layer of heat insulator, which is $l_2 = 0.40$ *m* deep and has the heat conductivity coefficient of $\lambda_2 = 0.04\frac{W}{m\cdot°C}$. The third layer below the heat insulator is a layer of filled-up sand, which was initially frozen in refrigerators; this layer is $l_3 = 3.0$ *m* deep and has the heat conductivity coefficient of $\lambda_{gr} = 1.73\frac{W}{m\cdot°C}$. The sand layer carries thermosiphon evaporators which are placed $l_x = 1.25$ *m* away from the edge of the heat insulator parallel to each other, spaced apart at the distance of $l_y = 1.0$ *m*. For the general layout of the thermosiphons in three projections see Fig. 1.

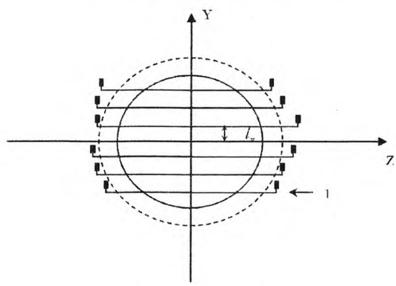

Fig.1. (a)

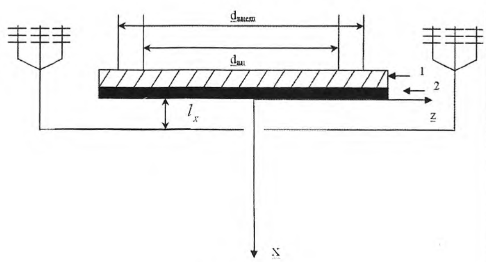

Fig.1. (b)

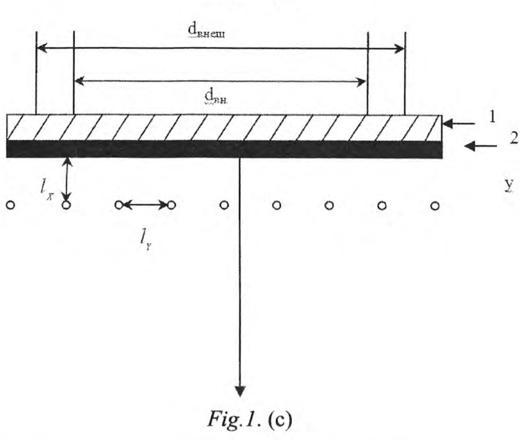

Fig.1. (c)

The thermosiphon evaporators have the grade of 1–2 degrees, and can, therefore, be considered horizontal.

To calculate the heat and mass transfer in the soil we used the effective thermal capacity method [5], which formulates the heat conductivity equation as follows:

$$[c + L\delta(T - T_f)]\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad (1)$$

where c—volumetric heat capacity of the soil, λ—heat conductivity coefficient, T—temperature, T_f—transition temperature, x, y, z—Cartesian coordinates, t—time, $\delta(T - T_f)$—Dirac delta function, L is determined by the formula:

$$L = r \cdot (w - w_{\text{нв}})\gamma_{\text{ск}} \quad (2)$$

where r—heat of ice melting, w—water content of soil, w_{nf}—water content of unfrozen soil, $\gamma_{\text{ск}}$—body density of soil.

The spatial grid in the computational domain is given by the formulas:

$$x_i = i \cdot h_x \quad 0 \le i \le 100 \quad h_x = 0.1 \text{ м}$$
$$y_j = j \cdot h_y \quad 0 \le j \le 1000 \quad h_y = 0.1 \text{ м}$$
$$z_k = k \cdot h_z \quad 0 \le k \le 100 \quad h_z = 1 \text{ м}$$
$$t_n = \tau \cdot n \quad 0 \le n \le \infty \quad \tau = 0.01 \text{ day.}$$

The heat stabilizing evaporators are parallel to z-axis. The difference scheme which corresponds to the equation in (1) is formulated as follows:

$$T(i,j,k,n+1) =$$
$$= T(i,j,k,n) + \frac{a(i,j,k)\cdot\tau\cdot(T(i+1,j,k,n) + T(i-1,j,k,n) - 2T(i,j,k,n))}{h_x^{\ 2}}$$
$$+ \frac{a(i,j,k)\cdot\tau\cdot(T(i,j+1,k,n) + T(i,j-1,k,n) - 2T(i,j,k,n))}{h_y^{\ 2}}$$
$$+ \frac{a(i,j,k)\cdot\tau\cdot(T(i,j,k+1,n) + T(i,j,k-1,n) - 2T(i,j,k,n))}{h_z^{\ 2}}$$

where $a(i, j, k)$ is described with the following formula:

$$a(i,j,k) = \begin{cases} a_{\text{м}} & \text{with } T(i,j,k,n) < T_f - \Delta \\ \dfrac{0.5(\lambda_{\text{м}} + \lambda_{\text{т}})}{0.5(c_{\text{м}} + c_{\text{т}}) + \frac{L}{2\Delta}} & \text{with } T_f - \Delta \le T(i,j,k,n) \le T_f + \Delta \\ a_{\text{т}} & \text{with } T(i,j,k,n) > T_f + \Delta \end{cases}$$

Where a_m, a_f stand for values of thermal conductivity for melted and frozen soil respectively, λ_f, λ_m are heat conductivity coefficients for melted and frozen soil, $c_{\text{М}}$, $c_{\text{Т}}$ are values of volumetric heat capacity of melted and frozen soil. Under the method of effective thermal capacity [5] the value of Δ determines the temperature range of the water-ice phase change which equals $T_f - \Delta \le T(i,j,k,n) \le T_f + \Delta$. When carrying out numerical evaluation of $a(i,j,k)$ Dirac delta function in equation (1) was replaced with the function $f(T-T_f)$ which is given by [5]:

$$f(T-T_f)=\begin{cases}0 \ with \ |T-T_f|>\Delta\\ \frac{1}{2\Delta} \ with \ |T-T_f|\le\Delta\end{cases}$$

On the lateral surface of the computational domain we assume the boundary condition of the second type (the thermal flux is zero). On the bottom surface of the computational domain we assume the boundary condition of the first type, with the temperature equal to the initial one. On the top surface of the computational domain we assume the boundary condition of the third type; at that, for the area under the tank we take into account heat exchange between the soil and the tank, while for the rest of the surface we take into account the heat exchange between the soil and the atmosphere.

We use the data from Varandey meteorological station on the temperature and wind speed for 2007–2012 to get the temperature and wind speed distributions for each of the twelve months of the year. The distribution of temperature variance within each month conforms well to the Gauss distribution [6]:

$$w(T)=\frac{e^{-(T-m)^2/2\sigma^2}dT}{\sqrt{2\pi}\,\sigma} \tag{4}$$

where T is temperature, m is mean of distribution, σ is root-mean-square deviation.

The distribution of wind speed variance within each month conforms well to the gamma distribution [6]:

$$w(v)=\frac{\lambda^{\alpha}}{\Gamma(\alpha)}v^{\alpha-1}e^{-\lambda v}dv \tag{5}$$

where v is wind speed, $\Gamma(\alpha)$—gamma function, α and λ are related to moda η and dispersion Dv as follows:

$$\eta=\frac{\alpha-1}{\lambda^2} \qquad Dv=\frac{\alpha}{\lambda^2} \tag{6}$$

Optimal parameters for the respective temperature and wind speed distributions for each month are given in Table 1.

Table 1

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
m	-14.78	-18.9	-13	-7.13	-1.55	6.07	10.72	9.16	6.47	1.53	-7.83	-11.03
σ	7.18	8.8	6.93	6.61	5.09	5.9	4.6	3.0	3.16	3.49	7.7	9.02
α	3.04	3.07	2.73	3.79	4.0	3.57	3.86	4.94	3.4	5.03	2.73	4.73
λ	0.47	0.48	0.48	0.67	0.72	0.67	0.66	0.82	0.6	0.74	0.52	0.62

We used the distributions (4) and (5) and applied the Monte-Carlo method [7] to simulate 47 different random paths for temperature and wind speed changes over an eight years period. For each of these future scenarios we calculated the temperature field within the computational domain. Then average temperature for the central axis and the value of arithmetical mean for all the scenarios were calculated as well as each scenario deviation from this mean. The largest positive deviation (the warmest scenario) and largest negative deviation (the coldest scenario) were determined. Temperature distributions at all depths along the central axis of the computational domain for both of the above scenarios are shown in Fig. 2.

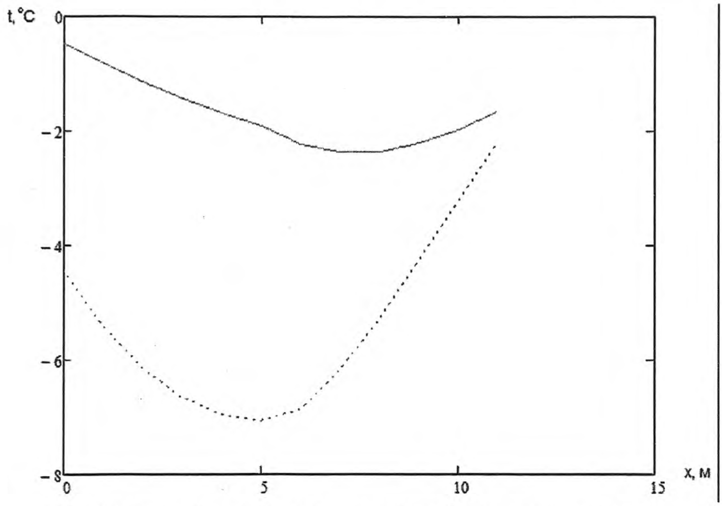

Fig. 2. Temperature distributions at all depths along the central axis

As it can be seen from Fig. 2, the difference for these scenarios can be 5 degrees, which means that the deterministic approach, often used to this end, yields incorrect results and it is important to apply the stochastic prognosis.

The calculations were made on the supercomputer NKS-30T with the use of MPI-technology of parallel computing [8]. The corresponding calculation results for the temperature fields under the oil tank are shown in Fig. 3.

In conclusion it is important to mention that the main factor which determines the mechanical safety of infrastructural objects in the cryolithic zone is stability and deformation resistance of the foundation soils, which are prone to changes under the natural and man-made influences [9, 10]. When developing the computational model of the soil temperature dynamics, which can lead to loss of mechanical safety (deformations), it is important to use the stochastic approach. It helps to make a reliable forecast of possible negative temperature scenarios and to develop effective technical solutions to control them.

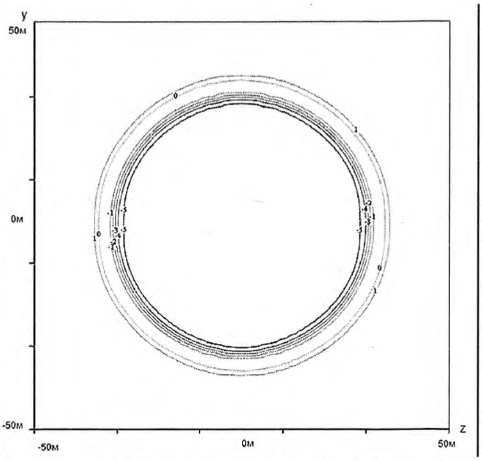

Fig. 3a. The temperature field at the level of cooling pipes at the end of August in the eight-year calculation period (the coldest scenario)

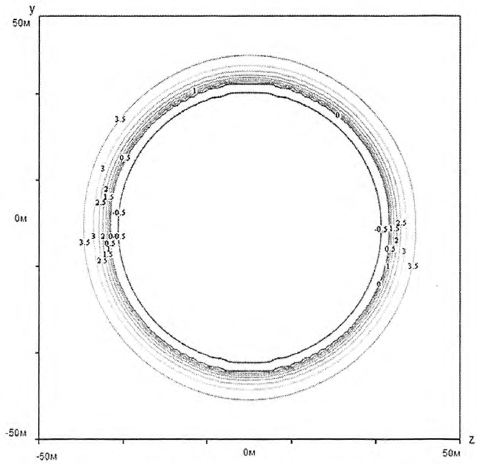

Fig. 3b. The temperature field at the level of cooling pipes at the end of August in the eight-year calculation period (the warmest scenario)

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