EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Kriosfera Zemli, 2021, vol. XXV, No. 4, pp. 30–39

PERMAFROST ENGINEERING

EFFICIENCY OF SURFACE COOLING OF FROZEN FOUNDATION SOILS USING A FORCED REFRIGERANT CIRCULATION UNIT

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A method for surface cooling of frozen foundations has been proposed. It includes heat insulation through the soil surface and a unit for forced circulation of a refrigerant. The latter is used only in summer during the entire period of operation of the structure. The method has important advantages in comparison with the known methods of surface cooling: a) a seasonally thawed layer can't be formed at any time of the annual cycle and the cooling impulse enters the ground base throughout the entire calendar year; b) in urban conditions, the use of a machine cooling method (instead of seasonally operating cooling systems) is quite reasonable since it does not require significant space for its implementation. Analysis of the results of temperature fields calculating demonstrates quick cooling of the ground base: for all calculation options, the temperature at the depth of zero annual amplitude in the second year of operation reaches a value corresponding to hard frozen state of most of the soils. The decrease becomes even more significant in the third year of operation. The calculation results are rather weakly dependent on the distance between the cooling elements of the applied cooling system within the considered range of variation of that value (from 0.7 to 1.0 m).

Key words: *frozen soils, seasonal thawing layer, ground temperature regime, heat-insulation layer, forced cooling, time to reach the required temperature.*

INTRODUCTION

Surface methods of cooling and thermal stabilization of frozen soils of the structure foundations eliminate the need to perform laborious work on drilling the soil, its moving and deepening it into the base of the elements of cooling devices and require significantly lower implementation costs in comparison with other methods. The gain in reducing labor intensity is most obvious when such work must be carried out manually on a previously prepared pile field, or in the presence of overlapping of the ventilated underfloor space of buildings [*Dolgikh, 2014; Abrosimov et al., 2018*]. At the same time, all the cooling experience available until recently indicates that surface methods are significantly inferior in cooling efficiency both in terms of the duration of reaching the design temperature regime and in the amount of temperature decrease at the base [*Makarov, 1985; Konovalov, 1989; Bubelo, 2003*]. However, relatively recently, based on the analysis of the formation mechanism of a temperature shift in the presence of covers of arbitrary nature on the soil surface [*Gorelik, Zemerov, 2020*], it was possible to select a surface coating design that can provide the required temperature in the base at a sufficiently high cooling rate. Such the coating includes a layer of high-quality heat insulation and a cooling element of a horizontal, naturally operating tubular system laid under it on the ground surface (GET) [*Dolgikh et al., 2014*]. Since the depth of seasonal thawing is significantly being reduced with high-quality heat insulation, then with the onset of the cold period, the thawed layer quickly freezes. After that, the 'zero curtain' disappears [*Kudryavtsev, 1978*], the cold from the surface (cooling impulse) begins to spread into the depth of the soil, and that process continues until the end of the winter period. As a result, the duration of cooling impulse increases significantly in comparison with the usual freezing conditions.

Since in winter time a sufficiently low temperature is maintained on the soil surface, under the layer of snow and heat insulation (due to the action of cooling element of the GET system), and the bottom of the active layer is located close to that surface, then the temperature at its bottom will be much lower for a long time than under normal conditions. As a result of the enhanced action of those two factors, – a decrease in the average annual temperature at the base of the seasonal freezing layer and an increase in the duration of the cooling impulse – the above-noted increase in the cooling rate is possible when the required temperature at the base is reached. The corresponding calculation results and their analysis are given in [*Gorelik, Khabitov, 2021*], where the main emphasis is placed on the use of the GET cooling system, which is capable of operating only in the winter season. However, as shown in that work, the cooling intensity significantly increases if for a short time (during one summer season) a forced circulation of refrigerant unit is connected to the evaporator of the GET system. In the presence of high-quality heat insulation, the summer source of cold prevents the formation of a layer of seasonal thawing, thereby eliminating the power-intensive process of its freezing in winter. In that case, the duration of the cooling impulse reaches its maximum value, which leads to the reaching of a positive effect. At the same time, it is not difficult to understand that if, in the considered scheme of surface cooling, the use of the condensing unit of the GET system is completely excluded, reserving the forced cooling unit, which will be switched on only during the summer period of the entire service life of the structure, then the formation of a layer of seasonal thawing on the soil surface under the heat insulation will be impossible. In that case, the formation of temperature at a depth of zero annual amplitude occurs under the influence of the average annual temperature on the soil surface (the concept of the average annual temperature at the bottom of the active layer loses its meaning here).

Approximate estimates of the average annual surface temperature, performed according to the formulas given in [*Gorelik, Khabitov, 2021*] demonstrate a quite comparable result of cooling by the method proposed here in comparison with the options for using the GET system. In fact, the proposed method replaces the use of cooling devices in the winter season (using the GET system) for summer time by machine way. That replacement has significant advantages in urban areas, where the placement of very large capacitor units in residential areas will inevitably lead to known problems. The use of a machine cooling method is a completely industrial method that does not require significant space for its implementation. We also note that at present, domestic manufacturers have developed and mastered the production of units with the necessary parameters [*Okunev, Dolgikh, 2017*].

In addition to the aforesaid, the proposed method can be used in a number of areas of the globe with a hot climate with a global rise in temperature to create zones of climatic comfort. They can be created in the near-surface layers of the soil by surface cooling. However, we will not dwell on that issue in this article.

The purpose of this work is to calculate the cooling of frozen foundations using sufficiently accurate methods, to analyze them and to draw conclusions about the effectiveness of the proposed cooling method.

Calculation procedure for cooling using a forced circulation refrigerant unit

Calculations of the temperature dynamics in the basement soils with the machine cooling method have been performed for a building with an underfloor space having lateral dimensions of 12 × 24 m and, in general repeat the same procedure used in [*Gorelik, Khabitov, 2021*] for the GET cooling system. The design and location of the cooling system elements within the pile field are shown in Fig. 1. The evaporator pipes of the cooling system are laid in a coil along the major axis of the building and covered with a leveling layer of sand. Standard heat-insulating panels are laid end-to-end along the leveling layer (with the necessary trimming at the points of pile bypass) within the entire surface of the ventilated underfloor space.

The horizontal distance between the axes of adjacent evaporator tubes (L) is taken in two versions: 1.0 m and 0.7 m, the diameter of the tubes (D) is 37 mm. The thickness of the heat insulation of the standard panel (h) is 100 mm, the thermal conductivity coefficient of the material (λ_i) is 0.03 W/(m·°C). The main trends in the behavior of temperature fields can be determined for a soil homogeneous in terms of thermal properties. The heterogeneity of those properties can only be associated with local quantitative deviations from the general trend in the behavior of temperature, which do not fundamentally affect the general nature of its change. That is justified by the fact that, in the problem under consideration, the frozen soil lying below the bottom of the active layer does not change its state in the course of temperature changes.

To describe the dynamics of temperature in it, in a first approximation, we can neglect the change in the amount of unfrozen water with temperature (which is a good approximation for sandy and sandy-loam soils, and for water-saturated fine-dispersed soils, the calculation error is not critical). In that approximation, the process of heat transfer is purely conductive and is described by the classical equation

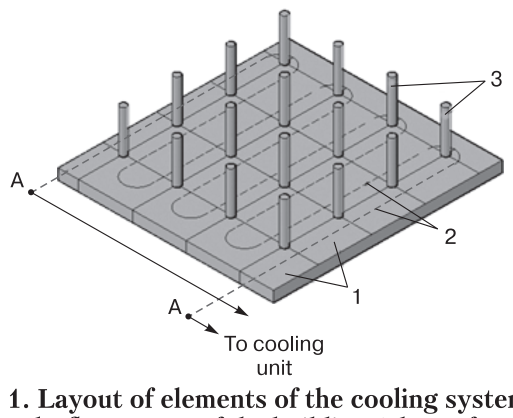

Fig. 1. Layout of elements of the cooling system in the underfloor space of the building (above-foundation structures are not shown).

1 – heat insulation plates; 2 – evaporator pipe (cooling element); 3 – foundation piles; A – points of connection of the cooling unit to the cooling element.

of thermal conductivity [*Kudryavtsev, 1978*] with variable coefficients (thermal conductivity and volumetric heat capacity) varying along the vertical coordinate in accordance with the change in soil properties through the section. In standard calculation schemes, the change in these coefficients along the vertical is approximated by step functions, which makes it possible to reduce the heat conduction equation to a form containing only one parameter – the thermal diffusivity of frozen soil (μ_f), which also depends on the vertical coordinate. The change in that parameter in different type of soils within the entire range of their density and water content, determined, for example, from the table of thermal properties [*SNiP 2.02.04-88, 1990*], can be represented as: $\mu_f = k \cdot 10^{-6}$ m^2/s, where the k value is within a rather narrow range: $0.5 \leqslant k \leqslant 1$. This means that general conclusions about the behavior of temperature in frozen soils can be obtained for a constant value of the μ_f coefficient from the specified range, while they remain valid (with small quantitative variations) for a wide range of practically important cases.

For ease of comparison with the results of calculations in [*Gorelik, Khabitov, 2021*], in all calculation options, the same soil characteristics are adopted as in the cited work (indexes for thawed soil and frozen soil are taken correspondingly as u and f). Thermal conductivity coefficient: $\lambda_u = 1.75$, $\lambda_f = 1.80$ W/(m·°C); volumetric heat capacity: $C_u = 2.68 \cdot 10^6$, $C_f = 2.20 \cdot 10^6$ J/(m^3·°C); density of dry soil: $\gamma_s = 1500$ kg/m^3; soil water content: $w = 0.2$. The transition of a unit volume of frozen soil to the thawed state is characterized by the value of the latent volumetric heat: $\kappa_v = \kappa\gamma_s w$, where $\kappa = 3.34 \cdot 10^5$ J/kg ($\kappa_v = 10^8$ J/m^3) – that value in the considered cooling method is important only for the surface soil layers beyond the building plan projection. The soil water content due to unfrozen water: $w_u = 0$. The freezing point of soil: $t_b = 0$ °C. The initial temperature of the soil at the base (t_0) is taken as –0.7 °C.

The problem setting includes the heat conduction equation for a half-space (excluding the inner regions of the circles corresponding to the location of the evaporator tubes), which is written in enthalpy form for the purpose of applying numerical solution methods [*Samarsky, Vabishchevich, 2003*]:

$$\frac{\partial H}{\partial \tau} = \frac{\partial}{\partial y}\left(\lambda \frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right), \qquad (1)$$

where: y, z are horizontal and vertical coordinates; enthalpy $H(t)$ is a function of temperature t at an arbitrary point of the soil body and is determined taking into account the heat of the phase transition localized near the interphase boundary:

$$H(t) = \begin{cases} k_v + C_u, & \text{if } t \geq 0\ ^\circ C, \\ C_f t, & \text{if } t < 0\ ^\circ C. \end{cases}$$

After differentiation with respect to temperature and time, on the left side of the (1), before the derivative of temperature with respect to time, a factor is formed which has the meaning of the effective heat capacity of soil and contains a δ function of temperature for which the smoothing procedure can be carried out [*Samarsky, Vabishchevich, 2003*]. For the numerical solution of the equation (1), the setting of boundary conditions on the moving boundary (which is formed during seasonal processes outside the contour of the structure) is not required.

The boundary condition on the upper surface of the soil is set by the 3rd kind condition:

$$\alpha\left(t_a(\tau) - t_s\right) = -\lambda\left(\frac{\partial t}{\partial z}\right)_s .$$

Here t_s is the temperature of the soil surface (determined during the counting process); λ is the thermal conductivity coefficient of the soil, which, depending on its state, takes the values of λ_u or λ_f; α is the coefficient of heat exchange between the soil surface and air, which takes on the values of α_s (summer) or α_w (winter) in the corresponding seasonal intervals. Their determination has been carried out according to the method of work [*Gorelik, Pazderin, 2017*]. The calculated values of those coefficients turn out to be equal: $\alpha_s = 23.2$, $\alpha_w = 1.12$ W/(m^2·°C).

According to the data of [*Okunev, Dolgikh, 2017*], on the evaporator wall, the cooling unit can maintain the temperature within the range of –15 to –32 °C. For calculations, the maximum temperature value out of that range is taken. Accordingly, the boundary condition on the side of the evaporator tube during the active period of the unit operation is written in the form of a constant temperature $t_t(\tau) = -15$ °C. The start of operation of the unit and its interruption are associated with the dates of the spring and autumn transition of the average daily air temperature through 0 °C. In the calculation examples those dates are taken as May 01 and October 01.

The progress of air temperature ($t_a(\tau)$) throughout the year is taken as a piecewise constant function of mean-month temperatures. As in the work [*Gorelik, Khabitov, 2021*], data on air temperature have been taken from the Urengoy Meteorological Station (Table 1). Within the underfloor space, the soil body is considered as a two-layer vertically, where the upper layer corresponds to heat insulation and is characterized by thickness (h), thermal conductivity coefficient (λ_i), and zero contribution of the phase transition heat to the effective heat capacity.

The coordinate system is located in a horizontal plane which coincides with the soil body surface, its center coincides with the geometric center of the building in the plan. The Oz axis is directed vertically downward, the Ox and Oy axes lie in the horizontal

Table 1. **Annual variation of air temperature at the Urengoy Meteorological Station**

Month	Mean air temperature,°C	Month	Mean air temperature,°C
January	–26.4	July	15.4
February	–26.4	August	11.3
March	–19.2	September	5.2
April	–10.3	October	–6.3
May	–2.6	November	–18.2
June	8.4	December	–24.0

plane and are directed, respectively, along the long and short axes of the building. The dimensions of the computational domain along each of the axes are determined by the radius of thermal influence [*Gorelik, Pazderin, 2017*] and when calculating for no more than a 5-year period, that radius does not exceed 35 m. Thus, the boundaries of the computational domain should be removed by 35 meters from the boundaries of the underfloor-space contour in plan and at the same distance into the depth of the soil vertically. At those boundaries, the heat flux is set to zero.

The problem is solved numerically. A finite-difference scheme is used, in which the domain of the required function is covered by the computational grid [*Aziz, Settary, 2004*]. To obtain discrete analogs of the equations, the model uses the control volume method [*Patankar, 2003*]. In [*Gorelik et al., 2008*], a finite-difference analogue of the equation (1) is presented.

The calculation procedure used here has been repeatedly tested on various problems and described earlier [*Gorelik et al., 2014, 2019; Gorelik, Khabitov, 2019a,b*].

CALCULATION RESULTS AND THEIR DISCUSSION

As demonstrated in [*Gorelik, Khabitov, 2021*], when using surface methods, there is an optimal sequence of installation and switching-on of the cooling system elements. In the case under consideration, such a sequence includes the following stages: a) *the initial stage* starts from the beginning of the first winter period and finishes with its end, no elements of the cooling system are installed, the seasonally thawed layer completely freezes due to the atmospheric natural cold; b) *the stage of installation of the cooling system elements* begins at the end of the first winter season: the evaporator of the system is laid, a leveling layer of sand is added, and the entire surface is covered with heat insulation, the cooling unit is connected, the work is completed by the beginning of the summer season; c) *the stage of forced cooling* is counted from the beginning of the summer season: the cooling unit is turned on, which operates continuously until the start of the new winter season, after which it is turned off. Further, the process is periodically repeated with a fully connected cooling system for the entire service life of the structure, while in the summer there is cooling by means of a forced cooling unit, and in winter, a certain amount of cooling is added from the atmospheric air due to the imperfection of the applied heat insulation (although the characteristics of its material taken in the calculations are quite high). An important feature of the described method is the absence of a layer of seasonal thawing at any time of the annual cycle, which eliminates the need for a very power-intensive process of its freezing, and the effect of the cooling impulse continues throughout the year.

Figure 2 presents the results of calculating the temperature fields at the basement of the building at $L = 1$ m in the central section ($x = 0$) for the 1st and 2nd year of the building's operation; the calculation results for the edge of the building ($x = 12$ m) are presented in Fig. 3. Similar results for $L = 0.7$ m are presented in Fig. 4, 5. The lines in the field of Figures 2–5 demonstrate the position of the isotherms in the considered section of the basement, the numbers along the line indicate the corresponding temperature of the isotherms. The color scale at the bottom demonstrates the correspondence of a certain color in the picture field to the calculated temperature value.

Figure 6 presents the three-year dynamics of temperature change in the central section and along the edge of the building at a depth of 0.2 m and at a depth of zero annual amplitude ($z_0 = 10$ m).

Comparison of the temperature fields shown in those figures demonstrates a high rate of decrease in soil temperature at the base both in its central section and along the edge of the building: in all options of the calculation, the temperature at a depth of zero annual amplitude in the second year of operation reaches a value corresponding to the solid-frozen state of most soils. An even more significant decrease is reached in the third year of operation (Fig. 6, *b*, *d*). Such rates of temperature decrease correspond to similar results for the most effective options of surface cooling with the combined use of the GET system and a forced cooling unit, which are considered in [*Gorelik, Khabitov, 2021*]. The rate of temperature decrease is several times higher than the typical values of 3–5 years for the known methods [*Vyalov et al., 1979; Khrustalev, Nikiforov, 1990*]. The calculation results are rather weakly dependent on the distance between the evaporator tubes (L) within the considered range of its value (from 0.7 to 1.0 m).

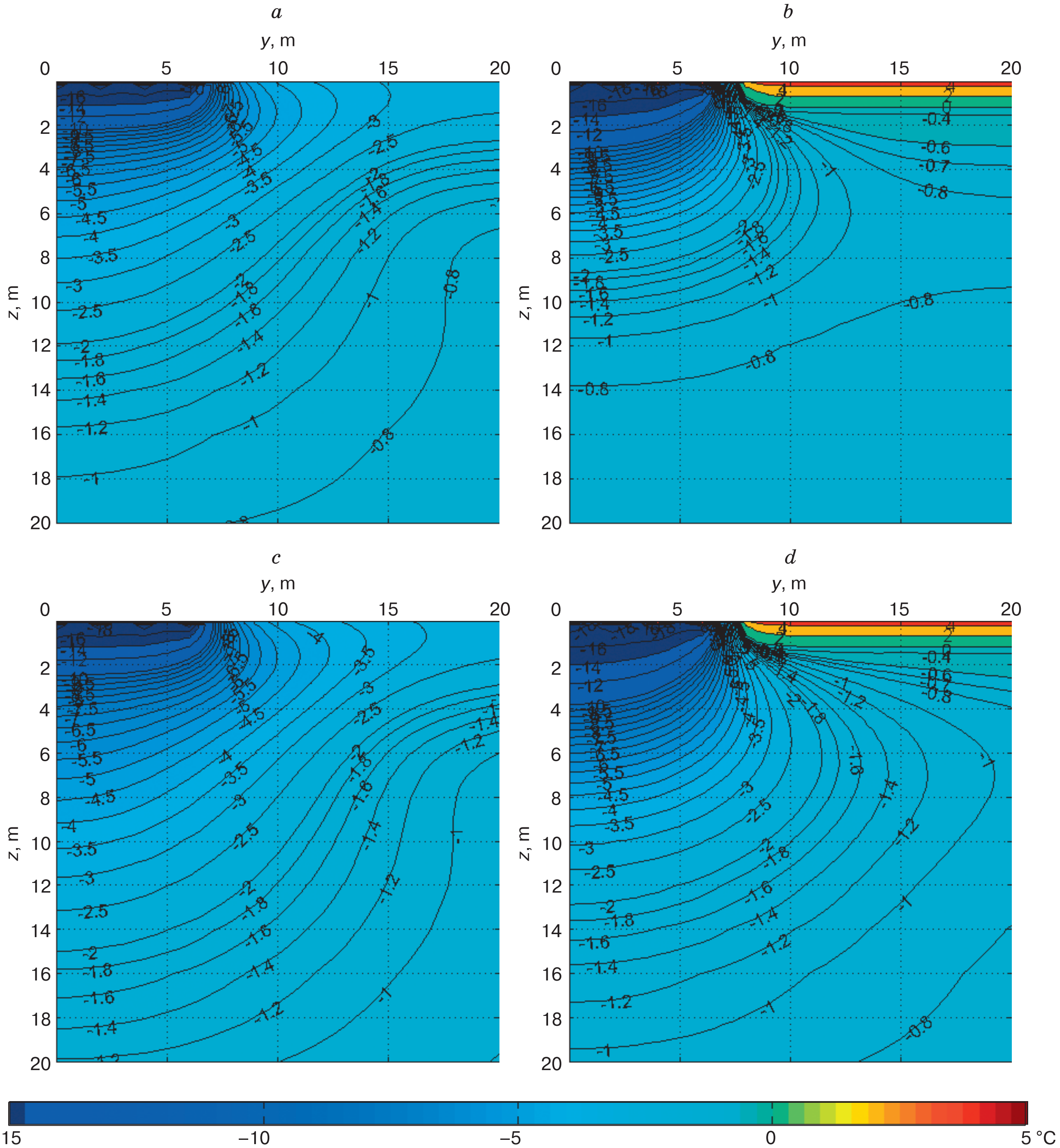

Fig. 2. Temperature fields at the base of the building in the central section (x = 0) with the distance between the evaporator pipes (L) equal to 1 m.

a, b – the 1st year of operation; c, d – the 2nd year of operation; a, c – end of winter; b, d – end of summer.

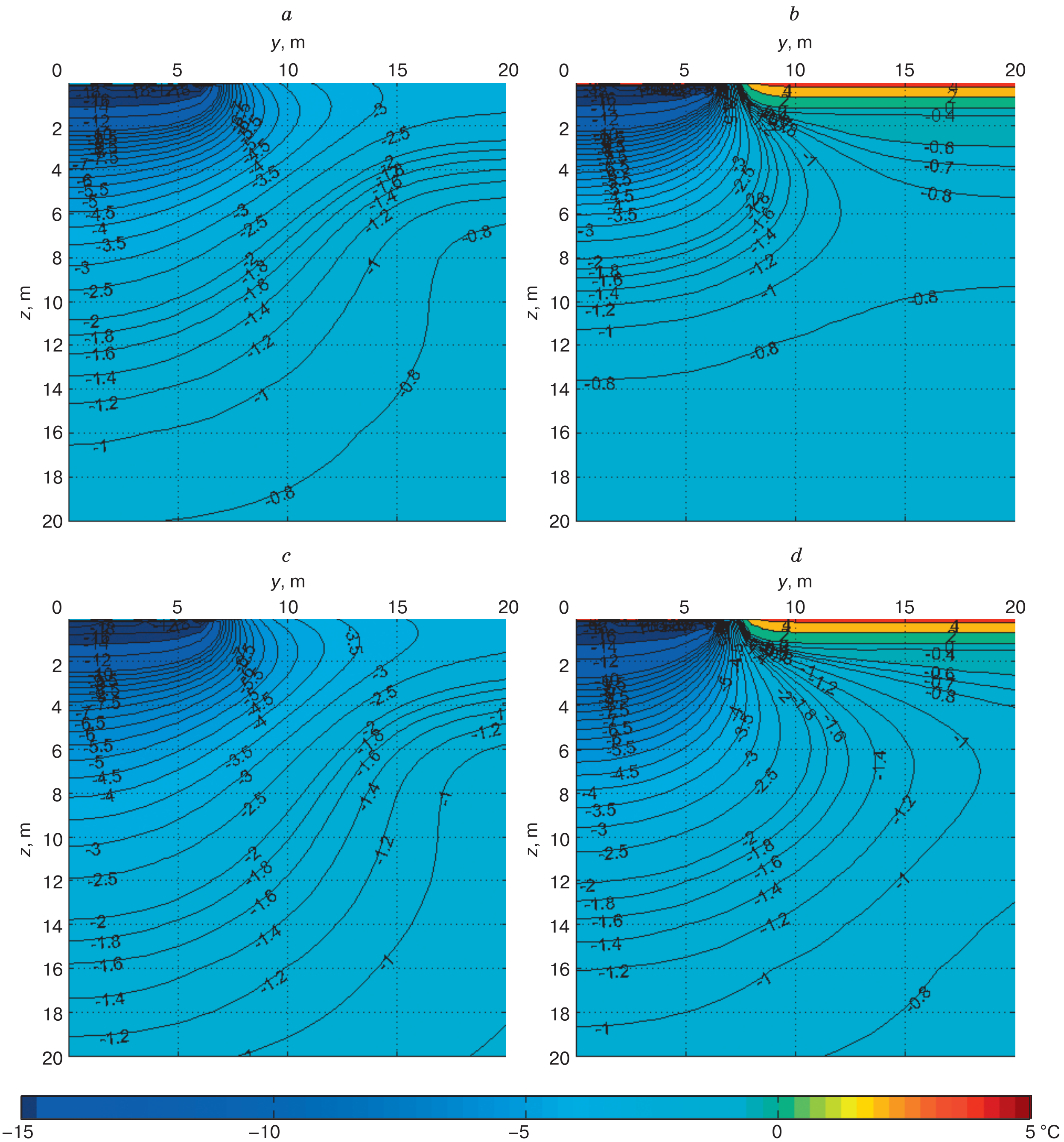

Fig. 3. Temperature fields at the base for the edge of the building (x = 12 m) with the distance between the evaporator pipes (L) equal to1 m.

a, b – the 1st year of operation; c, d – the 2nd year of operation; a, c – end of winter; b, d – end of summer.

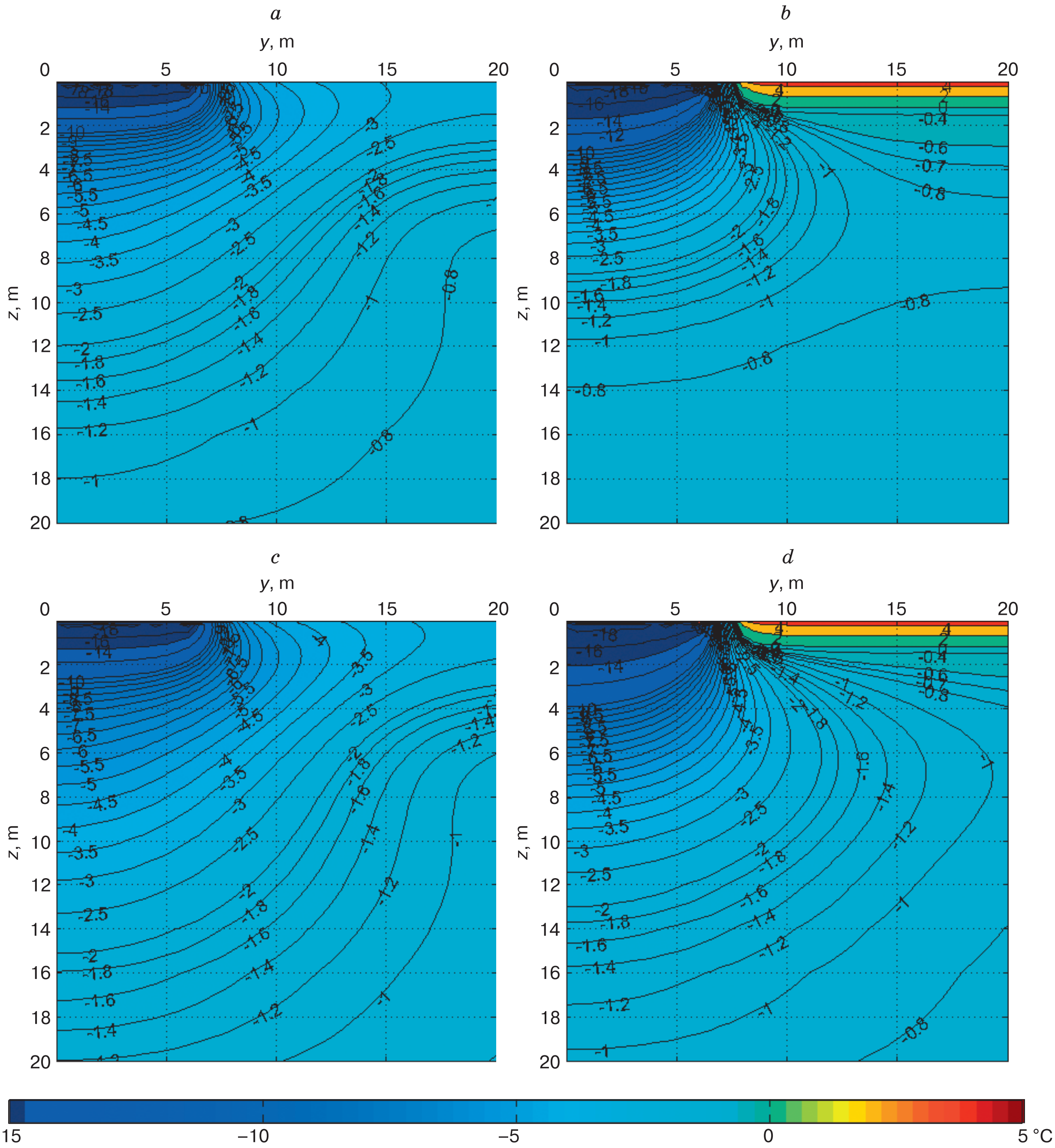

Fig. 4. Temperature fields at the base of the building in the central section (x = 0) with the distance between the evaporator pipes (L) equal to 0.7 m.

a, b – the 1st year of operation; c, d – the 2nd year of operation; a, c – end of winter; b, d – end of summer.

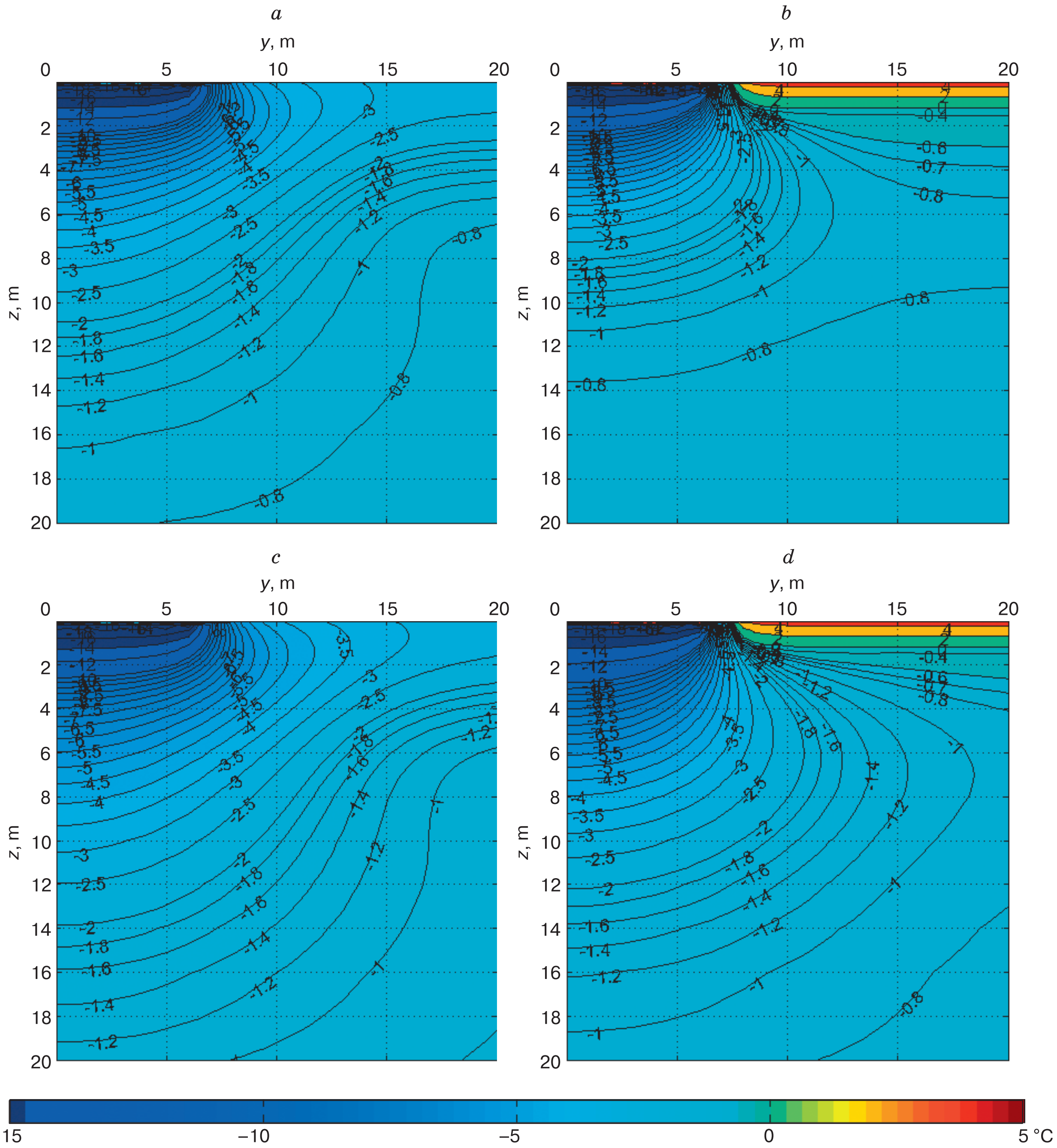

Fig. 5. Temperature fields at the base for the edge of the building (x = 12 m) with the distance between the evaporator pipes (L) equal to 0.7 m.

a, b – the 1st year of operation; c, d – the 2nd year of operation; a, c – end of winter; b, d – end of summer.

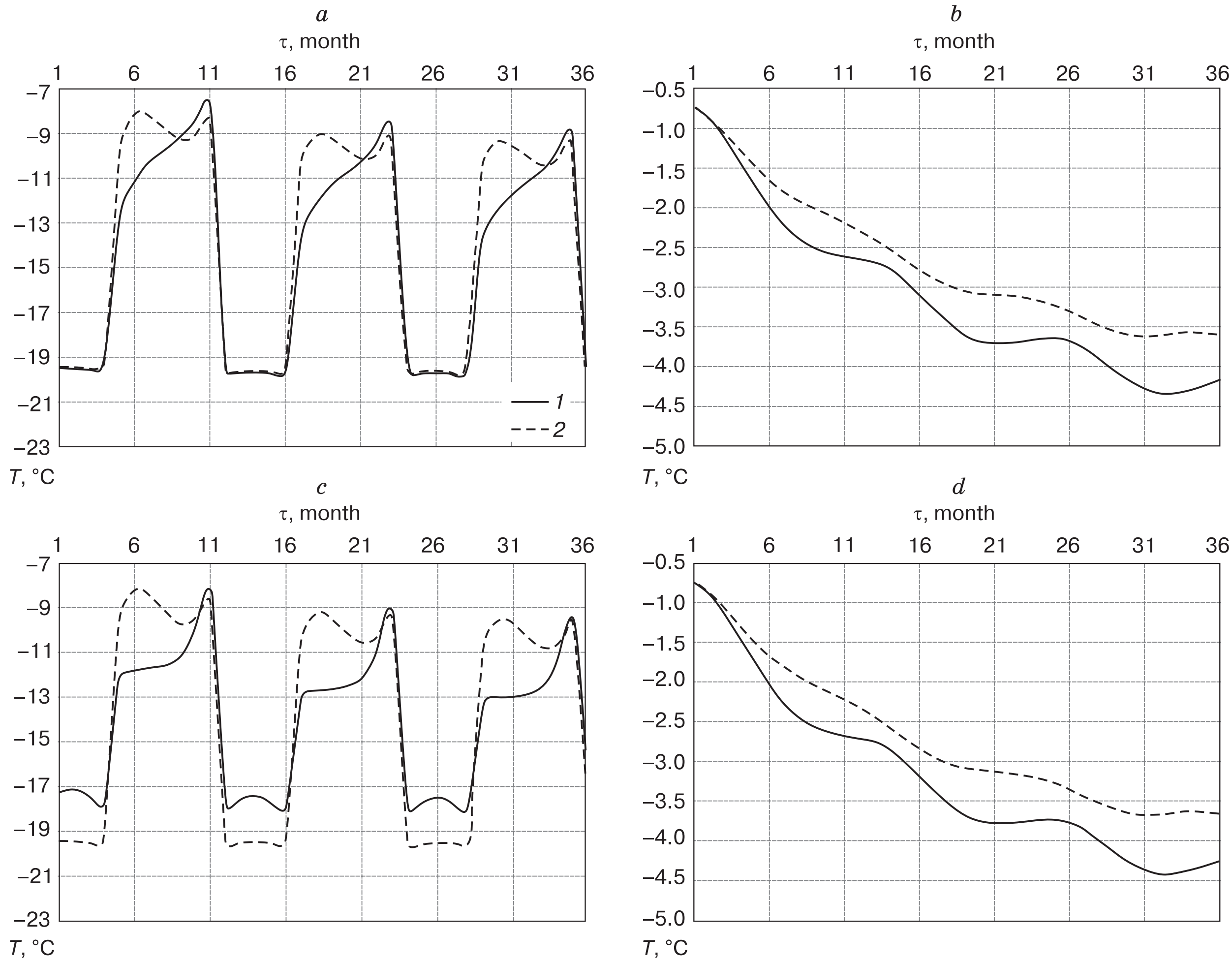

Fig. 6. Temperature dynamics at the base of the building at a depth of z = 0.2 m (a, c) and at a depth of zero amplitudes z_0 = 10 m (b, d) for the central section (1) and for the edge of the building (2) within 3 years of operation.

a, b – L = 1 m; c, d – L = 0.7 m; 1 – x = 0; 2 – x = 12 m.

CONCLUSION

A method of surface cooling is proposed. It includes the placement of heat insulation on the soil surface and cooling pipes laid under it, connected to a forced circulation unit of the refrigerant with the latter turned on only in the summer period of the year during the entire service life of the structure. The method has important advantages: a) at any time there is no possibility of the formation of a seasonal thawing layer, which eliminates the need to freeze it, as a result of which the cooling impulse enters the basement of the structure throughout the entire calendar year; b) in the conditions of urban development, where the placement of very large condensing units of the natural convective system GET will inevitably entail the emergence of certain problems, the use of a machine cooling method is quite industrial, which does not require significant space for its implementation.

The results of mathematical modeling of the process of temperature field formation in a frozen soil with a surface cooling method using the considered technical means, presented in the article, allow us to draw the following conclusions:

1. Comparison of the temperature fields presented in Figures 2–5 demonstrates a high rate of decrease in soil temperature at the basement both in its central section and along the edge of the building. In all calculation options, the temperature at a depth of zero annual amplitude in the second year of operation reaches a value corresponding to the solid-frozen state of most soils. An even more significant decrease is reched in the third year of operation (Fig. 6, *b*, *d*).

2. High rates of temperature decrease correspond to similar results for the most effective options for

surface cooling with the combined use of the GET system and a forced cooling unit, which are considered in [*Gorelik, Khabitov, 2021*]. The calculation results are rather weakly dependent on the distance between the evaporator tubes *L* within the considered range of variation of its value (from 0.7 to 1.0 m).

3. The rate of temperature decrease is multiple times higher than the values of 3–5 years, typical of the known methods [*Vyalov et al., 1979; Khrustalev, Nikiforov, 1990*].

The results obtained in this work may turn out to be very important for the development of technologies for the restoration of buildings and structures which have undergone deformations during operation due to a violation of the temperature regime of frozen soils of their foundations.

Acknowledgements. *The work has been carried out within the framework of the theme of the state assignment Reg. R&D No. AAAA-A17-117051850061-9.*

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Received October 20, 2020
Revised version received February 28, 2021
Accepted March 14, 2021