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AFFECTIVITY OF SURFACE COOLING OF FROZEN GROUND IN CONNECTION WITH MECHANISM OF TEMPERATURE SHIFT FORMATION

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The analysis of affectivity of frozen soils surface cooling methods based on the theoretical understanding of temperature shift formation with seasonal processes in the upper ground layers is provided. The surface cooling method for the building with aerated underfloor space is suggested on the base of this analysis. This method includes heat-insulation layer ground surface and free convection cooling system with its horizontal evaporator under insulation layer. Condenser of the cooling system is out of the building contour and it makes evaporator temperature near to winter air temperature. The results of mathematical modelling demonstrate that suggested method provides a significant and rapid decrease of the ground temperature as compared to other methods (up to 1.0–2.5 °C for not more than 1.5 year instead of 3–5 years). An additional temperature decrease by 1.5 °C may be obtained by connecting of the forced cooling device to the cooling system for one summer season. The calculation results allow us to propose the best sequence for connecting the cooling elements of the system at the initial stage of its operation.

Key words: *frozen soils, seasonal thawing layer, ground temperature regime, heat-insulation layer, GET cooling system, forced cooling, relaxation time to project temperature regime.*

INTRODUCTION

The regulation of the temperature regime of structure's foundations, its stabilization and restoration are widely used in the construction and operation of structures, as well as during the repair work in the areas where permafrost soils are distributed. The technical implementation of those measures is associated, as a rule, with the use of various kinds of cooling devices. The constructions of most of them (for example, thermal stabilizers of the vertical and inclined seasonal action), to ensure operability, must be deepened with their parts into the soil base. Providing high work efficiency, that significantly increases the laboriousness of the activities, since it requires drilling operations, which often have to be performed manually on a previously prepared pile field [*Dolgikh, 2014*].

Alternative methods of surface cooling of the soil have also been using in practice for a long time. The most important of them is the method based on the use of an aired underfloor space, which is still the main one in ensuring the design temperature regime of the building foundations and areal structures erected according to the first principle, and maintaining it during operation. However, the possibilities of its application are often insufficient to achieve the required temperatures. For example, for the open underfloor spaces, there is a high probability of snow accumulation on the ground surface in winter, which entails a corresponding decrease in the cooling efficiency. For the underfloor spaces with a reduced ventilation module (with airholes in the cooling structures), the cooling efficiency decreases due to a decrease in the speed of the air flow, as well as its heating from plumbing communications and the heat release from the floor. In addition to a decrease in the amount of cooling, that also leads to an increase in the time required to reach the required temperature regime of the foundation [*Vyalov et al., 1979*].

To intensify the process of soil cooling from the surface, the so-called surface heat-semiconducting coatings have been proposed, the design of which provides asymmetric heat transfer through the soil surface throughout the year: increased heat removal from the base in winter and a significant decrease in heat supply to the base in summer [*Makarov, 1985; Bubelo, 2003*]. However, they did not give the expected effect, probably because the same negative factors continue to act on the upper surface of those devices as on the underfloor space.

At the same time, it is easy to see that none of the currently known methods of surface cooling excludes the processes of seasonal freezing-thawing and, therefore, the prospects for the development of those methods can be characterized by assessing the extreme values of the temperature shift [*Dostovalov, Kudryavtsev, 1967; Kudryavtsev, 1974*], arising from the application of that group of measures. As is known, the most important parameter that determines the magnitude and dynamics of changes in soil temperature regime under the influence of surface factors, as well as the magnitude of the temperature shift at a given mean-annual temperature of the soil surface, is the value of the mean-annual temperature at the bottom of the active layer. Difficulty of performing an analysis of the effectiveness of surface cooling methods is that until recently there were no simple and at the same time sufficiently general models of the mechanism for the formation of a temperature shift, allowing in simple analytical expressions to obtain estimates of the required calculated values depending on the main group of influencing factors. Such a model has been recently proposed in [*Gorelik, Zemerov, 2020*]. First of all, it is useful here to consider the simple estimates and conclusions derived from the results of that work regarding the effectiveness of surface cooling methods.

Basic relations for the dynamics of temperature in the simplest model of the frozen base

A frozen soil layer of finite thickness has been proposed as the simplest physical model of a frozen base [*Gorelik, Zemerov, 2020*]. That makes it possible, when analyzing seasonal processes, to use quasi-stationary relations for the temperature distribution not only from the side of the thawed zone (as was done earlier [*Balobaev, 1964; Porkhaev, 1970; Feldman, 1977; Shur, 1988*]), but also from the side of the frozen ground. That approach allows one to obtain a fairly simple expression for the mean-annual temperature at the bottom of the seasonal thawing layer t_m [*Gorelik, Zemerov, 2020*] in the following form (this value forms the soil temperature throughout the entire permafrost thickness below the active layer):

$$t_m = t_w \tau_w + t_s \tau_s \frac{\lambda_u}{\lambda_f}. \qquad (1)$$

Hereinafter, the following designations are introduced: t_s, t_w, t_y are mean-summer, mean-winter and mean-annual temperature (°C) of the soil surface under cover of any nature; τ_s, τ_w are the relative duration (u.f.) of the year periods with the positive and negative mean-daily air temperatures; λ_u, λ_f are coefficients of thermal conductivity (W/(m·°C)) of soil in the thawed and frozen states.

The above-mentioned surface temperatures, generally speaking, should be established by calculating the heat exchange between the soil surface and atmospheric air for the given characteristics of the soil cover. However, in some cases, they can be assessed by their extreme values. In the relation (1), the first term is negative, the second one is positive. The relation (1) demonstrates that the temperature shift $\Delta t = t_m - t_y$ depends both on the thermophysical characteristics of the soil and on the climatic parameters of a given area, and also establishes the nature of that dependence. Apparently, the earlier works do not focus on the role of climatic factors (although the influence of the difference in the values of the coefficients λ_u and λ_f is noted [*Dostovalov, Kudryavtsev, 1967; Kudryavtsev, 1974*]), since they remain practically constant for the large territories referenced to a specific meteorological station, while the properties of soils within its limits are subjected to more drastic changes. However, from the point of view of engineering geocryology, the dependence of the t_m value on the entire group of influencing factors is important, as well as the fact that each of the parameters included in the relation (1) can be changed within a specific construction site by technical means.

In the particular case, when $t_s = -t_w$, $\tau_s = \tau_w = 1/2$ (or $t_y = 0$), the expression (1) turns into the following:

$$t_m = -\frac{t_e}{2}\left(1 - \frac{\lambda_u}{\lambda_f}\right),$$

which gives the noted dependence on the ratio of the soil thermal conductivity coefficients.

In accordance with the previously proposed methodology [*Gorelik, Pazderin, 2017*], the direction of change in the temperature of the permafrost (below the bottom of the active layer up to the depth of zero annual amplitudes) is set in relation to the initial state, which is determined empirically at the stage of engineering surveys by two parameters: the depth of the active layer (ξ_m) and the temperature at the depth of zero annual amplitudes (t_0).

To derive the relationship that determines the time of the formation of a new temperature regime, it is assumed that with the beginning of the 'switching on' of the technical method of surface cooling, the conditions of heat exchange between the outside air and the soil surface change rather quickly (abruptly). Taking that into account, the time τ_f of the formation of a new temperature regime (characterized by the temperature t_f at the depth of zero annual amplitudes z_0 under the influence of the changed surface factor is determined by the relations [*Gorelik, Zemerov, 2020*]:

$$\tau_f = \frac{z_0^2}{12\mu_f\left(1 - \sqrt{1-n}\right)^2}, \quad n = \left|\delta t_{mf} / \Delta t_{0m}\right|,$$

$$\Delta t_{0m} = t_0 - t_m, \quad \delta t_{mf} = t_f - t_m. \qquad (2)$$

Here: μ_f is thermal diffusivity of frozen soil; t_m is defined by the relation (1). It is important that at a depth of zero annual amplitudes, the temperature t_m is reached in the asymptotic limit of an infinite time interval, while at the bottom of the active layer it is being established already in the first year after the changing conditions on the surface of the soil [*Feldman, 1977; Gorelik, Zemerov, 2020*]. The δt_{mf} value is the deviation of the current temperature value of t_f (corresponding to the time instant of τ_f) from the asymptotic value t_m. If, using the first of the relations (2), we express the temperature t_f in terms of the time τ_f, then we can also estimate the dynamics of the temperature change at the depth of z_0 during the service life of the structure.

The n parameter demonstrates the degree to which the temperature approaches a new equilibrium state. For $n = 0$, that state exactly corresponds to the temperature of t_m, but the time to reach it is equal to infinity. At $n = 1$, the temperature at the depth of z_0 only begins to change and the time to reach that moment coincides with the time when the radius of the thermal influence reaches the depth of z_0. Taking the standard value of $z_0 = 10$ m, we obtain the dependence of the τ_f time on the n parameter, which is shown by the graph in Fig. 1. In particular, for $n = 0.3$ we get $\tau_f = 10.4$ years, and for $n = 0.5$ we get $\tau_f = 3.2$ years. The characteristic value can be taken as $n = 0.4–0.5$, which demonstrates that the proximity of the intermediate temperature state (determined by the parameter of δt_{mf}) to a new stable one corresponds to approximately half the maximum length of the full range of temperature changes (from t_0 to t_m). That is, $\delta t_{mf} \approx (0.4–0.5)\ \Delta t_{0m}$ and the corresponding change occurs within 3–5 years. That corresponds to the rate of commonly observed processes [*Vyalov et al., 1979; Khrustalev, Nikiforov, 1990*]. The important thing here is the dependence of the τ_f time on the design (required) temperature of t_f and its limiting values of t_0 and t_m. It is easy to see that a decrease in the value of t_m, with the other two fixed, brings the value of n closer to one, while the value of τ_f decreases rapidly.

Evaluation of the effectiveness of the proposed method of cooling the foundation

It is easy to make certain that for fixed values of τ_s, τ_w, the minimum temperature of t_m, according to the relation (1), can be achieved when two conditions are met: a) minimization of the mean-summer temperature t_s (within the limits of up to 0 °C); b) reaching a minimum value of the mean-winter temperature t_w (within the limits of up to equal in magnitude to the air temperature). In that case, it is important to ensure the conditions under which the value of t_w does not depend on side factors (for example, snow-carrying of the surface, negative heat release in the underground, etc.). The first of those conditions can be ensured by the use of a layer of high-quality thermal insulation, which minimizes the heat flux to the surface in the warm season. In the construction of the heat-insulating layer, standard heat-insulating panels of light enclosing structures can be used, which have an external metal casing that protects against mechanical stress and performs the functions of waterproofing. The second condition can be achieved by using the GET cooling system [*Dolgikh et al., 2011*], the evaporative element of which is placed under the thermal insulation layer over the entire soil surface inside the structure contour (Fig. 2). The principle of operation, design and application possibilities of the GET system is summarized in the article [*Gorelik, 2015*]. The optimum pipe laying density must be determined by calculation. The evaporator temperature of the GET system is determined only by the outside air temperature (according to the test data of existing

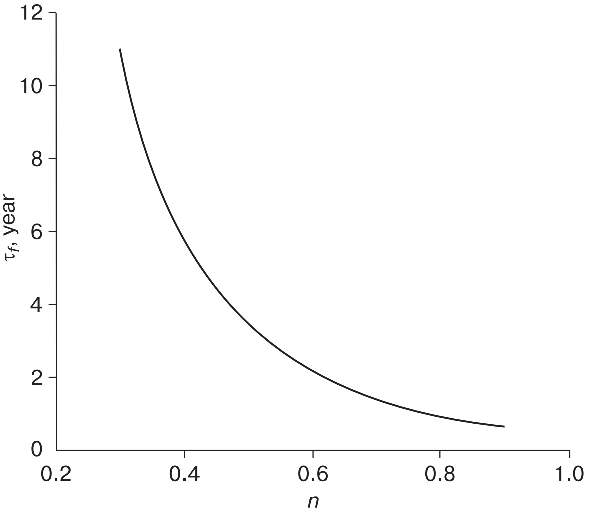

Fig. 1. The dependence of the time of approach τ_f to the new temperature state on the approximation parameter n.

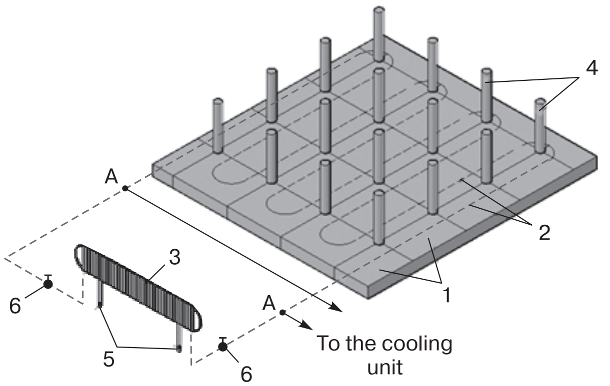

Fig. 2. The layout of the elements of the GET system near the underfloor space (above-foundation structures are not shown):

1 – thermal insulation plates; 2 – evaporator pipe (cooling element); 3 – condenser of the GET system; 4 – foundation piles; 5 – support legs of the condenser; 6 – valves for cutting off the condenser from the evaporator. The letter A indicates the connection points of the refrigeration unit to the evaporator.

structures, that temperature is approximately by 5–6 degrees higher than the air temperature and is practically constant along the length of the evaporator [*Dolgikh, Okunev, 1989; Feklistov et al., 2008*]). The independence of the evaporator temperature on the conditions inside the underfloor space is ensured by the fact that the condenser of the device is taken out of the contour of the structure. Shown in Fig. 2, the design of the cooling method should be especially convenient when restoring the temperature regime of the foundation that was disturbed during the operation of the structure. The use of vertical thermal stabilizers in that case encounters additional difficulties in their installation, associated with the limitation of the height of the underfloor space. To install such devices, special designs with a flexible evaporator are used [*Abrosimov et al., 2018*], which, however, does not eliminate the main disadvantages of the method. It should be noted that, in conventional applications, the cooling element of the GET system is also deepened in the basement soils [*Dolgikh et al., 2011*].

Here are some estimates for the case of restoration of the temperature regime of the basement disturbed during the operation. Let the current temperature at the structure's basement at a depth of zero annual amplitudes have reached a value of t_0, which has exceeded the design value of t_f. As an example, let us take the duration of the winter period of 8 months, $\tau_w = 8/12 = 2/3$. Assuming that the thermal insulation is ideal, we will neglect the second term in the formula (1). Taking $t_w = -15$ °C, according to the formula (1) we obtain $t_m \approx t_w\tau_w = -15(2/3) = -10$ °C. Let $t_0 = -0.7$ °C, $t_f = -2.0$ °C, then $\Delta t_{0m} = 9.3$ °C, $\delta t_{mf} = 8.0$ °C, $n = 0.86$. According to the graph (Fig. 1) we find that the required temperature regime is reached after about one year of cooling. In another example, let us take $t_0 = -2$ °C, $t_f = -3.0$ °C, $\tau_w = 2/3$, then $\Delta t_{0m} = 8.0$ °C, $\delta t_{mf} = 7.0$ °C, $n = 0.88$. Accordingly, we find that in that case the required temperature regime is also reached after about one year of cooling. The specified time is counted from the beginning of the first summer season, by the time of the onset of which a layer of thermal insulation and cooling elements of the GET system must be laid on the soil surface (as described below when characterizing the design option Ib in the section 'Calculation results and their discussion'). It is important that the speed of reaching the design temperature is determined by the low mean-annual soil temperature at the bottom of the active layer, as well as by a significant increase in the duration of the cooling impulse [*Gorelik, Zemerov, 2020*].

An even greater efficiency of the described method can be achieved if, in the summer period of the first year of its application, a forced cooling unit is connected to the evaporator pipes. In that case, the duration of the summer period turns to zero, and the duration of the winter period coincides with the duration of the year ($\tau_s = 0$, $\tau_w = 1$), while the value of t_w decreases accordingly. The temperature t_m will also decrease, and the time of τ_f will decrease even more (at the same values of t_f and t_0). After the first summer season, the forced cooling unit can be dismantled without any damage, and there is no need for its further use at that facility.

However, it should be remembered that the above methods for estimating the temperature of t_m, as well as the time interval of τ_f, although convenient, are approximate and only the main trends in the dependences can be understood with their help. It is difficult to predict quantitative differences from the exact values, since the estimates do not take into account many important details of specific design solutions for the cooling method. Strict calculation procedures must be followed to obtain reliable results. In addition to increasing the accuracy due to the procedure itself, those methods allow taking into account the dynamics of the air temperature, the real properties of the applied thermal insulation, the density of the evaporator pipes, the heterogeneity of soil properties, changes in the temperature field in space and other factors. In the next section, the results of calculating the dynamics of the recovery of the temperature-regime restoring in the basement of the building with the underfloor space are presented using the strict numerical methods for the two examples considered above.

Calculation procedure for soil cooling using the GET system

Calculations of the dynamics of temperature restoring in the basement soils with a surface cooling method using the GET system have been performed for a building with an underfloor space with dimensions in the plan of 12 × 24 m. The design and location of the cooling system elements within the pile field are demonstrated in Fig. 2. The evaporator pipes of the GET 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 underfloor space. The condenser of the GET system is located on a special site outside the building contour on support racks. If it is necessary to connect the unit for forced circulation of the refrigerant, the condenser is cut off from the evaporator using special valves.

The horizontal distance between the axes of adjacent evaporator's tubes (L) is taken in two versions, 1 m and 0.7 m, the diameter of the tubes (D) is 37 mm. Thermal insulation thickness of a standard panel (h) is 100 mm, material thermal conductivity coefficient (λ_i) is 0.03 W/(m·°C).

Table 1. **Annual variation of average monthly air temperature according to the Urengoy Meteorological Station**

Month	Average air temperature, °C	Month	Average 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

The main trends in the behavior of temperature fields can be established for a soil homogeneous in terms of thermophysical characteristics. 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. Below, for all calculation options, the following soil characteristics are adopted (for the thawed and frozen soil, the u and f indexes are adopted correspondingly): thermal conductivity coefficients $\lambda_u = 1.75$ and $\lambda_f = 1.80$ W/(m·°C); volumetric heat capacity $C_u = 2.68\cdot10^6$ and $C_f = 2.20\cdot10^6$ J/(m^3·°C); dry density $\gamma_s = 1500$ kg/m^3; moisture content $w = 0.2$. The transition of a unit volume of frozen soil to a thawed state is characterized by the value of latent volumetric heat $\kappa_v = \kappa\gamma_s w$, where $\kappa = 3.34\cdot10^5$ J/kg ($\kappa_v = 10^8$ J/m^3). Soil moisture due to unfrozen water $w_u = 0$. Freezing point of soil $t_b = 0$ °C. The course of air temperature throughout the year is taken as a fragmentary-constant function of mean-monthly temperatures. Air temperature data were taken from the Urengoy Meteorological Station (Table 1).

The initial temperature of the soil at the basement in the disturbed state of the design thermal regime was taken, as above, in two versions: $t_0 = -0.7$ °C and $t_0 = -2.0$ °C. In accordance with the methodology of [*Gorelik, Pazderin, 2017*], the calculated values of the summer (α_s) and winter (α_w) coefficients of heat transfer between air and the underlying surface for the variant with $t_0 = -0.7$ °C are $\alpha_s = 23.2$, $\alpha_w = 1.12$ W/(m^2·°C); and for the variant with $t_0 = -2.0$ °C are $\alpha_s = 23.2$, $\alpha_w = 1.39$ W /(m^2·°C). As above, the corresponding design temperatures for those two options are taken as $t_f = -2.0$ and -3.0 °C.

The boundary condition on the wall of the evaporator tube during the active period of operation of the device was selected on the basis of experimental data on the testing device [*Dolgikh, Okunev, 1989; Feklistov et al., 2008*] in the form of setting its temperature $t_t(\tau)$ by a condition of the first kind:

$$t_t(\tau) = t_a(\tau) + 6\,,$$

where $t_a(\tau)$ is the air temperature (°C), given as a function of time (τ) according to Table 1. The interruption of the device operation during the passive period is determined by the disturbance of the condition of heat sink (q_t) from the ground to the evaporator wall: $q_t < 0$.

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

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

Here: z is vertical coordinate; t_s is the temperature of the soil surface (determined during the calculating process); λ is the coefficient of thermal conductivity of the soil, which, depending on its state, takes the values of λ_u or λ_f; α is the coefficient of heat exchange of the surface of the soil covering with air, takes the values of α_s, or α_w in the corresponding seasonal periods of time. Within the underfloor space, the soil massif is considered as two-layered vertically, where the top layer corresponds to thermal insulation with the above-mentioned characteristics.

The coordinate system is located in a horizontal plane that coincides with the soil surface, its center coincides with the geometric center of the building in the plan. The Oz axis is directed vertically downwards, the Ox and Oy axes lie in the horizontal 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 the 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 massif vertically. At those boundaries, the heat flux is set to zero.

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

Calculation results and their discussion

When carrying out the calculations, two technological cooling schemes have been considered: a) using only the seasonally operating GET system; b) with additional connection to the evaporator pipes of the forced cooling unit during one summer season. It should be borne in mind that the connection of various elements of the cooling system can be carried out at different points in time in the annual cycle, which can affect the cooling efficiency. The purpose of the calculations was, among other things, to determine the optimal time for connecting the cooling systems. Here is a brief description of the options for the technological schemes considered below and their designations.

Option Ia: the GET system together with thermal insulation is installed at the end of the summer season; the seasonally thawed layer is formed under the influence of natural factors (its thickness is close to the average long-term value); the GET system turns on with the onset of the winter season and automatically turns off at the end of winter; the second and all subsequent cycles of thawing of the seasonally thawed layer occur under the influence of thermal insulation. That process is cyclically repeated from the second year to all subsequent ones.

Option Ib: the GET system together with thermal insulation is installed at the end of the winter season; the seasonally thawed layer is formed under the influence of natural factors and thermal insulation (its thickness is close to the minimum value); the GET system turns on with the onset of the winter season and automatically turns off at the end of winter; the first and all subsequent cycles of thawing of the seasonally thawed layer occur under the influence of thermal insulation. That process is cyclically repeated from the first year to all subsequent ones.

Option IIa: installation and start of operation of the GET system before the end of the first winter period is similar to the option Ia; at the beginning of summer, a forced cooling unit is connected to the evaporator pipe, which operates during the summer; at the end of summer, forced cooling is turned off and dismantled (no longer used); further in the winter season, the GET system works together with thermal insulation; the second and all subsequent cycles occur under the influence of thermal insulation and winter switching-on of the GET system.

Option IIb: the GET system is mounted similarly to the option Ib; at the beginning of the summer season, a forced cooling unit is connected, which operates during the summer; at the end of summer, forced cooling is turned off and dismantled (no longer used); then only the GET system works together with thermal insulation.

Option IIc: the GET system is mounted similarly to the option Ib; the forced cooling unit is connected at the beginning of the second summer season, which operates during the summer; at the end of the second summer, forced cooling is turned off and dismantled (no longer used); then only the GET system works together with thermal insulation.

The first two options correspond to the scheme without using a forced cooling method, the next three include that method. Each of the presented options is characterized by an additional set of parameters: an initial soil temperature (t_0); the distance between the parallel sections of the evaporator pipes (L); the coordinate (x) of the cross-section of the basement, in which the results of the calculation are considered; the time interval (τ) from the start of the cooling system, which corresponds to the presented calculation results. The calculation results for the options Ia and IIa are displayed at the end of the first, second, etc. annual cycles. The calculation results for the items Ib, IIb and IIc are displayed at the end of the second, third, etc. summer seasons (with a summer season duration of 5 months – after about 1.4; 2.4, etc. years from the moment of installation of the cooling system). The output of the results corresponds to the maximum ground temperature (at the end of the summer season). The calculation results are presented in Figures 3–8. The lines in the figure field represent 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 shows the correspondence of a certain color in the picture field to the calculated temperature value.

Figures 3 and 4 demonstrate the results of calculating the soil temperature when using cooling systems in the options Ia and Ib for two values of its initial temperature (–0.7 and –2.0 °C). As can be seen from a comparison of soil temperatures, from the surface to the depth of zero annual amplitudes (10 m), the cooling efficiency in the second of those options is significantly higher than in the first one. Based on the values of the design temperature t_f (–2.0 and –3.0 °C) for the corresponding initial soil temperatures given in the examples of the 'Evaluation of efficiency ...' section, it can be argued that for the option Ib, the design values are achieved for the central section (Figures 3, *b* and 4, *b*), and they are achieved with a slight disadvantage for the edge section (Figures 3, *d* and 4, *d*) after completion of one cycle of operation of the cooling system (1.4 years) with a standard distance between the evaporator tubes (L = 1 m).

The corresponding temperature distribution in the option Ia demonstrates that both in the central and in the edge sections the temperature remains significantly higher than the design value (Figures 3, *a*; 4, *a*; 3, *c*; 4, *c*) even for a denser pipe laying (L = 0.7 m) and with a longer (two-year) cycle of the cooling system. That difference has a simple explanation, which is that the first activation of the GET system in the option Ia is spent on a very energy-intensive process of freezing the layer of seasonal thawing, which in that option has a maximum value. As a result, the duration of the cooling impulse, which determines the process of cooling the basement [*Dostovalov, Kudryavtsev, 1967; Feldman, 1977; Gorelik, Zemerov, 2020*], is significantly reduced. The option Ib is free from that drawback, since the layer of seasonal thawing is formed under the influence of thermal insulation and has a minimum value.

The results of short-term use of a forced cooling system in combination with thermal insulation and the GET system are shown in Fig. 5–8. The presented results demonstrate that the use of technological op-

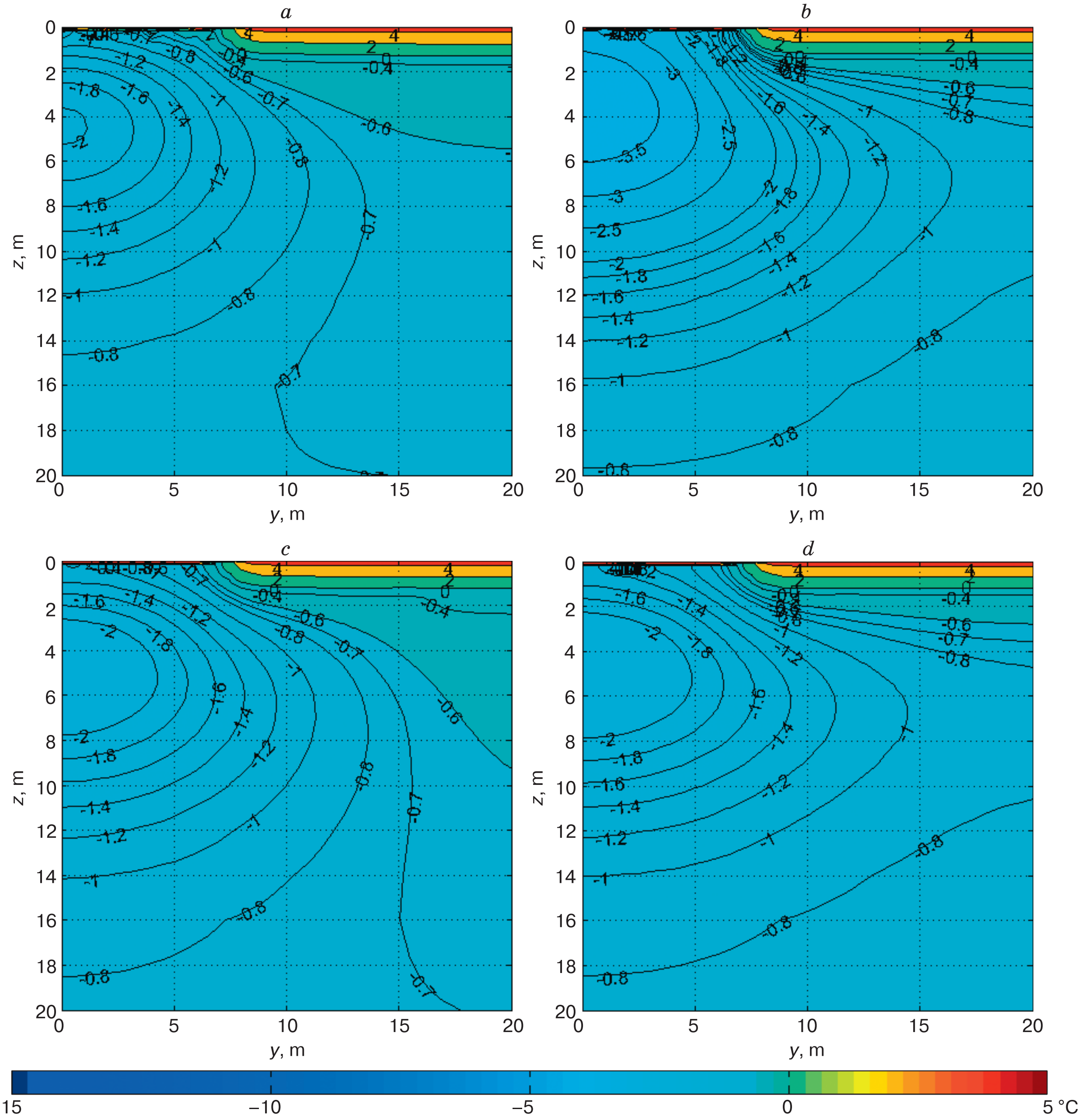

Fig. 3. The results of soil temperature calculations during the cooling only with the use of the GET system at $t_0 = -0.7$ °C:

a – option Ia ($L = 0.7$ m, $x = 0$ m, 1 year); *b* – option Ib ($L = 1.0$ m, $x = 0$ m, 1.4 year); *c* – option Ia ($L = 0.7$ m, $x = 12$ m, 2 years); *d* – option Ib ($L = 1.0$ m, $x = 12$ m, 1.4 year).

tions IIb and IIc in all cases ensures the achievement of the design temperature for both the central and the edge sections in the basement after completion one cycle of the cooling system (1.4 years) with a standard distance between the evaporator tubes ($L = 1$ m). Moreover, in the option IIb, that temperature is reached with a noticeable margin of 0.5–1.0 °C (Fig. 5, *c*, *d*; 6, *c*, *d*; 7, *c*, *d*; 8, *c*, *d*). Fragments of the same figures (Fig. 5, *a*, *b*; 6, *a*, *b*; 7, *a*, *b*; 8, *a*, *b*) demonstrate that the scheme IIa does not ensure the attainment of design temperature within the minimum period of its operation. The reason for the lack of effectiveness of the option IIa is similar to that stated when comparing the options Ia and Ib. The highest efficiency of the cooling system in the option IIb is due to the fact that the duration of the continuously

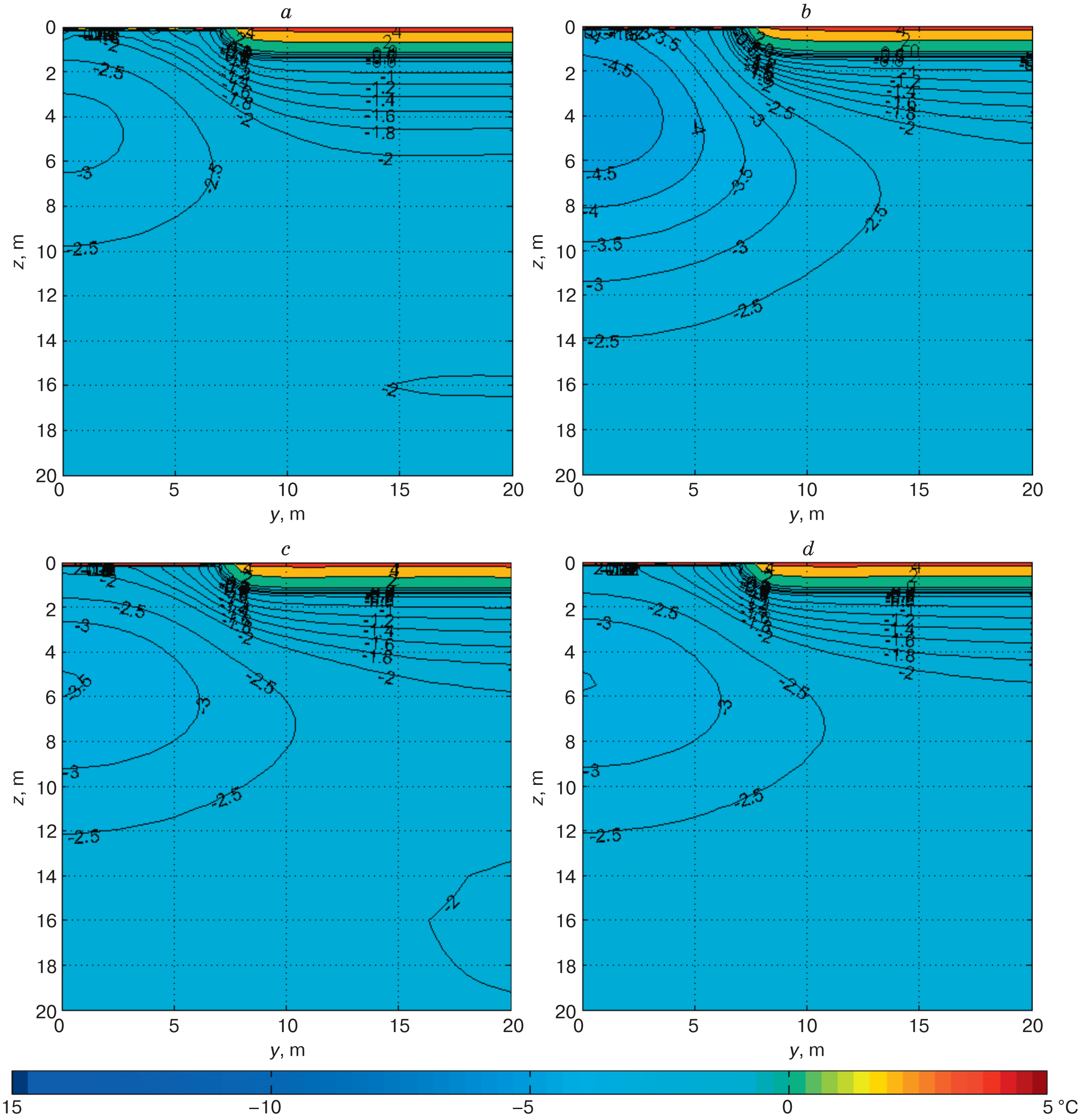

Fig. 4. The results of soil temperature calculations during the cooling only with the use of the GET system at $t_0 = -2.0$ °C:

a – option Ia ($L = 0.7$ m, $x = 0$ m, 1 year); *b* – option Ib ($L = 1.0$ m, $x = 0$ m, 1.4 year); *c* – option Ia ($L = 0.7$ m, $x = 12$ m, 2 years); *d* – option Ib ($L = 1.0$ m, $x = 12$ m, 1.4 year).

operating cooling impulse in that case turns out to be as high as possible. The time of τ_f is determined by the sum:

$$\tau_f = \tau_{w1} + \tau_s + \tau_{w2}, \qquad (3)$$

where τ_{w1} is the duration of the impulse in the winter period preceding the moment of assembly of the GET system (natural cooling factors are at work); τ_s is the duration of the summer period (during which forced cooling is active); τ_{w2} is the duration of the subsequent winter period (during which the GET system is in effect). The duration of the cooling pulse in variant IIc is shorter than the value determined by the formula (3) by the τ_{w1} value. In fact, the winter conditions on the soil surface in the option IIb continuously exist for about 1.5 years.

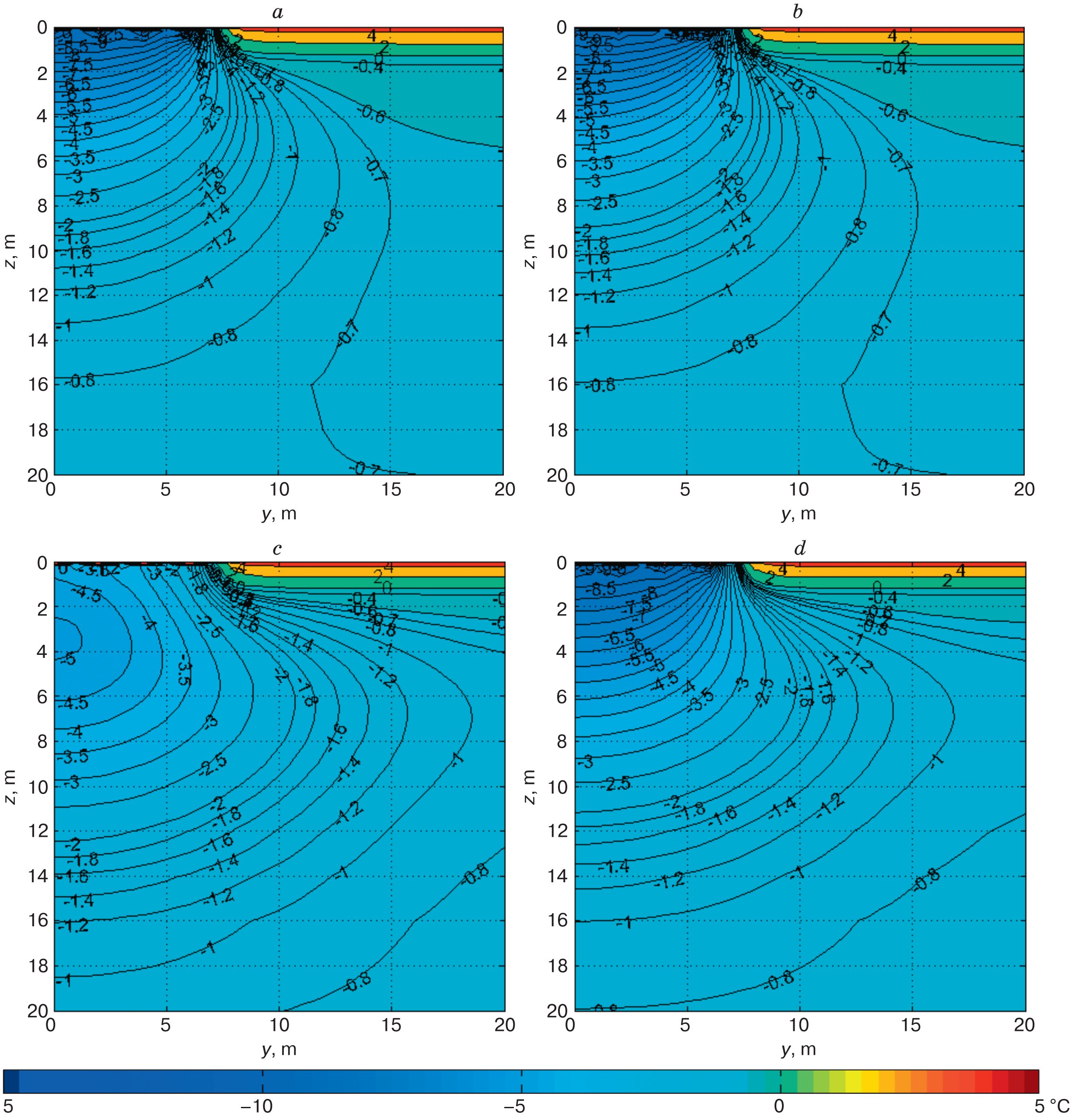

Fig. 5. Results of calculations of soil temperature during cooling using forced cooling and the GET system for the central section (x = 0 m) at t_0 = –0.7 °C:

a – option IIa (L = 1.0 m, 1 year); *b* – option IIa (L = 0.7 m, 1 year); *c* – option IIb (L = 1.0 m, 1.4 year); *d* – option IIc (L = 1.0 m, 1.4 year).

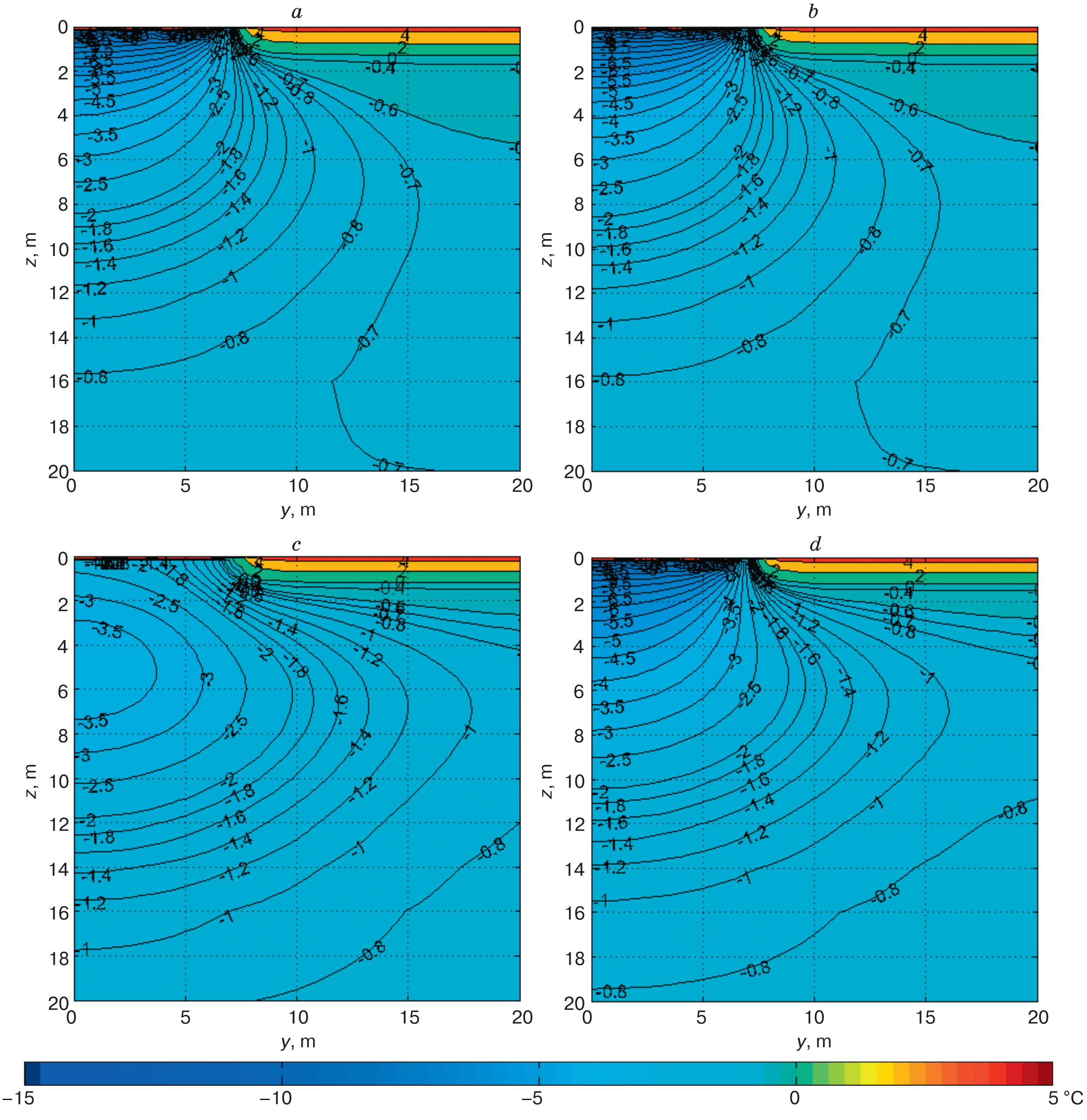

Fig. 6. Results of calculations of soil temperature during cooling using forced cooling and the GET system for the edge section (x = 12 m) at t_0 = –0.7 °C:

a – option IIa (L = 1.0 m, 1 year); *b* – option IIa (L = 0.7 m, 1 year); *c* – option IIb (L = 1.0 m, 1.4 year); *d* – option IIc (L = 1.0 m, 1.4 year).

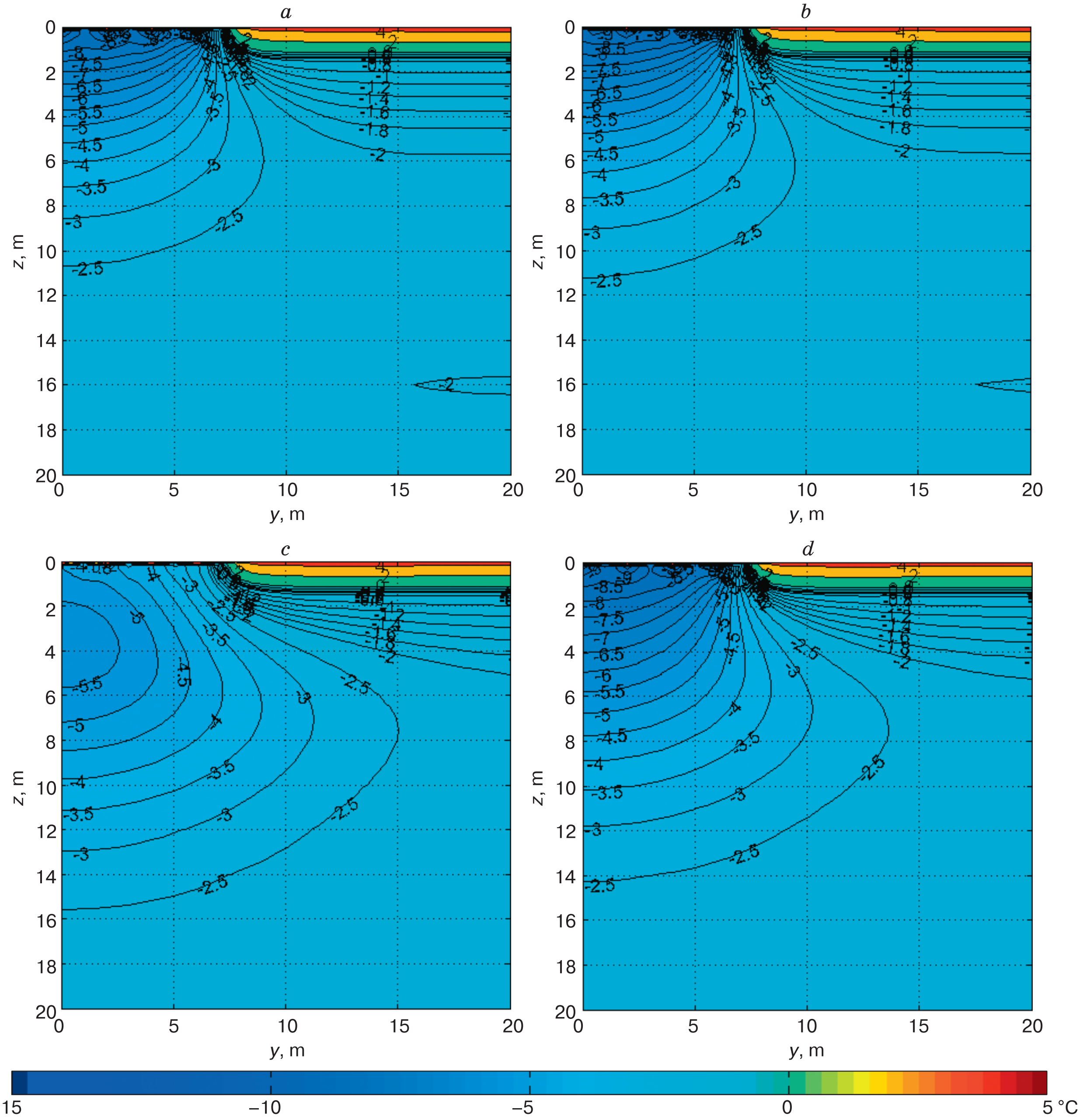

Fig. 7. Results of calculations of soil temperature during cooling using forced cooling and the GET system for the central section (x = 0 m) at t_0 = –2.0 °C:

a – option IIa (L = 1.0 m, 1 year); *b* – option IIa (L = 0.7 m, 1 year); *c* – option IIb (L = 1.0 m, 1.4 year); *d* – option IIc (L = 1.0 m, 1.4 year).

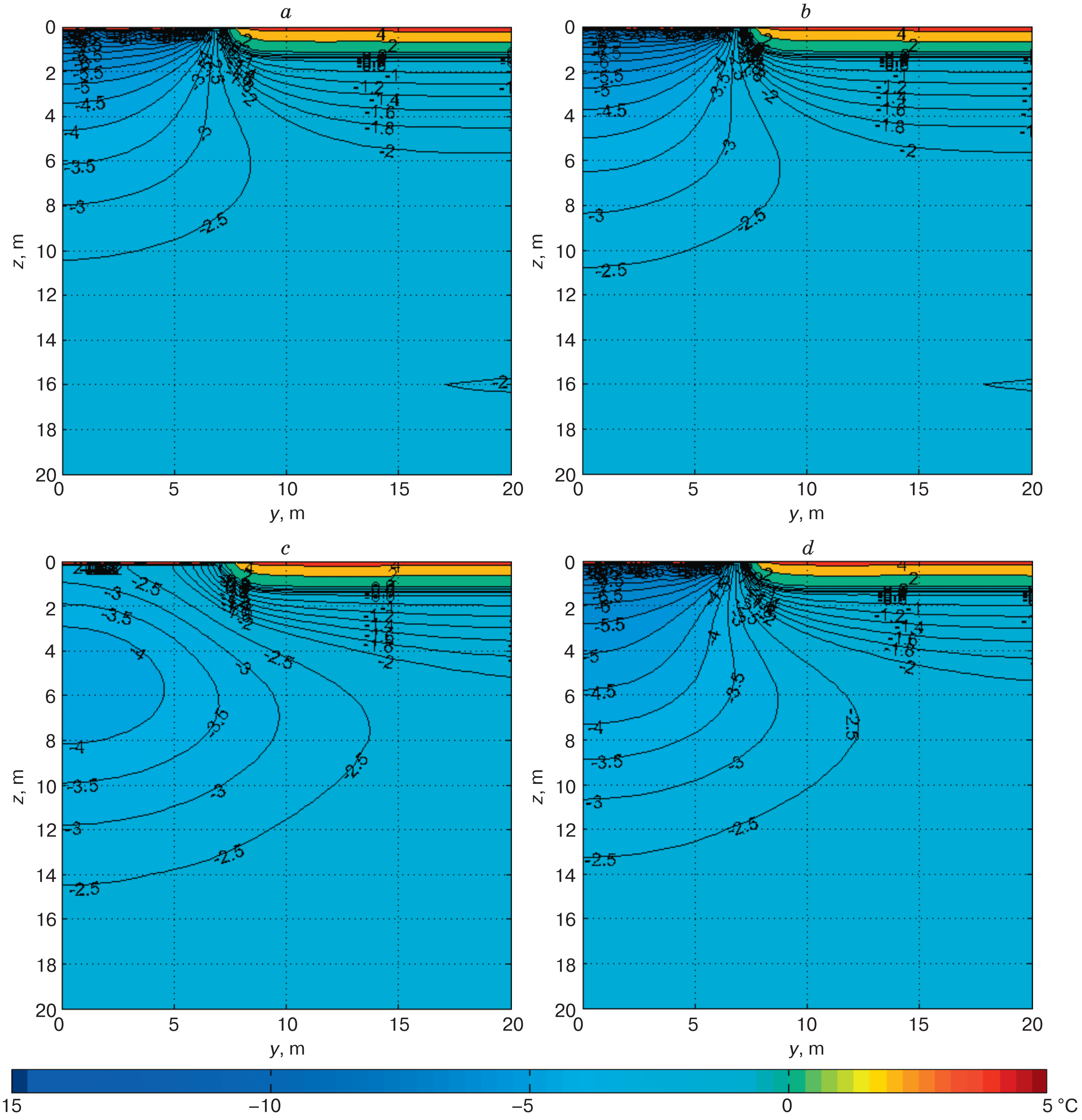

Fig. 8. Results of calculations of soil temperature during cooling using forced cooling and the GET system for the edge section (x = 12 m) at t_0 = –2.0 °C:

a – option IIa (L = 1.0 m, 1 year); *b* – option IIa (L = 0.7 m, 1 year); *c* – option IIb (L = 1.0 m, 1.4 year); *d* – option IIc (L = 1.0 m, 1.4 year).

CONCLUSION

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

1. The proposed method of surface cooling of the structure foundations (with the use of thermal insulation, the GET system and a forced cooling method (if necessary, for a short time) allows the soil temperature to be lowered by 1.0–2.5 °C to a depth of zero annual amplitudes, which in many cases is sufficient to ensure their solid-frozen state. At the same time, the time for reaching the design temperature value is significantly reduced in comparison with other methods (1.5 years instead of 3–5 years). The method is characterized by a decrease in labor intensity for the installation and mantling of cooling systems due to the absence of the need to perform the drilling and other laborious earthworks.

2. The efficiency of the proposed method is highest if the active elements of the cooling system (GET, forced cooling unit) are switched on at the moment when the layer of seasonal thawing is in a completely frozen state. In that case, the duration of the cooling impulse, which forms the temperature of the soil to a depth of zero amplitudes, turns out to be more than one year.

3. The earlier proposed [*Gorelik, Zemerov, 2020*] simple quantitative estimates of the time to reach the design temperature in the soil based on the existing ideas about the mechanism of the formation of the temperature shift generally correspond to the calculation results obtained by strict numerical methods.

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