PREVENTING THE NEGATIVE IMPACT OF FLOODING ON THE TEMPERATURE REGIME OF THE FROZEN BASE OF ROAD EMBANKMENTS

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The article presents the initial assumptions of the predictive model of changes in the temperature regime of the frozen soil massif in the case of surface flooding. Heat exchange of the soil surface with the atmosphere through a shallow (up to 1 m) water cover is described using an effective heat exchange coefficient, which takes into account the intensity of mixing of the water layer in the summer. The results of calculation of two parameters of the new thermal condition of the frozen massif (temperature at a depth of zero annual amplitude and the maximum depth of seasonal thawing) appearing as a result of flooding are presented. In addition, the rate of transformation to the new condition is considered. Significant warming of the frozen base occurs in the case of intense mixing of the water layer during the summer season. If the mixing process does not take place in the water reservoir of a shallow depth, its cooling effect is possible. In deeper reservoirs, the warming effect is possible, but it is weaker than that under mixing conditions. This analysis has been performed for the least studied element of the "roadway embankment – reservoir – frozen soil" technical system in order to control the correctness of the calculation procedure in a more complex case for a two-dimensional process. The results of numerical modeling of the temperature field in the frozen base of the roadway in contact with a shallow water basin are presented. It is demonstrated that the frozen base warms up essentially, if the water layer is mixed intensively (by wind) in summer time. The initial temperature state may be preserved during the whole period of road exploitation, if the summer mixing of water is blocked by fairly simple technical measures that are proposed in this paper.

Keywords: *frozen ground, seasonal thawing, depth of seasonal thaw penetration, depth of zero annual amplitude of temperatures, surface water reservoir, roadbed.*

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INTRODUCTION

During road construction in permafrost areas, the formation of shallow (up to 1-m-deep) water bodies is often observed. These water bodies remain in contact with the slopes of road embankment for a long time and have an uncontrolled thermal effect on its frozen base [*Vorontsov et al., 2014; Grebenets, Isakov, 2016; Kondratiev, 2016; Dydyshko, 2017*]. Their occurrence may be associated with a change in natural factors or with flaws in the design of drainage and culvert constructions along the embankment. The main technical measures to eliminate the negative impact of flooding include special drainage solutions and repair and restoration works on existing structures, or the construction of new ones. Meanwhile, the efficiency of these works is low and requires additional measures to strengthen the foundation [*Andrinov, 2011; Litovko, 2011*]. As a result, this method of eliminating the negative impact of watering turns out to be ineffective and labor-intensive.

Today, in fact, the issues of assessing and forecasting the impact of such water bodies on the temperature regime of the frozen foundation of embankment structures, the practical significance of which for ensuring embankment stability is very important, remain unresolved. The purpose of this work is to create an adequate method for predicting the consequences of the influence of a shallow reservoir on the temperature regime of the frozen base of an embankment, to establish on this basis the most important factors that determine the intensity of the negative impact, and to evaluate possible proposals for its elimination.

INITIAL ASSUMPTIONS OF THE PROPOSED FORECASTING MODEL

The forecast of changes in the temperature regime of frozen soils under any violation of the conditions of heat exchange with the environment should answer two main questions: (a) what will be the values of the parameters of the new stable state of soils after the impact of disturbing factors and (b) what is the characteristic time to reach a new stable state of soils.

Individual elements of the embankment and the embankment as a whole can have both cooling and warming effects on the base [*Ashpiz et al., 2008; Ashpiz, Khrustalev, 2013; Zhang et al., 2018*]. The influence of the reservoir on the frozen ground is also complex and is not known in advance. For the correct statement of the mathematical problem of calculating the temperature regime of the frozen base of the roadway embankment (this type of embankment is considered below as an example) in contact with a water body, it is advisable, first of all, to find out the nature of the separate (i.e., independent of the embankment) influence of the water reservoir on the underlying frozen ground. A certain step in solving this part of the problem was made in [*Gorelik, Zemerov, 2020*].

Determination of a new thermal state of soils in the event of water cover

In the complete formulation of the problem of the influence of a reservoir, the most important is the boundary condition that describes the heat exchange of the upper surface of the soil massif with the atmosphere through the water cover, and additional relations to it. It is usually written as a boundary condition of the 3rd kind. However, it should be noted that the exact recording of this relationship involves the division of the heat flux into radiative and convective components with specified methods for their determination, which significantly complicates the calculation procedure and is often impossible in practice because of the complexity of actinometric measurements with due account for the action of local factors of a particular terrain [*Pavlov, 1965*]. As a rule, the radiation component is not taken into account for solving practical problems, and the boundary condition has the form

$$\alpha\left(t_a - t\right) = -\lambda\left(dt/dz\right)_{z=0}. \quad (1)$$

This condition must be supplemented by the following relations:

$$\alpha_{ss} = \left(\alpha_s^{-1} + \frac{h}{\lambda_{ef}}\right)^{-1}; \quad (2)$$

$$\alpha_{ww} = \left(\alpha_w^{-1} + \frac{h}{\lambda_i}\right)^{-1}; \quad (3)$$

$$\int_0^{\tau_h} t_a(\tau)\,d\tau = \frac{h\kappa_v}{\alpha_s}; \quad (4)$$

$$\int_0^{\tau_i} t_a(\tau)\,d\tau = -\left[\kappa_v h\left(h + \frac{2\lambda_i}{\alpha_w}\right)\right]\Big/ 2\lambda_i. \quad (5)$$

Table 1. **Mean monthly air temperatures for the area of the Urengoy weather 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

Here t, $t_a(\tau)$ are the soil surface temperature and the time-dependent air temperature τ in the annual cycle; α is the heat exchange coefficient at the upper boundary of the massif with the atmosphere, the dependence of which on the season is piecewise constant; α_s, α_w are the time-averaged summer and winter heat transfer coefficients determined without taking into account the influence of the reservoir (i.e., in the state before its appearance); α_{ss} is the summer heat transfer coefficient after the formation of a reservoir determined from the thickness of the water layer h and its effective thermal conductivity coefficient λ_{ef}, which takes into account the nature of water mixing (the range of its possible change: $\lambda_w \leqslant \lambda_{ef} \leqslant \infty$, where λ_w = 0.5 W/ (m·°C) is the thermal conductivity of water); α_{ww} is the winter heat transfer coefficient after the formation of a reservoir, which is determined similarly to the summer coefficient through the thermal conductivity of ice (λ_i = 2.2 W/(m·°C)). Soil thermal conductivity coefficient λ in Eq. (1) also takes piecewise constant (seasonal) values: λ_u in the thawed state and λ_f in the frozen state. Equations (4) and (5) determine the time of melting of the ice layer τ_h with the onset of summer and the time of freezing of the water layer τ_i with the onset of winter (taking into account the prerequisites formulated in [*Gorelik, Zemerov, 2020*]); κ_v is the volumetric heat of the water–ice phase transition. In the examples considered below, the air temperature $t_a(\tau)$ is taken from the Urengoy weather station (Table 1).

The mean annual temperatures at the bottom of the seasonally thawed layer (t_m) and at the depth of zero annual amplitudes (t_0) are determined by averaging the time-dependent temperatures $t_m(\tau)$ and $t_0(\tau)$ at the corresponding levels according to the relations

$$t_m = \frac{1}{\tau_0}\int_0^{\tau_0} t_m(\tau)\,d\tau, \quad t_0 = \frac{1}{\tau_0}\int_0^{\tau_0} t_0(\tau)\,d\tau \quad (6)$$

(the depth of zero annual amplitudes z_0 is assumed to be 12 m; τ_0 is a year).

In the procedure for calculating the temperature field of the soil during periods of thawing and freezing of the water layer (the duration of which is a certain part of the summer and winter seasons), the temperature at the contact of water with the bottom of the reservoir is assumed to be 0°C [*Gorelik, Zemerov, 2020*]. Thus, in the presence of a reservoir on the surface of a frozen soil massif, the processes of seasonal freezing–thawing in its upper layers and the temperature dynamics below the base of the seasonally thawed layer beyond the time intervals of freezing and thawing of the reservoir itself in the general formulation of the mathematical problem are described by relations (1)–(3) for the corresponding seasons. During the periods of freezing or thawing of the water layer at the upper boundary of the soil (coinciding with the surface of the bottom of the reservoir), the boundary condition of the 1st kind (with a temperature of 0°C on its surface) is used. Note that under steady-state conditions of heat transfer, the temperatures t_m and t_0 coincide [*Carslaw, Jaeger, 1964; Dostovalov, Kudryavtsev, 1967; Tikhonov, Samarsky, 1972*].

In all the examples of calculations given below, the following characteristics of soils and initial conditions are assumed (index *u* refers to thawed soil, and index *f*, to frozen soil): heat capacity (J/(m^3·°C): $C_u = 2.86 \cdot 10^6$, $C_f = 2.20 \cdot 10^6$; thermal conductivity of the soil (W/(m·°C)): $\lambda_u = 1.76$, $\lambda_f = 2.10$; thermal conductivity of water and ice $\lambda_w = 0.5$, $\lambda_i = 2.2$; bulk density of the skeleton $\gamma_s = 1500$ kg/m^3, thermal diffusivity $\mu_f = 9.55 \cdot 10^{-7}$ m^2/s, weight water content $w = 0.2$, initial temperature at the depth of zero annual amplitudes in the undisturbed soil massif $t_0 = -2.0$°C.

Equations (2)–(5) explicitly single out the contribution of only the water cover to the heat exchange with the soil surface. However, it must be remembered that even for undisturbed conditions, coefficient α in its seasonal components α_s and α_w implicitly depends on a significant number of influencing factors of a physical-geographical, climatic, and geological nature. It is difficult to establish the influence of the totality of these factors in the problem under consideration, and it is often impossible to single out the prevailing influence of their minimum number. To solve this problem, the work [*Gorelik, Pazderin, 2017*] proposes a method for determining coefficients α_s and α_w on the basis of empirical data obtained during engineering surveys, which contain actual information on the maximum depth of seasonal thawing (ξ_m) and temperature at the depth of zero annual amplitudes (t_0) (it is better to use monitoring data and calculated long-term average values). The coefficients determined by this method implicitly take into account the action of the entire group of influencing factors and ensure the invariance of the values of ξ_m and t_0 (in the area outside the contour of the structure) throughout the entire life of the structure (usually at least 30 years) provided that external conditions are constant. At the same time, to predict the effect of a structure on frozen soils, the thermal effect of the structure itself is considered separately in an explicit form (just as it was done for a reservoir).

For the above characteristics of soils and air temperature, the values of the coefficients for the undisturbed soil mass (W/(m^2·°C)) were obtained in this way: $\alpha_s = 17.5$, $\alpha_w = 1.02$. As seen from Fig. 1, these values ensure the constancy of the maximum depth of seasonal thawing $\xi_m = 1.7$ m (determined by the break point of temperature on the corresponding curves) and $t_0 = -2$°C for 30 years of cyclically recurring seasonal temperature fluctuations. It is important that this state of the soil, when using numerical methods, is also taken as the initial condition in the problems of finding the temperature field in the soil for surface disturbances of any nature. With this method of setting the coefficients α_s, α_w and the initial condition consistent with them, the systematic error of calculations associated with the "unreasonable influence" of the soil mass outside the zone of surface disturbances on the calculation results is eliminated.

Note that in some works, the constancy of the temperature t_0 for the entire life of the structure is ensured by a special selection of the dynamics of the snow cover depth during this period. In our opinion, this approach has a significant drawback, because it requires an additional prediction of the temperature at the base of the soil massif, which has no factual justification. Its inconsistency is seen from the absence of a trend in climate change during the period under consideration. In this case, there are no reasons for changing the average long-term values of any of the climatic parameters (in particular, snow accumulation), and they should be taken constant over time. At the same time, it is practically impossible to select seasonal heat transfer coefficients (based, for example, on the known relationships between wind speed and data from local weather stations) that ensure the constancy of temperature t_0 for a given period. This can lead to significant errors in the quantitative prediction of

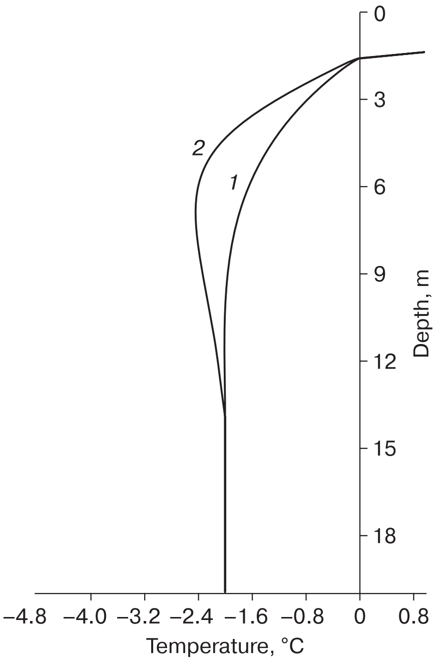

Fig. 1. Calculated temperature distribution over the depth of the soil mass under conditions of natural heat exchange during the first year (*1*) and the final calculation year (*2*) at α_s = 17.5 W/(m^2·°C), α_w = 1.02 W/(m^2·°C).

1 – July 1, 2000–July 1, 2001; *2* – July 1, 2031–July 1, 2032.

the thermal impact of structures on the frozen basement. The approach proposed by the authors is based only on actual data (long-term average values of ξ_m and t_0, which implicitly reflect the action of the entire set of influencing factors, including snow cover); thus, it is free from the indicated drawback. A modification of this approach can be applied to predict the temperature in the soil massif also in the case of some trend of climate change [*Gorelik, Zemerov, 2022*].

Using Eqs. (1)–(6), the dependences of the new steady-state temperature at a depth of zero annual amplitudes t_0 on the depth of the reservoir were obtained for two limiting cases related to mixing of the water layer (Fig. 2) [*Gorelik, Zemerov, 2020*]. Two independent methods – analytical (curves *1′*, *2′*) and numerical (curves *1*, *2*) – were applied. If necessary, additional calculations can be carried out for intermediate values of the coefficient λ_{ef}. If a sufficiently reliable method of preventing mixing is used, then the need for such calculations is eliminated.

Important features of the behavior of the new steady-state temperature t_0 are closely related to two characteristics of the water layer – its depth and the intensity of mixing in summer. With intensive mixing (due to wind action and natural convective motion), the soil temperature increases monotonically with increasing depth of the reservoir (Fig. 2, curves *1*, *1′*). If conditions arise in summer that prevent mixing of the water layer, then there is a range of depths at which the water layer has a cooling effect on the underlying soils (Fig. 2, curves *2*, *2′*). When analyzing the graphs (Fig. 2), it should be kept in mind that the point ($h = 0$, $t_0 = -2$°C) characterizes the state of frozen soil in the absence of a reservoir, it is the same for both pairs of curves *1*, *1′* and *2*, *2′*. Therefore, both pairs have this common starting point on the charts. The extraordinary behavior of temperature in the absence of mixing is due to the multidirectional influence of the depth of the reservoir on the time of freezing of bottom sediments and on the duration of the cooling pulse in winter. The magnitude of seasonal thawing monotonically decreases with increasing depth of the reservoir, which, at shallow depths, leads to a shorter time of water freezing in winter and increases the duration of the cooling impact on the soil. Starting from a certain depth, the duration of freezing of the water layer (in the first approximation, proportional to the square of its depth) begins to have a decisive influence, which leads to a reduction in the duration of the cooling pulse and an increase in soil temperature [*Gorelik, Zemerov, 2020*]. At the same time, it can be seen that in the depth range where the soil is heated in the absence of mixing ($h > 0.5$ m), the soil temperature remains significantly lower than in the case of water mixing.

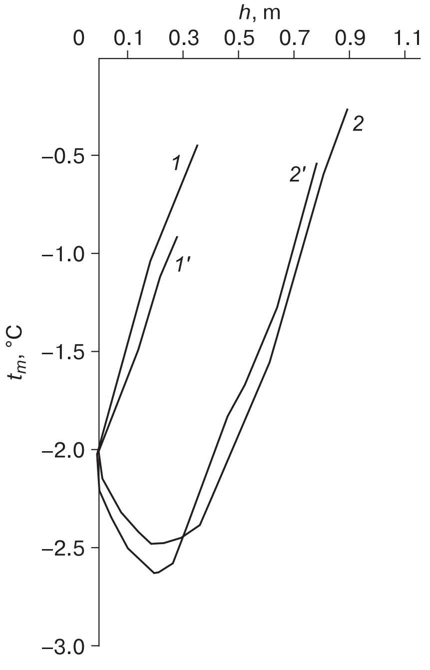

Fig. 2. Dependence of the mean annual temperature at the depth of zero annual amplitudes under the reservoir (t_m) on its depth h in the mode of steady oscillations:

1, 1′ – with full mixing ($\lambda_{ef} \to \infty$); *2, 2′* – in the absence of mixing ($\lambda_{ef} = \lambda_w$); *1, 2* – calculation by numerical method; *1′, 2′* – calculation by analytical method.

Conditions that prevent mixing may occur due to natural causes (for example, when a reservoir is overgrown or silted and enriched with organomineral matter brought in by wind or by flows from adjacent slopes). This explains the well-known facts of the attenuation of thermokarst during the overgrowing of thermokarst lakes at the initial stage, which leads to a reduction in the heat flux into the ice-rich frozen base, or the cooling effect of mires (with a significant proportion of the organomineral component) on the temperature regime of the underlying soils [*Dostovalov, Kudryavtsev, 1967; Kudryavtsev, 1978; Feldman, 1984; Shur, 1988*]. It is also possible to prevent the mixing of a shallow reservoir in the summer season by purely technical means [*Method..., 2021*]. For this, the following methods are used: (a) artificial sowing of marsh grasses (as opposed to sowing of field grasses on slopes of the embankment to strengthen them); (b) adding of organomineral substances (peat, peat–soil mixtures) in the required amount; (c) installation of lightweight mesh (or cellular) structures (for example, in the form of mats made of thin plastic threads or natural fibers). If necessary, mats can be attached to the bottom of the reservoir with anchor pins. It is possible to use various combinations of these methods.

The main requirements for the material filling the reservoir are a sufficiently high moisture capacity (ensuring considerable heat consumption during summer thawing) and the formation of a rigid or viscous structure in the water, which prevents water mixing under the influence of wind and natural convection.

The foregoing allows us to highlight the following main points: the most significant factors that determine the thermal effect of a reservoir on the underlying frozen soils are the depth of the reservoir and the intensity of mixing of the water layer in the summer season. It is possible to reduce the negative impact of water reservoirs via eliminating or minimizing the possibility of mixing of the water layer in the summer season. To determine the new thermal state of soils during watering of the surface, Eqs. (1)–(6) should be used for the mathematical description of heat exchange between the frozen soil and the atmosphere through the water layer (for preliminary analysis, the calculation results presented in Fig. 2 can be used).

Relaxation time to a new state

The time of transition τ_f of the soil temperature t_0 to a new stable state corresponding to a new value of t_m upon the appearance of water reservoir is determined by an approximate method using the formula [*Gorelik, Zemerov, 2020*]:

$$\tau_f = \frac{z_0^2}{12\mu_f\left(1-\sqrt{1-n}\right)^2}, \ \Delta t = t_0 - t_m, \delta t = t_f - t_m,$$

$$n = \left|\delta t/\Delta t\right|. \tag{7}$$

Due to the fact that the relaxation time from temperature t_0 to t_m is, generally speaking, infinite [*Carslaw, Jaeger, 1964; Tikhonov, Samarsky, 1972*], an auxiliary (intermediate) temperature t_f is introduced; t_f is sufficient to achieve engineering goals, but some-

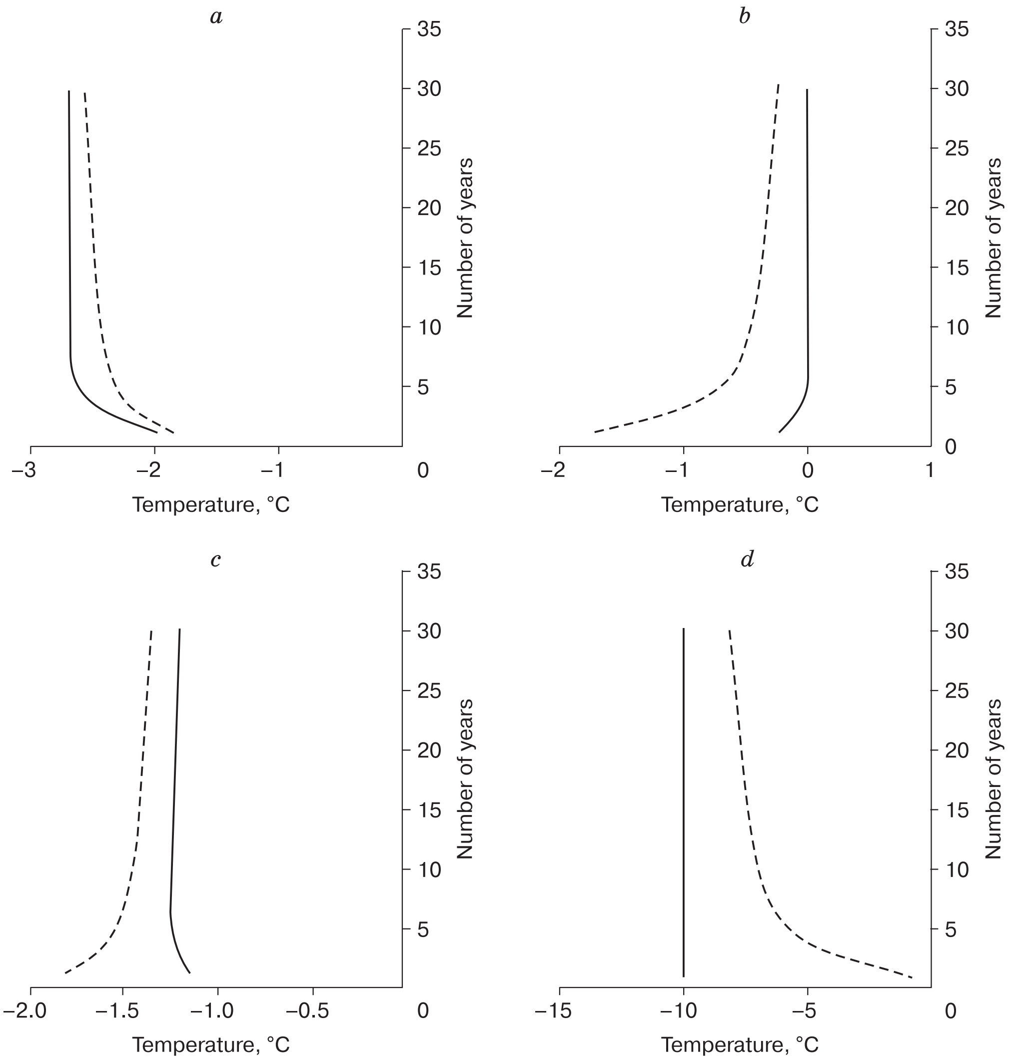

Fig. 3. Variation of the mean annual temperature at the base of the seasonally thawed layer (solid line) and at the depth of zero annual amplitudes (dashed line):

(*a*, *b*) h = 0.3 m without (*a*) and with (*b*) water layer mixing in summer; (*c*) h = 0.6 m without water layer mixing in summer; (*d*) when applying special technical measures ensuring a low mean annual temperature at the base of the seasonally thawed layer.

what differs from t_m. It follows from Eq. (7) that at $t_f = t_m$, we get $n = 0$, and the time τ_f goes to infinity. The temperature t_f is reached in a finite time τ_f, which is a function of this temperature. Previously, this formula was also used to estimate the relaxation time for special surface methods of base cooling [*Gorelik, Khabitov, 2021; Gorelik et al., 2021*].

At the time of publication of the work [*Gorelik, Zemerov, 2020*], the authors were not able to compare the results of calculations using Eq. (7) with the results of calculations by numerical methods. Such a comparison is given below for some important cases (Fig. 3). Figure 3*a* presents the results of calculations by numerical methods of the change in temperature over time at the bottom of the seasonally thawed layer and at a depth of zero amplitudes, when a reservoir with a depth $h = 0.3$ m appears on the surface of the soil without the possibility of mixing the water layer ($t_0 = -2$°C, $t_m = -2.6$°C). It can be seen that the temperature at depth z_0 reaches the value $t_f = -2.3$°C after $\tau_f = 5$ yr; at $t_f = -2.4$°C, $\tau_f = 10$ yr. The values of τ_f obtained from Eq. (7) for these cases are 3.2 and 8.2 yr, respectively. For the case of layer mixing at $h = 0.3$ m, the results of numerical calculations are shown in Fig. 3*b* ($t_0 = -2$°C, $t_m = -0$°C). Soil warming up to (for example) $t_f = -0.5$°C takes place over time $\tau_f = 10$ yr; according to Eq. (7), we get $\tau_f = 15$ yr. The dynamics of both temperatures at $h = 0.6$ m without mixing (but at which the warming process also occurs, see Fig. 2) is shown in Fig. 2*c* ($t_0 = -2$°C, $t_m = -1.24$°C). In this case, the relaxation time to the value $t_f = -1.5$°C is equal to $\tau_f = 7.5$ yr; according to Eq. (7), $\tau_f = 7.8$ yr.

In the case when, with the help of special technical means, the temperature at the bottom of the seasonally thawed layer is kept very low (Fig. 3*d*, $t_0 = -2$°C, $t_m = -10$°C), the temperature decrease by one degree at the depth z_0 ($t_f = -3$°C) is achieved very quickly (in about one year), which is confirmed by calculations both by the numerical method and by Eq. (7). The graphs can also be used to control the correctness of the computational procedure: the dashed curve should asymptotically approach the solid line as $\tau_f \to \infty$; in case of disturbances on the ground surface of a cooling nature, the solid curve should lie to the left of the dashed curve, and vice versa. In general, it can be argued that despite the lack of accuracy, Eq. (7) can be used for preliminary estimates. Its advantage lies in the simplicity of calculations, and the procedure for its derivation allows us to understand the physics of the ongoing processes. At the same time, numerical methods are more accurate and allow one to take into account the dependence of external factors on coordinates and time; also, they make it possible to obtain much more complete information about the spatial characteristics of the temperature field and its dynamics in cases, where the dimension of the computational domain exceeds unity. In studies of the dynamics of the temperature field under surface disturbances, both methods are useful and complement one another.

Meanwhile, during each year, there is a change in temperature at each of the two levels considered, which has the character of almost periodic changes during a 30-yr time cycle. Thus, the temperature behavior at the bottom of the seasonally thawed layer during the 1st, 5th, 15th, and 30th years after the formation of the reservoir is shown in Fig. 4*a*; at a depth of zero annual amplitudes, in Fig. 4*b*. The mean annual temperatures at these depths calculated according to Eq. (6) are shown as corresponding points on the curves (Fig. 4*b*). Note that with a noticeable

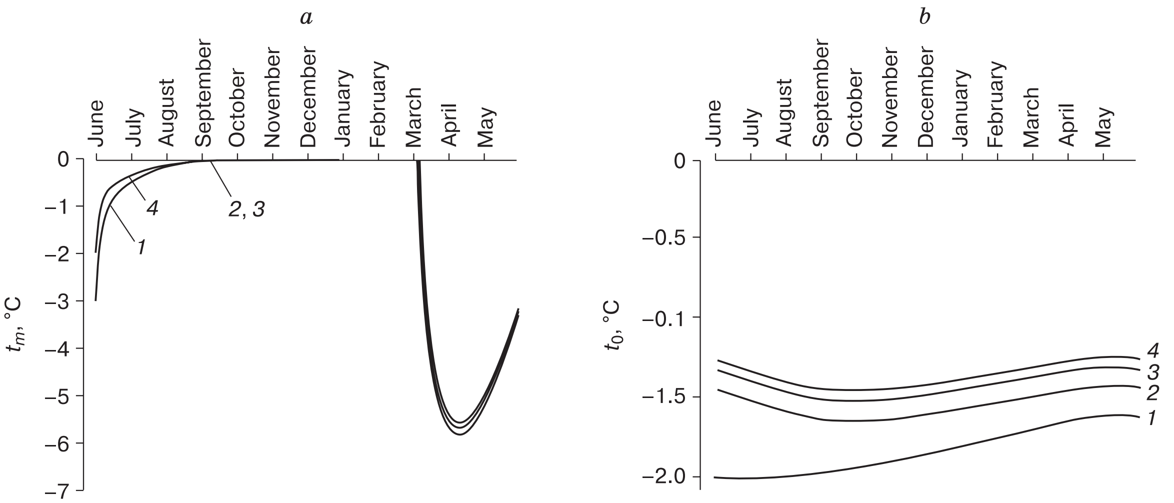

Fig. 4. Temperature change at the bottom of the seasonally thawed layer t_m (*a*) and at a depth of zero annual amplitudes t_0 (*b*) during the calculated years:

1 – 1st year; 2 – 5th year; 3 – 15th year; 4 – 30th year.

quantitative change in temperature at a depth of z_0, its behavior at the bottom of the active layer, after a short initial period, remains practically unchanged over a 30-yy-long period, which is reflected in the almost constant value of the mean annual temperature (Fig. 3*a*). That is, at the level ξ_m, a stable value of the new temperature is reached very quickly (the relaxation time does not exceed five years). A slight increase in this temperature (within 0.1°C over 30 yr) shown in Fig. 3*c* is most likely due to the insufficient accuracy of the calculations and will be analyzed in further studies. In this case, the value of ξ_m changes slightly: ξ_m = 0.59 m at τ = 1 yr, ξ_m = 0.57 m at τ = 30 yr.

At the level ξ_m, the differences in the temperature dynamics during each year are blurred, but they are noticeable in the mean annual values, which is reflected in the behavior of the initial segment of the solid curves in Fig. 3. It follows from the position of the curves in Fig. 3 that the mean annual temperature at base of the active layer is the main reason for the temperature change at the depth of zero annual amplitudes, which was previously noted in a number of works [*Porkhaev, 1970; Kudryavtsev, 1978; Feldman, 1984; Gorelik, Zemerov, 2020, 2022*]. The vagueness of changes in the mean annual temperature at the base of the active layer can contribute to the development of adequate criteria for determining the accuracy of temperature measurements within the active layer during monitoring studies.

The analysis of curves shown in Figs. 3–5 is very useful from the point of view of quantitative assessment of the influence of various types of surface disturbances or the application of special technical measures on the temperature regime of the frozen soil massif. For example, it follows from it that the efficiency of open ventilated underground or suspended structures can be significantly increased by periodical compaction of the snow cover in the winter season. An increase in snow density strongly increases thermal conductivity of the snow [*Feldman, 1977; Smorygin, 1988*], which leads to a noticeable decrease in its warming effect on soils in the winter season. A similar effect can be achieved by maintaining snow cover for most of the summer period (which can be achieved through the seasonal application of thermal insulation coatings). Although the possibility of implementing these measures in the form of any acceptable technologies is currently not achievable, they can be applied in extreme conditions using fairly simple technical means. It is also interesting that permafrost islands can be formed in this way inside massifs of thawed soil in areas with rather moderate depths of seasonal freezing provided that the initial temperature t_0 does not significantly exceed 0°C. In addition, an analysis of the results of calculation of the temperature dynamics of frozen soils will be useful for predicting their thermal response to climate change [*Gorelik, Zemerov, 2022*].

TEMPERATURE CALCULATIONS AT THE BASE OF EMBANKMENT IN THE PRESENCE OF A WATER RESERVOIR

This paper describes the problem statement and the results of calculating the temperature field in the frozen base of a road embankment during its service life (30 yr) in the presence of a shallow water reservoir near one of the slopes. The purpose of the calculations is to evaluate the efficiency of technical measures to eliminate the mixing of the water layer in summer to stabilize the frozen state of the embankment base.

Characteristics of design conditions

Figure 5 shows a diagram of the computational domain, which includes a cross section of a roadbed embankment laid on permafrost and in contact with a shallow water body. It is assumed that there is no water filtration through the body of the embankment, and in all parts of the soil massif (including the body of the embankment and base soils) heat transfer occurs only by conduction. Convective heat transfer is

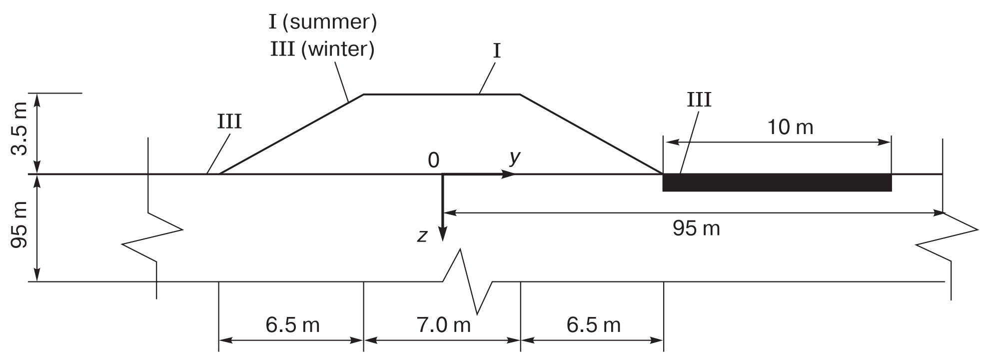

Fig. 5. Geometric parameters of the computational domain and the type of boundary conditions at the elements limiting it.

I, III – boundary conditions of the 1st and 3rd kind, correspondingly. Explanations are in text.

present only within the reservoir and is taken into account through the coefficient of effective thermal conductivity of the water layer. The problem statement includes: a non-stationary heat equation written in enthalpy form [*Gorelik et al., 2021*], a set of boundary conditions over the entire surface of the allocated computational domain, and initial temperature condition for its internal points.

The calculation of the dynamics of the temperature field in a soil mass that is inhomogeneous in properties is carried out taking into account the change in the phase state in the seasonally thawed layer. The boundaries of the computational domain from the top are formed by a combination of the outer boundary of the embankment, the bottom of the reservoir, and the horizontal surface of the natural massif (Fig. 5). The upper boundary of the water layer coincides with the level of the horizontal surface of the base soils (excavation of arbitrary genesis). The coordinate system is located in a horizontal plane coinciding with the surface of the base, its center coincides with the center of symmetry of the cross section of the embankment. The *Oz* axis is directed vertically downwards, the *Ox* and *Oy* axes lie in the horizontal plane and are directed along the longitudinal and transverse axes of the embankment, respectively. The dimensions of the computational domain along each of the axes are determined by the radius of the thermal influence [*Gorelik, Pazderin, 2017*]; when calculating for a 30-yr period, this radius is 95 m. Thus, the boundaries of the computational domain should be 95 m away from the boundaries of the embankment contour in the plan and at the same distance vertically deep into the array. At these boundaries, the zero value of the heat flux is set. The heat exchange of the upper boundary of the soil with the air (under natural conditions – outside the structure and reservoir) through the ground covers is taken into account by the boundary condition of the 3rd kind with different heat transfer coefficients in summer and winter. These coefficients ensure that the temperature remains unchanged at the depth of zero amplitudes ($t_0 = -2.0$°C) during the entire period under consideration (30 yr): $\alpha_s = 17.5$ W/(m^2·°C); $\alpha_w = 1.02$ W/(m^2·°C). The heat exchange of the surface of the carriageway of the embankment with the air is taken into account by the boundary condition of the 1st kind with a temperature equal to the air tempera-

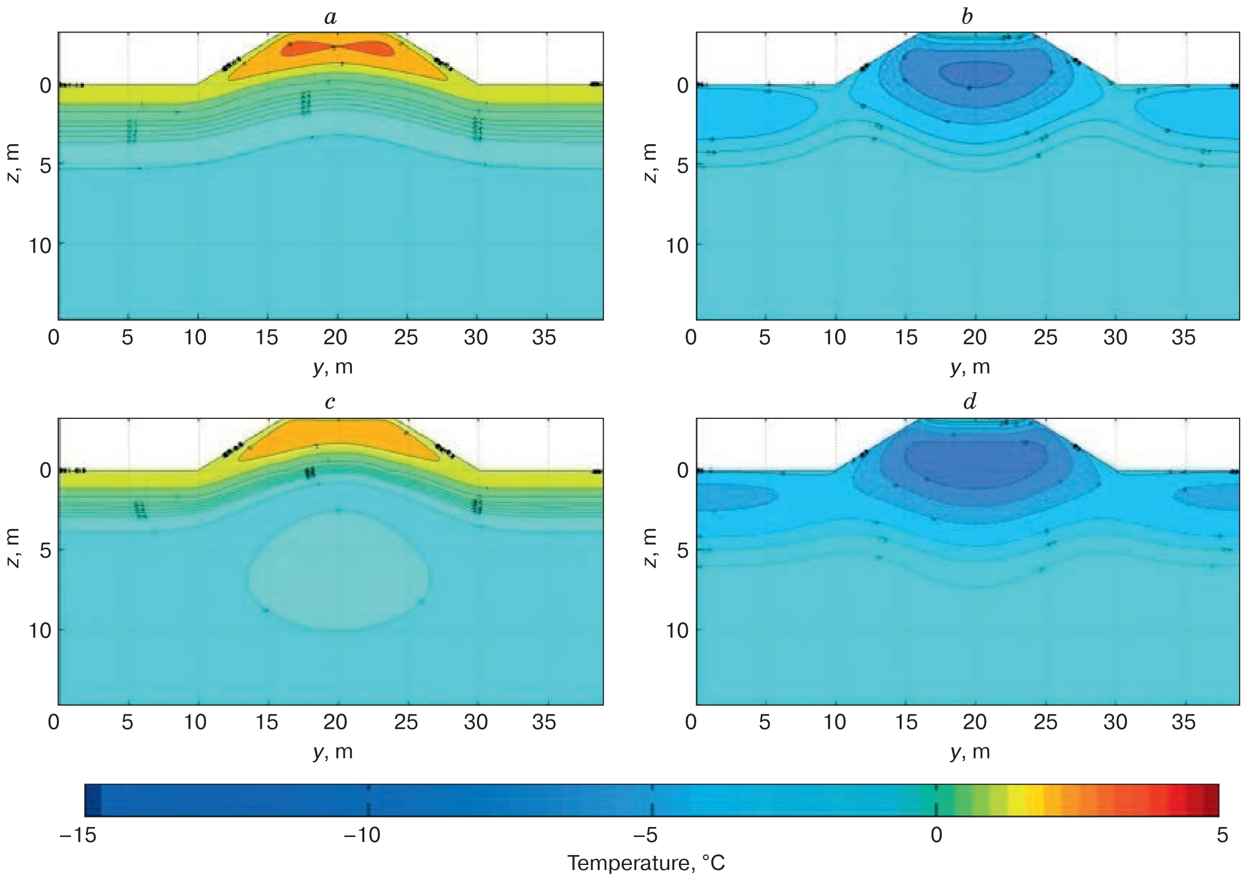

Fig. 6. Temperature field at the base of the embankment in the absence of watering.

a, *b* – the first year of operation: *a* – Oct. 1, 2000; *b* – June 1, 2001; *c*, *d* – the thirtieth year of operation: *c* – Oct. 1, 2030; *d* – June 1, 2031. At the lowest part of the figure is a scale for matching color and temperature.

ture (assuming the presence of a hard coating and regular snow removal in winter). The heat exchange of the upper boundary of the embankment slopes with the air in summer is determined by the boundary condition of the 1st kind at a temperature equal to the air temperature (taking into account the absence of moisture accumulation conditions), and in winter – by the 3rd kind boundary condition with a winter heat transfer coefficient, which is half as much as under natural conditions (α_w = 0.55 W/(m^2·°C)), taking into account additional snow accumulation due to clearing of the roadway and wind deposits.

The thermophysical characteristics of soils are piecewise constant, different for thawed and frozen states. For foundation soils, they are taken as described above. For the embankment material (sand), the characteristics are as follows: volumetric heat capacity (J/(m^3·°C)): C_u = 2.26·10^6, C_f = 2.10·10^6; thermal conductivity coefficients (W/(m·°C)): λ_u = 2.1, λ_f = 2.14; volumetric heat capacity of phase transition κ_v = 3.34·10^7 J/m^3. The initial soil temperature at the depth of zero amplitudes is t_0 = –2°C.

The geometrical parameters of the cross section of the embankment are taken as follows (the section has a trapezoidal shape): the height of the embankment is 3.5 m; width of the main platform (top of the embankment) is 7 m; width at the base is 20 m (Fig. 5).

The depth of the reservoir adjacent to the slope in the example is h = 0.6 m. The heat exchange of the surface of the soil base (bottom of the reservoir) with the air through the water layer is described by Eqs. (1)–(6), taking into account the above, relative to the temperature of the bottom of the reservoir during periods of freeze-up and ice cover melting. When describing convective heat transfer in the form (1), the heat transfer coefficient between moving media (or the equivalent effective thermal conductivity of the water layer λ_{ef}) increases without limit with increasing mixing intensity [*Mikheev, Mikheeva, 1973*]. The limiting values for intensive mixing of these coefficients can be taken to be infinitely large. Calculations show that the calculation results practically cease to depend on λ_{ef} if its value exceeds 200 W/(m·°C). For

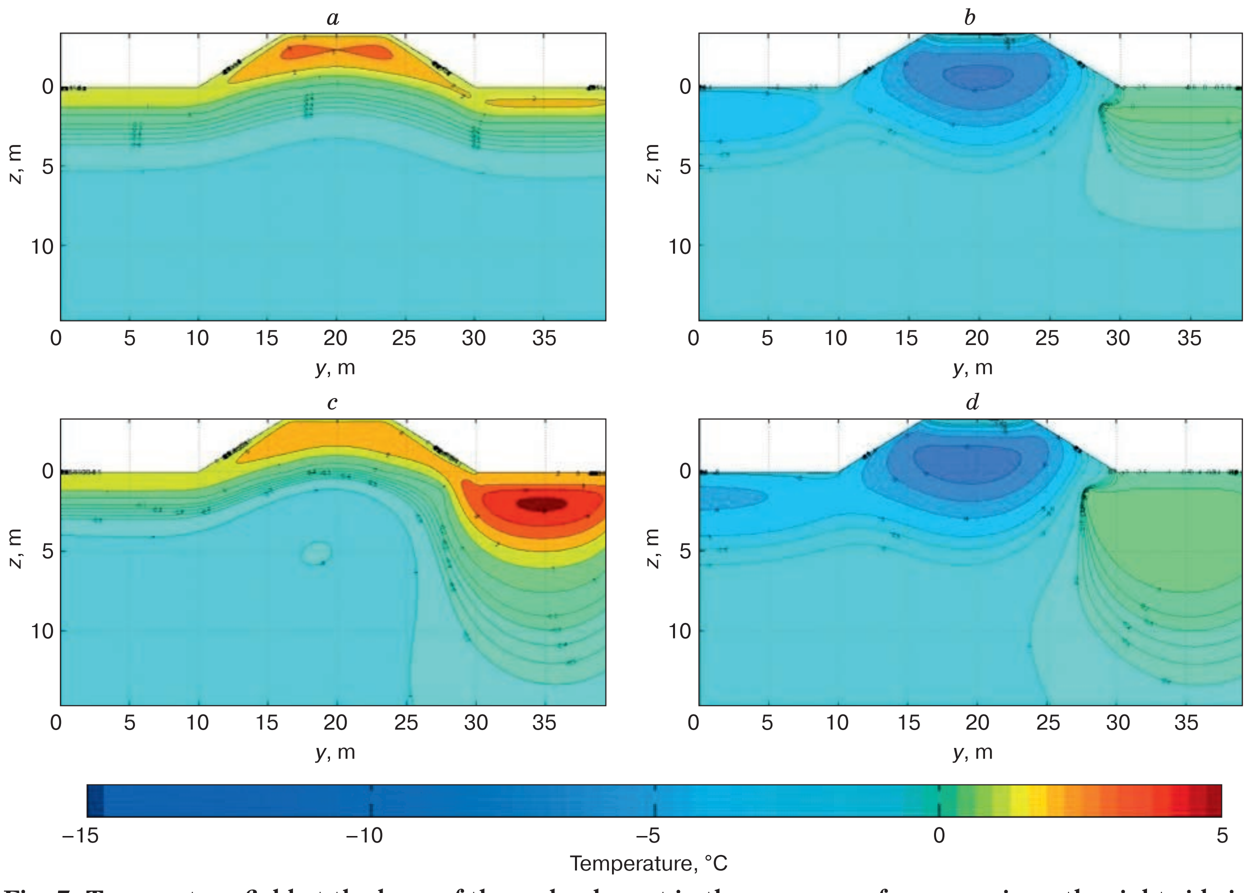

Fig. 7. Temperature field at the base of the embankment in the presence of a reservoir on the right side in the case of strong mixing.

a, *b* – the first year of operation: *a* – Oct. 1, 2000; *b* – June 1, 2001; *c*, *d* – the fifteenth year of operation: *c* – Oct. 1, 2015; *d* – June 1, 2016.

this reason (and also to maintain sufficient generality of the algorithm used), when considering the case of intense mixing in the summer, the effective thermal conductivity of the water layer is taken to be λ_{ef} = 300 W/(m·°C). Under the condition of absence of mixing λ_{ef} = 0.5 W/(m·°C) (conductive thermal conductivity of water). When a water body freezes in winter, the thermal conductivity of its frozen part is identical to the thermal conductivity of ice (2.2 W/(m·°C)), and mixing in the liquid phase of water is negligibly small, so the thermal conductivity of this part is assumed to be equal to the conductive thermal conductivity of water [*Gorelik, Zemerov, 2020*]. The melting of the ice cover with the beginning of the summer season occurs in a floating state [*Feldman, 1977; Pavlov, 2008; Gorelik, Zemerov, 2020*], and during this period the same assumptions regarding the values of the thermal conductivity coefficients of ice and water remain valid as during the freeze-up period.

The problem is solved numerically. The applied calculation procedure has been repeatedly tested on various problems and described earlier [*Gorelik, Khabitov, 2021; Gorelik et al., 2021*]. For verification calculations, we also used the Frost-3D computer program (academic version, License agreement of the Earth Cryosphere Institute, Tyumen Scientific Centre SB RAS with LLC "NTC Simmakers" no. D 8/20-01), as well as a version of the Q-Frost training program modified by the authors of this work.

Results of Temperature Dynamics Calculation

In the absence of a water reservoir, the embankment has a weak cooling effect on the base (Fig. 6). Figure 7 shows the calculation results in the presence of water body (shown in the right part of the figure) with its intensive mixing in the summer. The results are given at the end of the summer and winter periods in the first and fifteenth year of operation of the roadway. Compared to Fig. 6, the calculation results show a significant warming of the foundation soils on the 15th year of operation of the structure from the side of the slope of the embankment in contact with the reservoir. On the 30th year, these disturbances manifest themselves even more significantly.

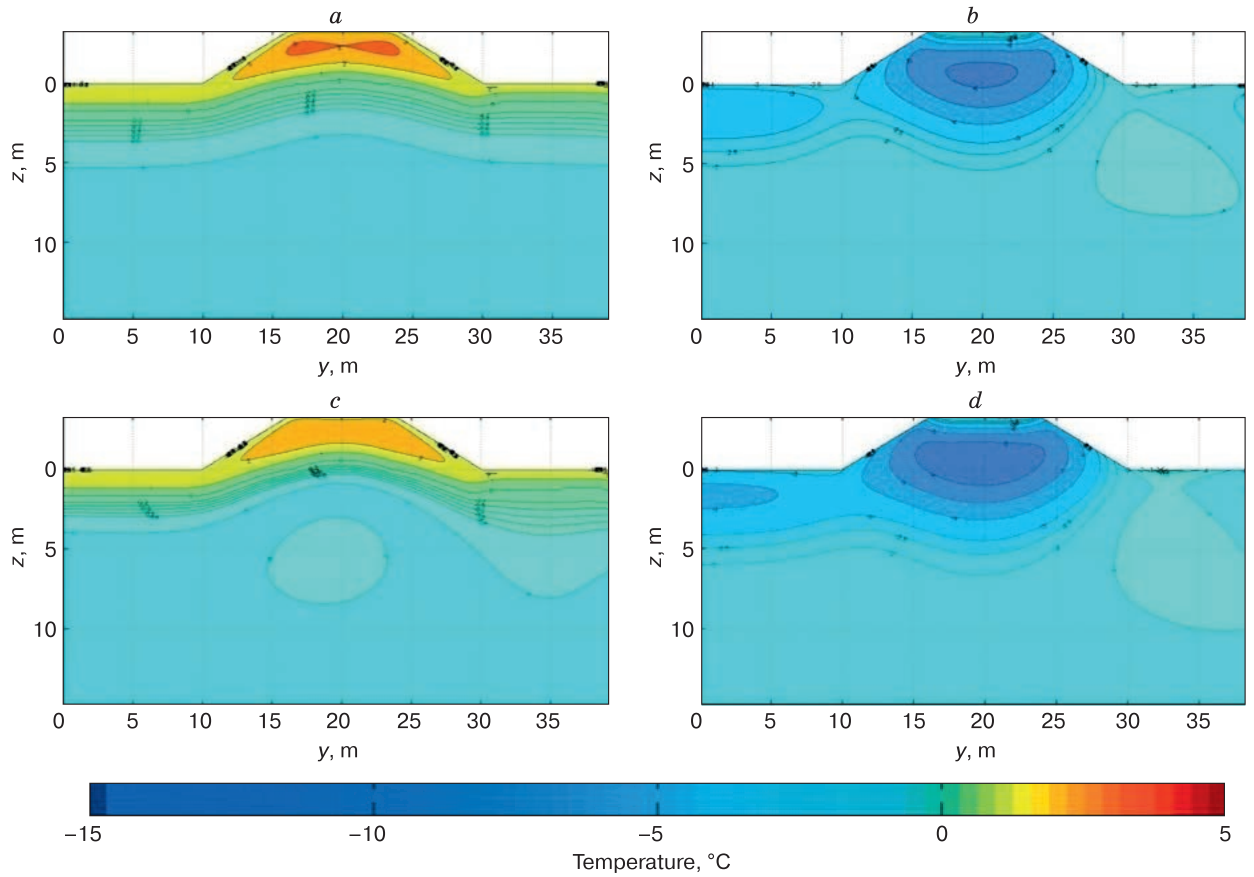

Fig. 8. Temperature field at the base of the embankment in the presence of a reservoir on the right side in the absence of mixing.

a, *b* – the first year of operation: *a* – Oct. 1, 2000; *b* – June 1, 2001; *c*, *d* – the thirtieth year of operation: *c* – Oct. 1, 2030; *d* – June 1, 2031.

In the absence of water mixing in summer, there are practically no disturbances in the 30th year of operation at the end of both the summer and winter seasons (Fig. 8).

CONCLUSIONS

The results of mathematical modeling of the formation of a temperature field in a frozen basement under a shallow water reservoir, as well as under an embankment of the roadway in the presence of inundation of one of its slopes, allow us to draw the following conclusions.

1. The general thermal interaction of the frozen base with the roadbed embankment and the water layer in contact with it is complex, and in order to ensure the correctness of the numerical modeling procedure for this process, it is advisable to first analyze the thermal effect of the reservoir on the base (as the least studied element of the overall system) with the selection of the most important factors that determine this interaction. It has been established that such factors in the problem under consideration are the depth of the reservoir and the nature of the mixing of the water layer in the summer season (Fig. 2).

2. An important preliminary assessment of the new stable thermal state of frozen soils and the relaxation time to it in the event of the appearance of a shallow reservoir on the surface of the massif is provided by an analysis of the temperature dynamics at the bottom of the seasonally thawed layer and at a depth of zero annual amplitudes of temperature, as well as their behavior during the expected period of operation of the structure. The proposed analysis method can be generalized to almost any type of changes in surface conditions of natural or artificial origin and can be useful in evaluating the efficiency of various technical measures aimed at improving the thermal state of soils during the construction and operation of structures.

3. Intensive mixing of water in a shallow reservoir occurs due to wind action and the influence of natural convection in the summer. With intensive mixing of the water layer in contact with the slope of the embankment, a significant warming of the base soils occurs. This warming occurs long before the completion of the life of the structure and can lead to partial (and uneven) thawing of the soil.

4. Prevention of the summer mixing of the water layer by any means leads stabilizes the initial temperature state at the base of the road, so that it can be maintained throughout the entire period of operation.

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