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FILTRATION AND TEMPERATURE REGIME OF A FROZEN-TYPE SOIL DAM IN THE CRYOLITHOZONE

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Abstract. In this paper, the solution of a joint temperature filtration problem is considered in relation to a soil dam in a cryolithozone. The dam is designed according to one of the principles adopted for the design and construction of structures in such climatic conditions. A description of the methodology used is given. Using the PLAXIS software package, a numerical solution to the problem was obtained, taking into account the phased construction of the structure, repair and reconstruction of the structure caused by the occurrence of an emergency situation after rapid filling of the reservoir. The obtained results of solving the temperature filtration problem revealed problems with ensuring the "frozen" regime of the structure and the need to take additional measures for this.

Keywords: cryolithozone, frozen type dam, temperature filtration problem, numerical solution, finite element method

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ФИЛЬТРАЦИОННО-ТЕМПЕРАТУРНЫЙ РЕЖИМ ГРУНТОВОЙ ПЛОТИНЫ МЕРЗЛОГО ТИПА В КРИОЛИТОЗОНЕ

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Аннотация. В данной работе рассматривается решение совместной температурно-фильтрационной задачи применительно к грунтовой плотине в условиях криолитозоны. Плотина запроектирована по одному из принципов, принятых для проектирования и строительства сооружений в таких климатических условиях. Дается описание использованной методики. С использованием программного комплекса PLAXIS получено численное решение задачи с учетом поэтапного возведения сооружения, ремонта и реконструкции сооружения, вызванными возникновением аварийной ситуации после быстрого наполнения водохранилища. Полученные результаты решения температурно-фильтрационной задачи выявили проблемы с обеспечение «мерзлого» режима сооружения и необходимости принятия для этого дополнительных мер.

Ключевые слова: криолитозона, плотина «мерзлого» типа, температурно-фильтрационная задача, численное решение, метод конечных элементов

Финансирование. Данная работа была поддержана грантом 2024 года на проведение фундаментальных и прикладных научных исследований (НИР/НИОКР) научными коллективами НИУ МГСУ, проект № 29-392/130.

INTRODUCTION

In this paper, the solution of a joint temperature filtration problem is considered in relation to an soil dam in a cryolithozone. The dam is designed according to one of the principles adopted for the design and construction of structures in such climatic conditions. A description of the methodology used is given. Using the PLAXIS software package, a numerical solution to the problem was obtained, taking into account the phased construction of the structure, repair and reconstruction of the structure caused by the occurrence of an emergency situation after rapid filling of the reservoir. The obtained results of solving the temperature filtration problem revealed problems with ensuring the "frozen" regime of

the structure and the need to take additional measures for this.

The rapid development of the territories of Russia belonging to the cryolithozone caused the need for the construction of hydraulic structures for various purposes in the second half of the twentieth century. Today, hydraulic works for water management, energy, reclamation and environmental purposes in large numbers (more than 1000) have been erected in permafrost territories [1-3]. As a rule, a hydraulic works includes a water support structure in the form of a soil dam and a spillway. The operability of an underground water supply structure in a cryolithozone is largely ensured by its temperature and filtration regime [4]. The practice of designing, erecting and operating such structures made it possible to formulate the basic principles of construction set out in the scientific literature and regulatory documents [4-7]. During the construction of groundwater dams on permafrost soils, two possible principles of the structure are accepted, the choice of which depends on the design and technological features of the dam, engineering and geocrylological conditions and the possibility of purposeful changes in soil properties [4-7].

In accordance with the 1st principle, the soils of the base are preserved in a frozen state during construction and operation, and the thawed soils of the anti-filtration elements of the dam and the base are frozen before operation and filling of the reservoir, when the effect of the filtration flow begins. The frozen state of these soils should be maintained throughout the entire period of operation [4-7]. In the practice of hydraulic engineering, such dams are called "frozen" type dams. In this case, the frozen soil mass of the dam is waterproof and performs the functions of an anti-filtration device that excludes filtration. High antifiltration and strength properties of frozen soils are the basis for ensuring the stability of frozen dams. The frozen state of the dam and foundation soils during operation can be ensured by natural freezing or artificial freezing of soils [4-7].

The second principle assumes that the permafrost soils of the base and the groundwater support structure are in a thawed or thawing state (with their preliminary thawing before the start of construction or with their possible thawing during operation) [4-7]. On the basis of principle 2, "melt" type dams are designed and erected. In this case, an obstacle to the filtration flow is an array of thawed soils – in the form of anti-filtration devices of the dam and the base, as well as part of the bottom prism. It provides filtration in the structure within acceptable limits: filtration flow, gradients and velocities do not exceed the limit values, the stability of the structure is ensured [4-7].

In practice, a soil dam is often a combination of frozen and thawed structures in separate sections of the reservoir [4-7]. The complex temperature and filtration regime of the "ground dam-base" complex should ensure both local and general filtration and static stability of the structure.

When designing groundwater dams in the cryolithozone, the main issue is the forecast of their temperature and humidity regime or their geocrylological condition. It is necessary to ensure a quasi-stable state of the soil structure array, its base and sides, ensuring the stability of the structure as a whole and its filtration efficiency. The complexity of the problem being solved is due to the need to jointly solve several interrelated tasks: temperature, filtration, determination of the stress-strain state and stability of the structure and foundation. In addition, during construction and operation, under the influence of external factors, the condition of the dam and foundation soils changes over time: a part of the soil is undergoing a transition from a thawed state to a frozen one and back. At the same time, the properties of soils change, which must be taken into account in calculations. Design miscalculations caused by errors in accounting for the temperature and filtration state of the structure can lead to an emergency situation up to its destruction [8-11].

In this paper, we consider the solution of a non-stationary joint temperature filtration problem for a soil dam in the permafrost zone. The results of the numerical solution using the PLAXIS software package are presented. An analysis and conclusions are made based on the results obtained and the forecast of the dam condition.

METHODS

The solution of the considered joint temperature-filtration problem for modeling the processes of transition of dam and foundation soils from a frozen state to a thawed state and vice versa is reduced to solving a differential equation that takes into account the processes of heat and mass transfer, taking into account the phase transitions of the soil [12-13].

$$\left(\rho_m c_{pm} + L_w \Theta \frac{\partial \Theta_u}{\partial T}\right)\frac{\partial T}{\partial t} + \rho_w c_{pw} V_x \frac{\partial T}{\partial x} = \lambda_m \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (1)$$

where T is the temperature of the medium; t is time; x, y are the coordinates of the coordinate system; ρ, c_p, λ – are density, heat capacity and thermal conductivity, respectively (the designations of the indices m and w relate to soil and water), V_x is the component of the velocity of the filtration flow, determined by the Darcy formula:

$$V_x = -K\frac{dH}{dx} \quad (2)$$

where K is the coefficient of filtration of the dam or foundation soil, H is the filtration pressure.

The value $L_w\Theta\ (\partial\Theta_u/\partial T)$ on the left side of equation (1) determines the amount of heat released or absorbed as a result of phase transitions of the soil (transition from thawed to frozen state or vice versa).The value L_w is the latent heat of melting ice, Θ is the volume content of water in the pores of the soil, $\partial\Theta_u/\partial T$ is the change in the content of unfrozen water in the pores of the soil when the temperature of the medium changes. Phase transitions occur when the temperature changes in a certain range (approximately from -1 ° C to 0 ° C).

For areas of the computational domain where there is no filtration flow, the differential equation (1) is simplified and can be written as [12]:

$$\rho_m c_{pm}\frac{\partial T}{\partial t} = \lambda_m\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (3)$$

To determine the filtration flow rates included in equation (1), it is necessary to solve the filtration problem, which for the case of water-saturated soils is described by the basic differential equation of filtration theory using known boundary and initial conditions [14-15]:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial H}{\partial y}\right) - \mu\frac{\partial H}{\partial t} = 0 \quad (4)$$

where $H=f\ (x,\ y,\ t)$ is the desired pressure function in the computational domain, varying in time t; K_x, K_y, are the filtration coefficients in the directions of the coordinate axes X, Y; μ is the coefficient of soil water recovery.

A large number of Russian and foreign researchers have devoted themselves to solving joint temperature and filtration problems, taking into account heat and mass transfer and phase transitions. Analytical methods for solving some particular problems have been used [16-18], and, especially in recent years, numerical methods using the finite difference method [19-20] and the finite element method [21-23].

Temperature and filtration calculations were carried out by the finite element method using the PLAXIS 2D software package. The calculation of filtration in a non-saturated zone is based on models describing the hydraulic behavior of unsaturated soils. When calculating in the PLAXIS 2D PC, one of the most common and proven models was used – the Van Genuchten model [24-25], the main equation of which relates water saturation to pressure as follows:

$$S(\phi_p) = S_{res} + (S_{sat} - S_{res})\left[1 + (g_a|\phi_p|)^{g_n}\right]^{g_c}, \quad (5)$$

where $\phi_p = -\frac{p_w}{\gamma_w}$ and p_w is the pore suction pressure, is the specific gravity of the pore liquid, S_{res} is the residual water saturation, which characterizes the part of the liquid remaining in the pores even with high suction, S_{sat} may be less than one, since the pores may also be occupied by gas, g_a is a parameter characterizing the amount of gas that has penetrated into the soil, g_n is a parameter characterizing the rate of water discharge from the soil, $g_c = \frac{(1-g_n)}{g_n}$ – parameter used in the general Van Genuchten equation.

Further, the paper presents some results of numerical solutions of the joint temperature filtration problem for the considered object.

RESEARCH OBJECT

The object of research in this work is a soil dam as part of a hydroelectric complex that creates a reservoir to provide technical water supply to the facilities of the Srednebotuobinsk oil and gas condensate field. The hydraulic works is located in the Republic of Sakha (Yakutia), 130 km from the city of Mirny. The climate of the area is sharply continental, characterized by long, harsh winters (from October to April) and short summers. The coldest month of the year is January with an average monthly air temperature of minus 29.7°C. On some days, the air temperature can drop to minus 60 °C. The absolute minimum air temperature was recorded in December – minus 59.6 °C. The distribution of average monthly temperatures throughout the year is shown in Table 1.

Table 2.1 Average monthly and annual air temperatures (°C)

Statiom	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Год
Dorozhniy	-29,7	-26,1	-15,8	-4,7	5,3	14,2	16,9	13,2	5,0	-5,8	-21,1	-29,0	-6,5

The annual course of soil surface temperature is basically similar to the annual course of air temperature. The lowest soil surface temperature is observed in January - February (minus 32.8 °C), the highest in July (21.7 °C).

The earthen bulk dam is designed according to the First principle of construction on an ever-frozen foundation, that is, as a "frozen" type dam. The maximum height of the dam is 14 m with a crest mark of 354 m, the width along the crest is 12 m, the length along the axis of the dam is 628 m, the laying of the upper slope is 1:3.5, the lower slope above the berm is 1:3, the laying of the lower slope below the berm is 1:2.5. The calculated transverse profile of the dam is shown in Figure 1.

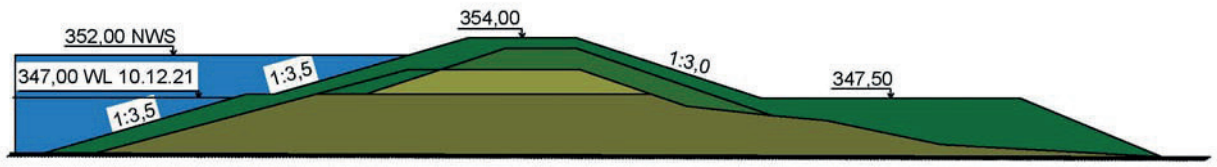


Figure 1. Calculated cross-section of a soil dam

The dam was built according to the project in 2016 and put into operation in 2017. In May 2017, 15 days after the intensive filling of the reservoir, a partial destruction of the dam occurred with the formation of a through hole 5-7 m wide. After the accident, repairs and reconstruction of the structure were carried out. The profile of the dam was increased due to additional filling of the soil. The crest of the dam is reinforced with a filling of rocky soil 0.6 m thick. From the side of the upstream, a layer of coarse-grained rocky soil with a thickness of up to 2.5 m is poured along the upper slope, which performs the function of protecting the dam body from cryogenic cracking, wave and ice effects, increases the stability of the upper slope, and also protects the heaving soils of the dam body from thawing. The side prism on the downstream side is reinforced with rock filling, 0.5 m thick. Additionally, to increase the stability of the lower slope of the dam, a berm is arranged at 346.7 m, with a width of 30.0 m. The profile of the dam before and after reconstruction is shown in Fig. 1.

PROBLEM STATEMENT

Calculations of the predicted temperature and filtration regime of the dam were performed by the finite element method using a PLAXIS 2D PC. The calculated area of one of the sections of the dam (7 in total were considered), broken down into finite elements of a triangular shape, is shown in Fig. 2.

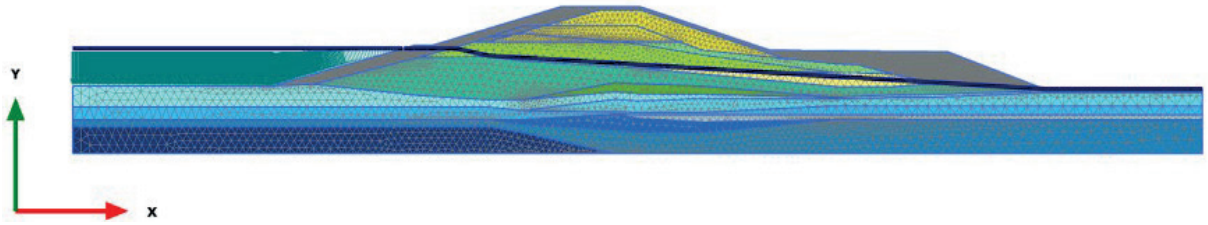


Figure 2. Computational domain of the numerical model

The physical and mechanical characteristics of the soils of the base and body of the existing dam were adopted based on the analysis of materials from engineering and geological surveys performed at the facility.

The depth of the calculated area is assumed to be equal to the depth of penetration of temperatures of an annual amplitude equal to 15 m, obtained on the basis of field observations. The width of the calculated area was selected based on the condition that it had no effect on the calculation results: an increase in the calculated area towards the upper and lower reaches from the dam profile is assumed to be twice the height of the structure.

The boundary conditions for solving the problem were set as follows. For filtration calculations on the lateral surfaces of the base and on the lower boundary of the calculated area, the condition of absence of flow along the normal to these surfaces was set: $\partial H/\partial n=0$, where H is the filtration pressure. The values of the corresponding filtration pressures were set along the surface of the base and part of the upper and lower slopes below the water levels of the upper and lower reaches.

For the non-stationary calculation of the temperature distribution, the corresponding boundary conditions were set in the model. Along the lateral boundaries of the model, a condition is assigned for the absence of heat flow normal to the surface $(\partial T/\partial n=0)$.

The lower boundary is assigned an average annual temperature value at a depth of zero annual amplitudes, equal to -0.75 ° C, taken into account in accordance with field observations at the facility. The conditions of convective heat exchange were set on the upper surface of the base and dam on contact with air, and the water temperature on contact with water. Changes in air temperature at each calculated time were taken in accordance with temperature change graphs (for air - Table 1).

When solving the problem, the process of constructing the initial profile of the dam was modeled with its subsequent reconstruction in accordance with the schedule and the scheme of phased construction.

RESULTS

As a result of calculations of the temperature and humidity regime of the dam-base system, temperature distributions in the calculated region for the corresponding time points were obtained. The time interval from the beginning of the construction of the structure was considered, including the stages of the construction of the initial profile, filling of the reservoir, discharge of the reservoir after an emergency, stages of reconstruction, refilling of the reservoir and the operational period until the end of 2025. Some results are presented in Fig. 3-5.

The temperature field of the ground dam (initial profile) and the base at the time of April 15, 2018 (after the emergency and emptying of the reservoir) is shown in Fig. 3, a. At this point in time, the dam body and base are completely frozen, the temperature ranges from -0.75 °C in the depth of the base to -4.5 °C at the surface foundations and dams.

In July 2018, after filling the reservoir to the UMO mark (347.0 m), the warming effect of water and positive air temperatures affects. This leads to the formation of a through zone of thawed soils along the surface of the calculated area with a depth of up to 2.0-2.5 meters (Fig. 3, b).

In the future, the temperature and humidity regime is formed by the constant warming effect of the reservoir and variable air temperatures throughout the year (Table 1).

Figure 4 shows the results obtained at the time points of January 15 and July 15, 2023 (before the start of reconstruction). It can be noted that the degradation of the frozen zone continues both in the ground dam and in the base under it.

After the completion of the reconstruction of the dam and filling of the reservoir to the NWS (352.0 m) in July 2024, the effect of the warming effect on the slope and the base under the reservoir remains, the depth of the thawed zone increases to 8 m. A through-thawing zone is observed in the body of the dam to a depth below the NWS.

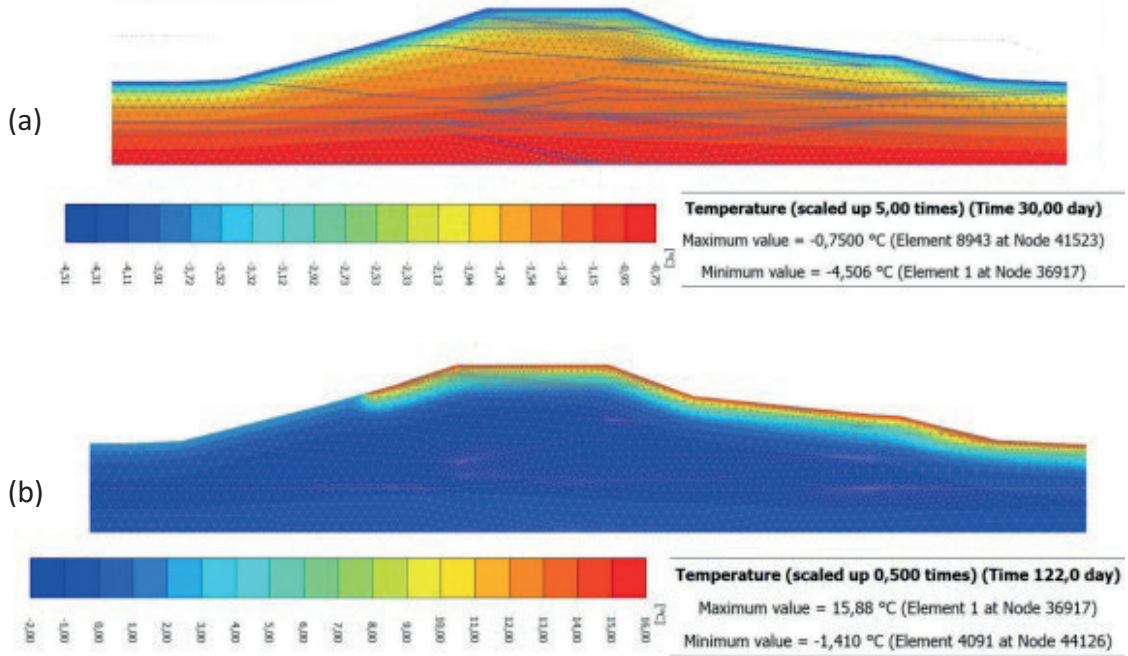


Figure 3. Temperature distribution in an underground dam in 2018: a - on April 15; b – on July 15 (after filling the reservoir to the dead storage level mark)

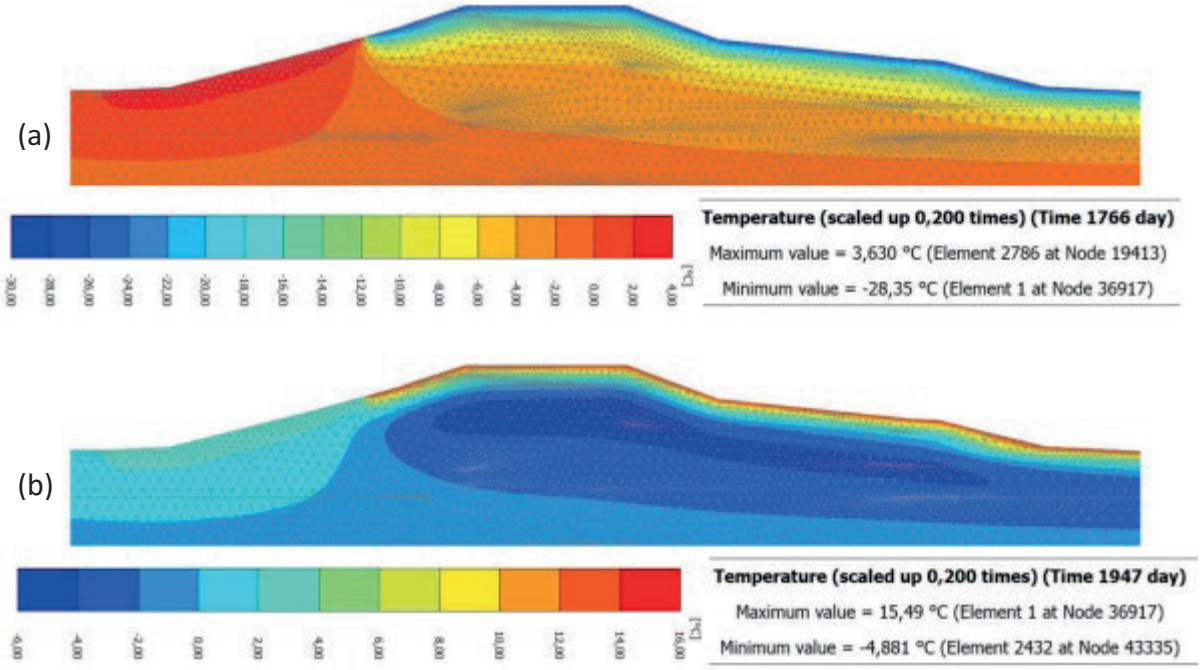


Figure 4. Temperature distribution in a soil dam in 2023: a - on January 15; b – on July 15

A similar picture has been obtained for 2025. If at the time of January 15, 2025 (Fig. 5, a) the frozen zone is restored from the base to the crest of the dam, which ensures the operability of the structure, then on July 15 (Fig. 5, b) in the zone at the crest of the dam, the thawing zone falls below the NWS mark, which violates the principle of operation of the "frozen" dam kind.

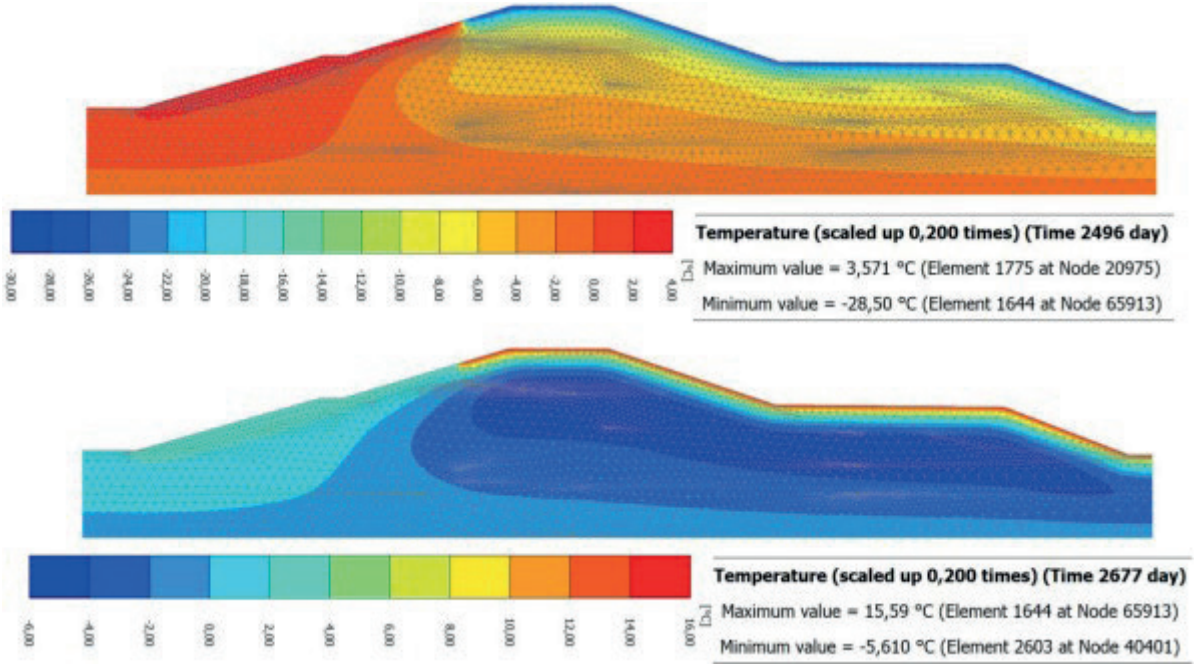


Figure 5. Temperature distribution in a soil dam in 2025: a - on January 15; b – on July 15

In the process of further operation, the situation is likely to worsen.

To ensure the necessary temperature and humidity regime for a "frozen" type dam, it is necessary to consider options for solving the problem. In particular, it is possible to propose an additional outline of the soil in the area near the crest of the dam, or the installation of a permafrost curtain, which will exclude thawing of the zone at the crest of the dam in the summer [26].

CONCLUSIONS

1. In this paper, the PLAXIS 2D software package was used for numerical modeling based on the forecast of the temperature and humidity regime of the soil dam-base system, which allowed taking into account many active factors and influences. This allowed us to get a reliable detailed picture.
2. The calculations took into account non-stationary filtration, which is based on the introduction of time-dependent hydraulic boundary conditions, water levels, non-zero time interval and filtration parameters of soils, as well as the effect of non-stationary heat flow.
3. In the temperature filtration calculation, it was assumed that there is no filtration through frozen soils. The temperature of the beginning of freezing of the soil was taken on the basis of data from engineering and geological surveys.
4. Based on the results of numerical modeling of temperature and filtration calculations, temperature distributions were obtained for the period of commencement of operation (from April 2018 to July 2023) and reconstruction of the dam from July 2023 to July 2025. Based on the results obtained, it can be concluded that a warming effect is observed during the reconstruction and initial operation of the dam from the upstream water and positive air temperatures to the upper slope of the dam and the base of the reservoir, reaching a depth of 8 m after filling the reservoir with water by 2022. and continuing until 2025.
5. The results of numerical modeling of temperature and filtration calculations showed that after filling the reservoir to the dead storage level and NWS marks in the warm season (5 months a year), a thawing zone appears in the dam body below the NWS mark, which makes it possible for water to filter freely through the dam body. Such a temperature-filtration regime is unacceptable when designing and operating a "frozen" type dam.
6. As a recommendation to ensure the necessary temperature and filtration regime, additional soil loading can be proposed in the area close to the crest of the dam, which will increase its thermal insulation, or the installation of a permafrost curtain.

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