DOI:10.22337/2587-9618-2025-21-2-116-128

NUMERICAL ASSESSMENT OF PERMAFROST DEGRADATION AND RECOVERY AND ITS IMPACT ON SOIL MASS STABILITY

Nikolay A. Aniskin, Stanislav A. Sergeev, Andrey V. Stupivtsev, Ilia A. Bokov

National Research Moscow State University of Civil Engineering, Moscow, RUSSIA

Abstract. The paper presents solutions of the unsteady temperature problem and the problem of determining the stress-strain state of the soil massif, which is a bulk construction of stacks used for gold extraction from ore by heap cyanide leaching. In the process of irrigation of the stacks with heated cyanide solution occurs, heating of the soil mass and base, which leads to the formation of a zone of thawed permafrost or the so-called talik. As a result of numerical solution of the non-stationary temperature problem taking into account the step-by-step erection of the soil massif, the impact of air temperature and irrigation solution, the temperature distribution in the massif and the base for the period from the beginning of the massif erection to the 50-year period after the end of construction was obtained. For the most dangerous moment of the end of construction, when the zone of ground thawing is maximum, the stability of the slope together with the base is evaluated using their stress-strain state. The problems were solved by numerical finite element method using PLAXIS software package.

Keywords: soil massif, temperature problem, frozen ground, thawed ground, ground thawing, numerical solution, finite element method, slope stability

ЧИСЛЕННАЯ ОЦЕНКА ДЕГРАДАЦИИ И ВОССТАНОВЛЕНИЯ ВЕЧНОЙ МЕРЗЛОТЫ И ЕЕ ВЛИЯНИЕ НА УСТОЙЧИВОСТЬ ГРУНТОВОГО МАССИВА

Н.А. Анискин, С.А. Сергеев, А.В. Ступивцев, И.А. Боков

Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ

Аннотация. В статье представлены решения нестационарной температурной задачи и задачи по определению напряженно-деформированного состояния грунтового массива, представляющего собой насыпное сооружение из штабелей, использующихся для добычи золота из руды путем кучного цианидного выщелачивания. В процессе орошения штабелей подогретым раствором цианида происходит, разогрев массива грунта и основания, что приводит к образованию зоны оттаявшей мерзлоты или так называемого талика. В результате численного решения нестационарной температурной задачи с учетом поэтапного возведения грунтового массива, воздействия температуры воздуха и орошающего раствора получено распределение температуры в массиве и основании на период с начала возведения массива до 50-летнего периода после окончания строительства. Для наиболее опасного момента окончания возведения, когда зона оттаивания грунта максимальна, дана оценка устойчивости откоса совместно с основанием с использованием их напряженно-деформированного состояния. Задачи решены численным методом конечных элементов с использование программного комплекса PLAXIS.

Ключевые слова: грунтовый массив, температурная задача, мерзлый грунт, талый грунт, протаивание грунта, численное решение, метод конечных элементов, устойчивость откоса

INTRODUCTION

Most of the territory of the Russian Federation, approximately (65-70) % according to different estimates, is located in permafrost areas. It is most widespread in Eastern Siberia. These regions play a crucial role in the development of the country's economy. This territory is home to a large number of mining enterprises that use various technologies to enrich ore and obtain metals, including precious metals. One of such methods is heap leaching, a technology that is quite simple and effective [1-7]. It includes several stages (Fig.1):

1. Ore preparation, including its crushing and grinding.
2. Preparation of the base for stacking stacks of crushed ore. Formation of a watertight screen on the sloping surface of the base for the stacks of crushed ore. As a rule, clay soils and polyethylene film are used for the screen device [8]. A drainage layer and reservoir beds for collecting enriched solutions are laid on the screen.
3. Stacking of enriched ore in the stack on the prepared impermeable base.
4. Irrigation of the stacked ore stack with a reagent (cyanide solution) [9-12]. When the solution penetrates through the thickness of crushed ore, gold is leached and carried by the filtering solution, which flows down the inclined reservoir beds and through the prepared chute into the settling pond.
5. Metal precipitation in the settling pond and its extraction [13].

The processed ore array is erected in stages in time with stack dumping. Ore stacks are irrigated, as a rule, year-round. In cold periods of the year the mortar is heated to positive temperatures. The movement of the heated solution down the dumped massif causes its heating, as a result of which a complex temperature regime of both the dumped ore massif and the adjacent base is formed in time. In the process of array construction and its irrigation there is a gradual penetration of heat flow into the base, causing an increase in the temperature of the base soil. In the case where frozen rocks are embedded in the subgrade, thawing occurs. This process gradually penetrates deep into the subgrade. This process causes phase transitions in the soils of the ore massif and the base: transition of water from the solid state - ice to liquid and from liquid to gaseous. These changes cause changes in the properties of soils: thermophysical, filtration, strength, which affects the ongoing processes. Thawing of ice contained in the pores of frozen ground increases its permeability, decreases its thermal conductivity and strength properties. Thus, in time there is a complex change of mutually influencing processes: filtration and temperature processes, formation of stress-strain state.

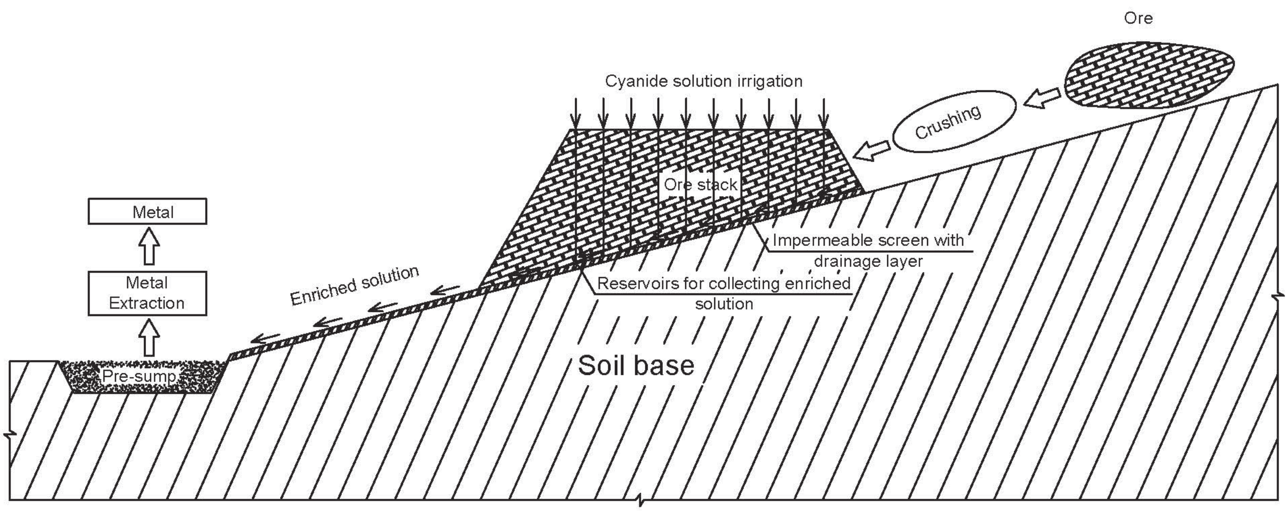


Figure 1. Schematic diagram of gold ore beneficiation process by heap leaching method

In order to assess the behavior of the system “enriched ore massif - base” it is necessary to forecast its formed temperature regime and stress-strain state. The solution of such a problem, taking into account the changes occurring in the system “ore dressing massif - base” is a rather difficult task.

The solution of non-stationary temperature problems is widespread in the field of hydraulic engineering, since the temperature regime of structures of this type has a significant impact on their operational characteristics. A considerable amount of research in the field of hydraulic engineering is devoted to studies of temperature field distribution, including filtration [14-18].

However, there are no studies of the temperature effects of the heap leach stack massif using the finite element method.

This paper presents some results on solving such a problem numerically using the finite element method. The solution is obtained using PLAXIS 2D software package. The solution allowed obtaining a detailed picture of the change in the temperature regime of the soil massif with an assessment of the degree of degradation of the permafrost base and the time of its recovery. The stability of the slope of the ore massif and the base for the most unfavorable case at the time of maximum thawing of the base was also assessed.

METHODS

The process of heat transfer in the soil massif of stacks of ore to be processed and base is considered. The soil, as it is known, is a porous medium, which consists of solid particles and pores, which can contain water in one of the possible forms: in solid, liquid or gaseous state. The process of heat transfer in a soil mass implies the accumulation of energy in all soil constituents. Quantitative assessment of the behavior of the soil mass in terms of temperature distribution can be carried out by distinguishing a number of simple processes such as: heat conduction, convection, radiation.

The main mode of heat transfer in the soil mass is heat conduction. The thermal conductivity of a soil mass is the rate at which heat energy passes a unit area of soil due to a unit temperature gradient.

The specific heat flux due to heat conduction is expressed by Fourier's law [19,20]:

$$H = -\lambda_s \frac{\mathrm{dT}}{\mathrm{dz}} \tag{1}$$

where λ_s is the thermal conductivity of a solid material; $\frac{\mathrm{dT}}{\mathrm{dz}}$ is the temperature gradient.

The solution of the temperature problem is reduced to the solution of the known equation of heat flow continuity in the design domain [19,20]:

$$\rho_s c_s \frac{\partial T}{\partial t} = -\frac{\partial G}{\partial z} \tag{2}$$

where ρ_s is the density of the solid material, c_s is the specific heat capacity of the solid material, G is the heat flux density in the soil.

The left side of equation (2) represents the rate of heat accumulation in the soil layer, and the right side represents the heat flux flow rate, or the rate of change in heat flux density with depth.

Taking into account equations (1,2), we obtain:

$$\rho_s c_s \frac{\partial T}{\partial t} = -\frac{\partial}{\partial z}\left(\lambda_s \frac{\mathrm{dT}}{\mathrm{dz}}\right) \tag{3}$$

The energy balance equation for a porous medium in a general form can be written as follows:

$$\frac{\partial T}{\partial t}\left(nS\rho_w e_w + n(1-S)\rho_v \rho_v + (1-n)\rho_s e_s\right) = -\nabla(J_{\mathrm{Aw}} + J_c) + Q_T \tag{4}$$

where e_w, e_v, e_s are the internal energy in the water, vapor, and solid phases, respectively, Q_T is the heat source (i.e., the rate of heat generation per unit volume).

In the program complex PLAXIS 2D, the input parameters are parameters for the solid part of the soil mass - for soil particles. And since the parameters determined by

geotechnical engineers are determined for the soil as a whole [21] - it is important to move from general values to private parameters for soil particles [22].
The following dependences are used for the thermal conductivity of soil in different states:
Non-porous material:

$$\lambda_{soil} = \lambda_s \tag{5}$$

Dry material:

$$\lambda_{soil} = (1-n)\lambda_s \tag{6}$$

Phase transition case:

$$\lambda_{soil} = (1-n)\lambda_s + nS[(1-w_u)\lambda_i + w_u\lambda_w] + n(1-S)\lambda_V \tag{7}$$

In other cases:

$$\lambda_{soil} = (1-n)\lambda_s + nS\lambda_w + n(1-S)\lambda_V \tag{8}$$

Where n is the porosity coefficient, S is the degree of water saturation, w_u is the unfrozen water content. Values with index i - ice properties, w - water properties, V - vapor properties.

The heat stored in the ground can be expressed as follows:
Non-porous material:

$$(\rho c)_{soil} = (\rho c)_s \tag{9}$$

Dry material:

$$(\rho c)_{soil} = (1-n)(\rho c)_s \tag{10}$$

Phase transition case:

$$(\rho c)_{soil} = (1-n)(\rho c)_s + nS[(1-w_u)(\rho c)_i + w_u(\rho c)_w] + n(1-S)(\rho c)_V \tag{11}$$

In other cases:

$$\lambda_{soil} = (1-n)(\rho c)_s + nS(\rho c)_w + n(1-S)(\rho c) \tag{12}$$

In addition to heat conduction inside the area under consideration, it is necessary to take into account temperature conditions at its boundaries. At the boundary of the design area with the atmosphere, surface heat transfer occurs, and the ground is heated to some temperature value not exceeding the air temperature. The heat transfer between the air and the ground is determined by the heat transfer coefficient, which is determined in accordance with paragraph D.3 of SP 121.13330.2019 [23] depending on the wind speed:

α_q=2,4v_a+2,3 when $v_a \le$4,6м/с;
α_q=3,4(v_a-1) when $v_a >$4,6м/с,

where v_a - is the monthly average wind speed, m/s.

При средней скорости ветра 1,5 м/с коэффициент теплообмена составляет 5,9 Вт/(м2·°С).
Using the results of the temperature problem solution, the slope stability coefficient of the design area was calculated using the method of lowering the strength characteristics (angle of internal friction, cohesion and shear strength) until failure was reached [24]. The position of the possible shear surface and the value of the stability coefficient were obtained.

RESEARCH OBJECT

The object of research in this article is the temperature regime and stress-strain state of the ground massif formed during the process of erection and operation, which consists of heap leach stacks of the gold extraction plant and the base. The facility is located in the permafrost zone. Climatic characteristics of the erection area are presented in Table 1.

Table 1. Mean monthly and mean annual air and cyanide solution temperatures

Month of the year,	1	2	3	4	5	6	7	8	9	10	11	12	Avg. year
Average monthly temperature, °C	-20,8	-18,7	-12,6	-4,4	2,0	7,7	12,5	13,5	8,6	-1,7	-13,7	-19,3	-3,9
Temperature solution °C	19,0	18,9	19,1	18,9	16,5	14,1	14,8	14,6	14,7	15,4	15,4	18,0	16,3

Ore irrigation is performed in the process of ore dumping into the stack, after formation of conventional sections. In cold periods of the year, the solutions are heated to positive temperatures before being fed for processing. Irrigation of the stack is assumed to be year-round. The temperature of the irrigation solution depends on the time of year and is presented in Table 1. The profile of the investigated structure with the stages of stack backfilling and base soils is presented in Figure 2.

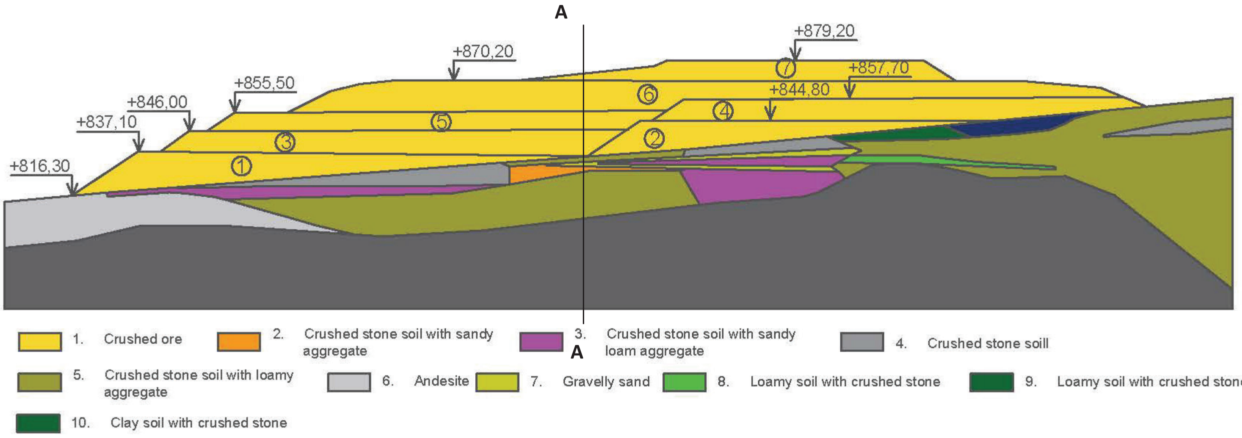


Figure 2. Profile of the investigated structure. Figures show the stage of stack placement

As part of the calculation it is accepted: the erection of the stage lasts from March to October, stacks are erected every year. Construction lasts for 7 years. The schedule of the heap leach stack construction phasing is shown in Figure 3.

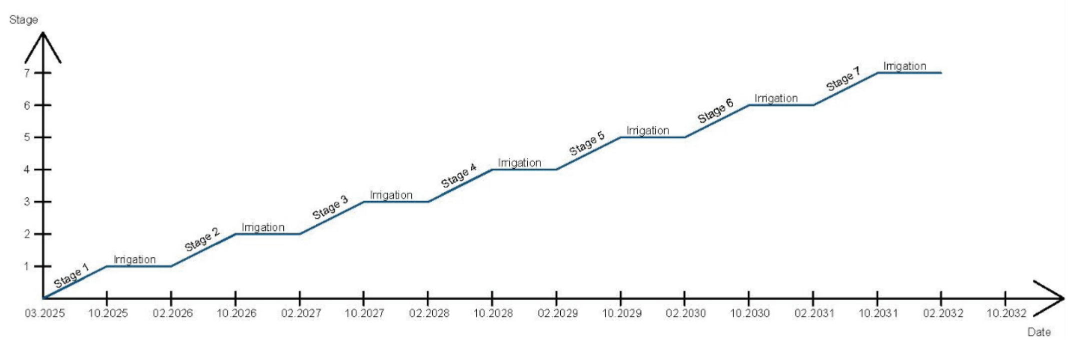


Figure 3. Heap leach stack erection schedule

Since the structures influencing the temperature regime of the ground massif in the permafrost zone require controlling the VAT taking into account the thawing zones, the results of the temperature pattern calculation are used to estimate the thawing zone in order to assess the VAT and slope stability of the heap leach stack. The forecast was performed for the period of massif erection and a period of 50 years from the end of the last stage of erection.

RESULTS

Some of the results of the studies are presented in Figs. 4-6. Fig. 4-5 show isopole patterns of the temperature of the soil massif of heap leach stacks and the base at the time corresponding to the end of backfilling and irrigation of the stacks in the middle of October (Fig. 4) and at the time corresponding to 50 years after the end of backfilling in the middle of December.

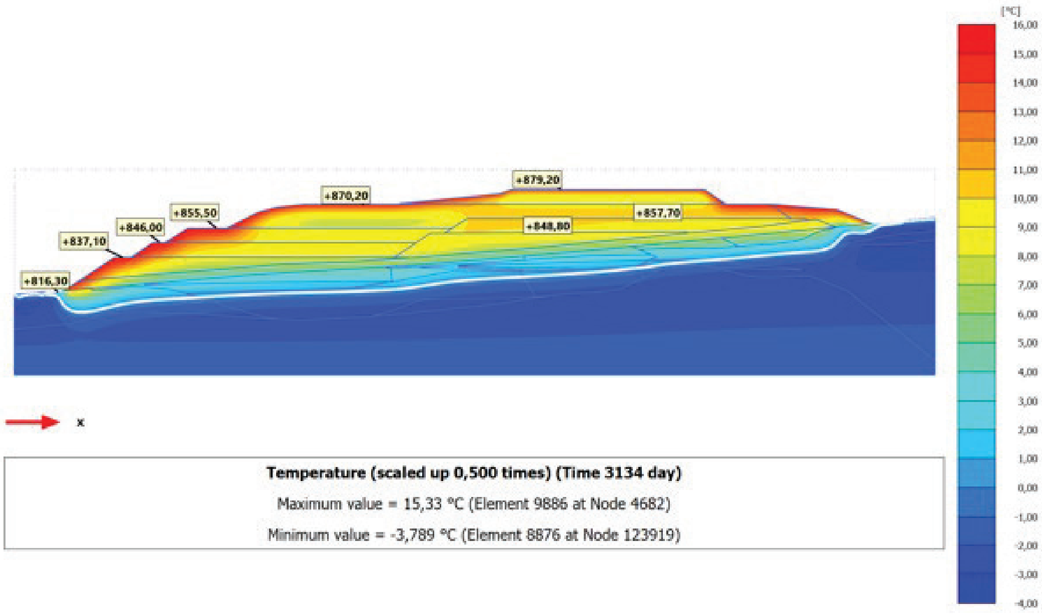


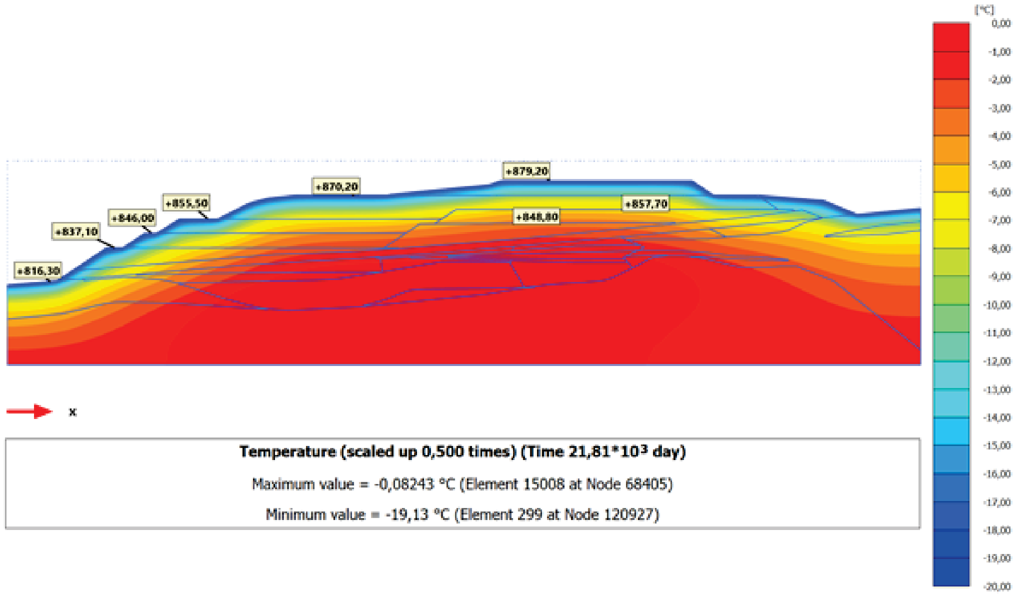
Figure 4. Isopoles of temperature distribution in the soil mass at the time of construction completion - year 7 (October)

Fig. 6 are plots of the temperature change of the considered massif along the vertical section A-A (the position of the section is shown in Fig. 2) at the moments of time 5, 10, 15, 20, 30, 40 and 50 years after the end of construction in the middle of December

The moment of the end of erection is characterized as follows (Fig. 4). Due to the irrigation of the stack array with heated mortar (in October, the mortar temperature is 15.4°C, Table 1), the surface layer of the stacks is warmed, the maximum temperature is the value of 15.3°C. At depth, the entire stack massif is heated, the temperature varies from 15°C in the upper layers to 4.0°C at the base. The base is warmed up to positive temperatures to a depth of 15.2 m. Below this depth, a frozen zone with a minimum temperature of -3.8 °C is preserved.

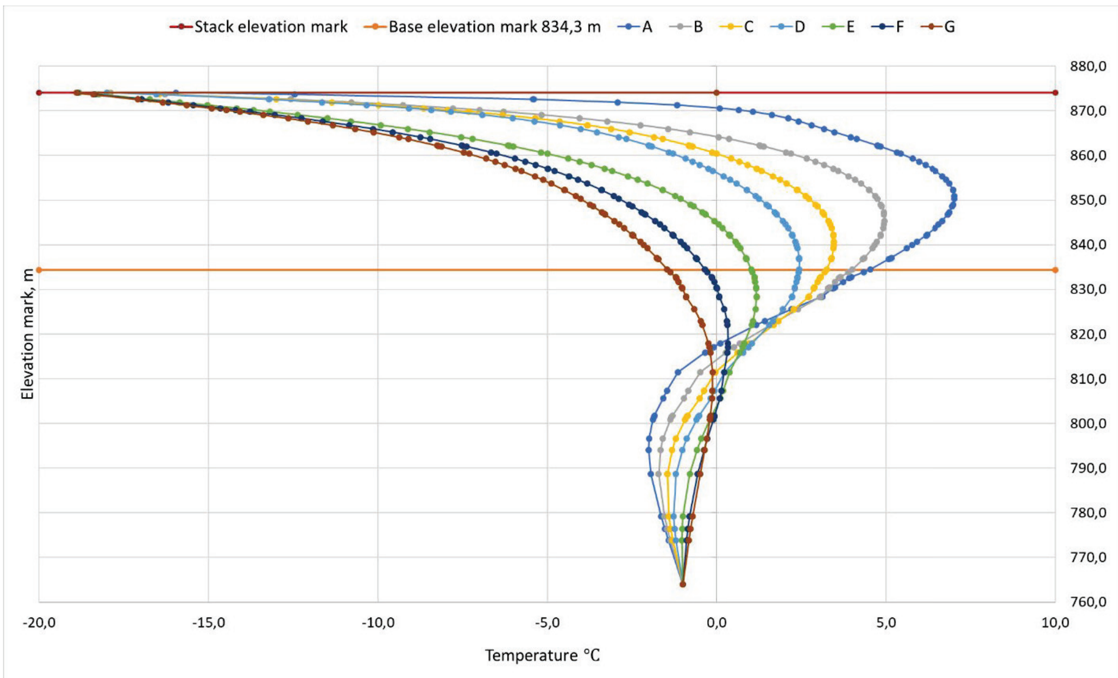
After the end of the irrigation process in October of the 7th year after the start of the array construction, the base and the stack array gradually cool down (Fig.6). In the stack massif, positive temperatures in its depth are maintained for 40 years after the end of the heap leaching process. By this time, a 34.0 m deep talik with a maximum temperature of 0.8 °C is preserved in the basement.

In 50 years after the end of the facility operation the zone of melted ground in the whole massif completely disappears (Fig. 5, 6). The maximum temperature of the base soil at a depth of 24.0 m is -0.4 °C.



<u>Figure 5.</u> Isopoles of temperature distribution in the soil mass 50 years after construction (December)

According to the results of the temperature regime calculation, the most dangerous moment from the VAT point of view is the moment when the largest part of the soil massif is in the melted state - the moment of stack erection and irrigation works completion. The VAT calculation was performed for the case of the end of construction - the greatest depth of thawing of the stack base at this moment is 15.2 m.



<u>Figure 6.</u> Temperature distribution in the soil massif of stacks along cross-section A-A: after A) 5 years, B) 10 years, C) 15 years, D) 20 years, E) 30 years, F) 40, G) 50 years after the end of construction

To assess the stability of the designed structures in the PLAXIS 2D PC, the Safety calculation [24] was used, in which the strength characteristics of the soils (angle of internal friction, cohesion and shear strength) are successively reduced until failure occurs. The results of the stability calculation are the determination of the potential shear surface, i.e. the most weakened surface along which failure may occur, and the calculated stability coefficient. The tangential shear stresses acting on this surface are maximum. The design stability factor is defined as the ratio of the actual strength to the fracture strength.

The normative criterion of slope stability is compliance with the condition of clause 5.2.2 of SP 116.13330.2012 [25]:

$$\Psi F \leq \frac{\gamma_d}{\gamma_n} R, \tag{13}$$

where F - design value of the generalized force impact on the structure or its structural elements (force, moment, stress), deformations (displacements) or other parameters for which the limit state is assessed; Ψ - load combination coefficient, γn - reliability coefficient for the responsibility of the structure, taken in calculations for the first group of limit states: for structures of responsibility level KS-2 - 1.20. The value of the normative stability coefficient k_{st} of slopes is calculated as the ratio of forces F and R:

$$k_{st}^{n} = \frac{R}{F} \geq \frac{\gamma_n \Psi}{\gamma_d}, \tag{14}$$

To ensure stability, the calculated stability factor should exceed the normative one, determined in accordance with clause 5.2.3 of SP 116.13330.2012 [25].

For structures of responsibility level KS-2 we have:

$$k_{st}^{n} = \frac{1{,}20 \cdot 1{,}00}{1{,}0} = 1{,}20$$

The result of stability assessment is presented in Fig. 7. The obtained value of the stability coefficient k_{st}=1.589 indicates a large stability reserve of the slope of the soil massif.

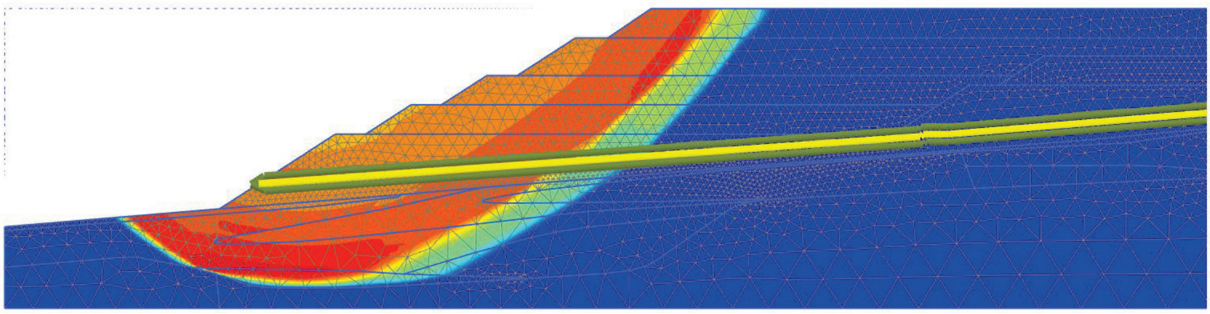


Figure 7. Sliding surface of the stack slope at the moment of erection completion with k_{st}=1.589

CONCLUSIONS

Within the framework of this work the problem of non-stationary temperature flow distribution for the heap cyanide leaching stack structure was set and solved. The solution of this problem allowed to establish thawing zones in order to correctly determine the VAT of the structure and to make a forecast for the service life of the structure.

When solving the problem, such factors as: external air temperature, temperature characteristics of the ground mass, heat transfer from cyanide solution to the stacks, heat transfer coefficient at the air-soil interface are taken into account.

Heap leach stacks are irrigated with cyanide solutions with a temperature of more than 14 °C. This factor forms a thick layer of melted soil in the body of the structure, which in the process of operation transfers heat to the underlying layers of the soil massif, thus creating a talik.

The thickness of the talik in the soil massif of the stacks and base at the time of completion of backfilling of the structure and irrigation is 50.8 meters. During the operation of the structure, the talik degrades and decreases in size. The time of full dispersion of the melted soil zone is 50 years from the end of construction.

The most dangerous situation in terms of the stability of the slopes of the structure occurs at the moment when the largest part of the soil massif is in the melted state. This situation occurs at the moment when the construction of the structure is completed. According to the results of stability calculations in the PC Plxais 2d the value of the calculated stability coefficient was obtained, which amounted to 1.589, thus the value of the stability coefficient of the stack massif does not contradict the requirements of the normative documentation.

FUNDING

This research was funded by the National Research University Moscow State. University of Civil Engineering (grant for fundamental and applied scientific research, Project No. 29-392/130).

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Aniskin Nikolay Alexeyevich, Professor, DSc, Acting Director of the Institute of Hydrotechnical and Power Engineering (IGES) of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, e-mail: Aniskin@mgsu.ru

Анискин Николай Алексеевич, профессор, доктор технических наук, исполняющий обязанности директора Института гидротехнического и энергетического строительства (ИГЭС) Национального исследовательского Московского государственного строительного университета (НИУ МГСУ), 129337, г. Москва, Ярославское ш., д. 26, e-mail: Aniskin@mgsu.ru

Sergeev Stanislav Alexeyevich, PhD, Associate Professor of the Department of Hydraulics and Hydraulic Engineering, Researcher at the Scientific and Educational Center "Geotechnics" of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, e-mail: SergeevSA@mgsu.ru

Сергеев Станислав Алексеевич, кандидат технических наук, доцент кафедры «Гидравлики и гидротехнического строительства», научный сотрудник Научно-образовательного центра «Геотехника» Национального исследовательского Московского государственного строительного университета (НИУ МГСУ) 129337, г. Москва, Ярославское ш., д. 26, e-mail: SergeevSA@mgsu.ru

Stupivtsev Andrey Vladimirovich, postgraduate student of the «Hydraulics and hydraulic engineering» department of the Institute of Hydrotechnical and Power Engineering (IGES) of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, e-mail: StupivtsevAV@gmail.com

Ступивцев Андрей Владимирович, аспирант кафедры «Гидравлики и гидротехнического строительства» Национального исследовательского Московского государственного строительного университета (НИУ МГСУ) 129337, г. Москва, Ярославское ш., д. 26, e-mail: StupivtsevAV@gmail.com

Bokov Ilia Alexeyevich, postgraduate student of the «Hydraulics and hydraulic engineering» department of the Institute of Hydrotechnical and Power Engineering (IGES) of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, e-mail: ibokov111111@gmail.com

Боков Илья Алексеевич, аспирант кафедры «Гидравлики и гидротехнического строительства» Института гидротехнического и энергетического строительства (ИГЭС) Национального исследовательского Московского государственного строительного университета (НИУ МГСУ), 129337, г. Москва, Ярославское ш., д. 26, e-mail: ibokov111111@gmail.com