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ANALYSIS OF THE DEGREE OF INFLUENCE OF INTERNAL AND EXTERNAL FACTORS ON THE TEMPERATURE REGIME OF A LOW-CEMENT CONCRETE DAM

***Nikolay A. Aniskin* [1], *Alexey A. Shaytanov* [1], *Mikhail M. Shaytanov* [2]**

[1] National Research Moscow State University of Civil Engineering (MSUCE), Moscow, Russia
[2] Lengiprorechtrans design institute

Abstract: In this paper, we consider the issue of assessing the degree of influence of the selected factors on the temperature regime and the thermally stressed state of a concrete gravity dam being built from low-cement concrete for several possible construction scenarios. The studies were carried out in relation to the design and conditions of the construction area of the Pskem hydroelectric complex in the Republic of Uzbekistan. Variation factors were: cement consumption in the mixture, the initial temperature of the concrete mixture, the heat release of cement, the thickness of the laid concrete layer, the month of commencement of work. The environmental factors were the variable ambient temperature during the year by months and the influence of solar radiation. The calculations were carried out taking into account the seasonality of the moment the construction of the structure began. 2 options were considered: autumn-winter with concreting of the zone at the base of the dam from September to February inclusive; spring-summer with concreting of this zone from March to August inclusive. In addition, options were considered taking into account additional heating from exposure to solar radiation and without it. The studies were carried out using the methodology of experiment planning in the search for optimal solutions (method of factor analysis). The numerical experiment was carried out on the basis of the finite element method using the ANSYS software package. Using the method of factor analysis, the influence of the main acting factors on the temperature regime of a gravity dam made of rolled concrete was studied. A variant of a combination of factors is proposed to obtain the most favorable temperature regime. Regression equations are obtained for predicting the temperature regime of concrete gravity dams being built from low-cement content concrete. The results of studies using the factor analysis technique can be used in the design of concrete dams from rolled concrete.

Keywords: concrete gravity dam, low-cement content concrete, numerical studies, temperature regime, thermal stressed state, factorial analysis, experiment planning theory

АНАЛИЗ СТЕПЕНИ ВОЗДЕЙСТВИЯ ВНУТРЕННИХ И ВНЕШНИХ ФАКТОРОВ НА ТЕРМОНАПРЯЖЕННОЕ СОСТОЯНИЕ ПЛОТИНЫ ИЗ МАЛОЦЕМЕНТНОГО БЕТОНА

***Н.А. Анискин* [1], *А.М. Шайтанов* [1], *М.В. Шайтанов* [2]**

[1] Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ
[2] Проектно-изыскательский институт «Ленгипроречтранс»

Аннотация. В настоящей работе рассмотрен вопрос оценки степени воздействия выбранных факторов на температурный режим и термонапряженное состояние плотины из малоцементного бетона при помощи методики факторного анализа для нескольких возможных сценариев учета. Исследования проводились применительно к конструкции и условиям района строительства Пскемского гидроузла в Республике Узбекистан. Факторами варьирования являлись: расход цемента в смеси, начальная температура бетонной смеси, тепловыделение цемента, толщина укладываемого слоя бетона, месяц начала работ. Факторами внешней среды являлись переменная температура окружающей среды в течение года по месяцам и влияние солнечной радиации. Расчеты проведены с учетом сезонности (2 сезона: осенне-зимний с сентября по февраль включительно; весенне-летний с марта по август включительно) для двух вариантов: с учетом дополнительного разогрева от воздействия солнечной радиации и без него. В результате было определено суммарное температурное воздействие на поверхности возводимого сооружения (среднемесячная температурой окружающей среды совместно с нагревом от солнечной радиации). Основываясь на полученных результатах, были сделаны выводы о вкладе каждого из вышеперечисленного факторов в температурный режим и термонапряженное состояние рассматриваемого сооружения, а также получены уравнения регрессии, позволяющие определить значения искомых показателей в заданных характерных точках, распределенных по сечению плотины. Уравнения применимы для любых массивных плотин из малоцементного бетона с шириной подошвы не менее 20 м, расположенных в любых климатических условиях.

Ключевые слова: бетонная гравитационная плотина, малоцементный бетон, численные исследования, температурный режим, термонапряженное состояние, факторный анализ, теория планирования эксперимента

INTRODUCTION

Forecasting the temperature regime of a gravity dam made of rolled concrete during construction and operational periods is necessary at the design stage of the construction. The solution of this task is rather complicated due to numerous functioning and changing in time factors. The issues of predictive modelling of the temperature regime and thermally stressed state of gravity dams have been considered in a number of works in Russia as well as abroad [1-12]. In recent years there have been significant changes in solving this issue, connected with the development of massive concrete dams' construction technologies as well as calculation methods allowing to take into account various acting factors. Nevertheless, temperature regime control and thermally stressed state of building remain topical today. This article represents results of a temperature regime and thermally stressed state of the gravity dam made of low-cement rolled concrete. The analysis of degree of influence of selected factors on temperature regime and thermally stressed state of the dam is carried out using the method of factor analysis [13-14].

Several possible scenarios for determination and evaluation of influence degree of various factor on stress-deformed state of the building. The calculations were carried out taking into account the seasonality of pouring concrete: starting in March and in September. The effect of solar radiation on the temperature regime is considered in detail. The calculations are provided for two variants: taking into account additional heating of the surfaces of the constructed structure from the influence of the solar radiation and not taking these into account. The solution of the problems of determining the temperature regime and thermally stressed state of the considered variants was obtained using the ANSYS software package on the basis of the finite element method [15-21].

A mathematical model of the structure, which makes it possible to predict the temperature regime and the thermally stressed state of the structure, was obtained from the results of the research. The best and the worst variants of value combinations of the considered factors from the point of view of the temperature regime of the structure were determined.

1. METHODS

1.1. Theoretical basis for solving the temperature problem

Numerical modelling of the temperature nonstationary problem taking into account heat emission by hydration of the cement is based on the solution of the well-known equation of thermal conductivity theory [1-6]:

$$k\nabla^2 T + Q = \rho c \frac{\partial T}{\partial \tau}, \qquad (1)$$

where: T – temperature function, ^{0}C; k – thermal conductivity of material, m^2/s; c – material specific heat capacity, kJ/kg·$^\circ$C; ρ – density of

material, kg/m^3; Q – heat released during hydration, kJ/m^3; τ - time, days.
The equation (1) can be written the following way:

$$\frac{k}{c\rho}\nabla^2 T+\frac{Q}{c\rho}=\frac{\partial T}{\partial \tau}, \quad (2)$$

The amount of heat released in the hydration process is defined as:

$$Q = C \cdot E, \quad (3)$$

where: C – cement consumption per cubic meter of concrete, kg/m^3; E – maximum heat release of cement, kJ/kg). Thus, the solution of the temperature problem for a constructed concrete block with thermal insulation of surfaces is reduced to the solution of the basic differential equation of the theory of heat conduction with internal heat sources (2). A boundary condition of the 3rd kind (convective heat exchange) was considered as the limiting condition on the border of the structure.
The heat release of cement was taken into account using the known dependence for the isothermal process (4) [8-9,12,18-19]:

$$Q = Q_{max} \cdot [1-(1+A_t \cdot \tau)^{-0,833}], \quad (4)$$

where: $A_t -$ coefficient of heat release rate (5):

$$A_t = A_{20} \cdot 2^{\frac{t-20}{\varepsilon}}, \quad (5)$$

where: $\varepsilon = 10\ °\mathrm{C},\ A_{20} -$ coefficient of heat release rate at 20 °C [8-9,12,18-19,21].

2. OBJECT OF STUDY

As the object of study, a concrete gravity dam with a height of 197 m made of rolled concrete was considered, designed for the Pskem hydroelectric complex (Republic of Uzbekistan), the site of which is located in the mountains of the Western Tien Shan. The average heights in the construction area there vary between 2 000 m – 4 400 m and decrease from the source to the outlet.

2.1. Climatic conditions of construction area of the facility

The climate of the construction area is characterized by an average annual air temperature of 9,5 ºC. The average long-term air temperature of the coldest month falls on January – minus 3,2 ºC, the warmest – on August – plus 24,4 ºC. The distribution of average monthly temperatures throughout the year is presented in Table 1 and Figure 1 (curve without solar radiation). The data were obtained for the observation period from 1938 to 2016.

Table 1. Average monthly and average annual temperatures in the area of the object

Characteristic	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Avg. year*
Average monthly temperature ºC	-4,0	-2,0	3,0	11,0	16,0	21,0	24,0	24,0	19,0	11,0	4,0	-1,1	9,5
Concrete surface temperature taking into account solar radiation, ºC	3,5	10,1	18,1	29,6	33,5	36,2	41,2	40,9	35,4	25,8	13,4	5,9	23,5

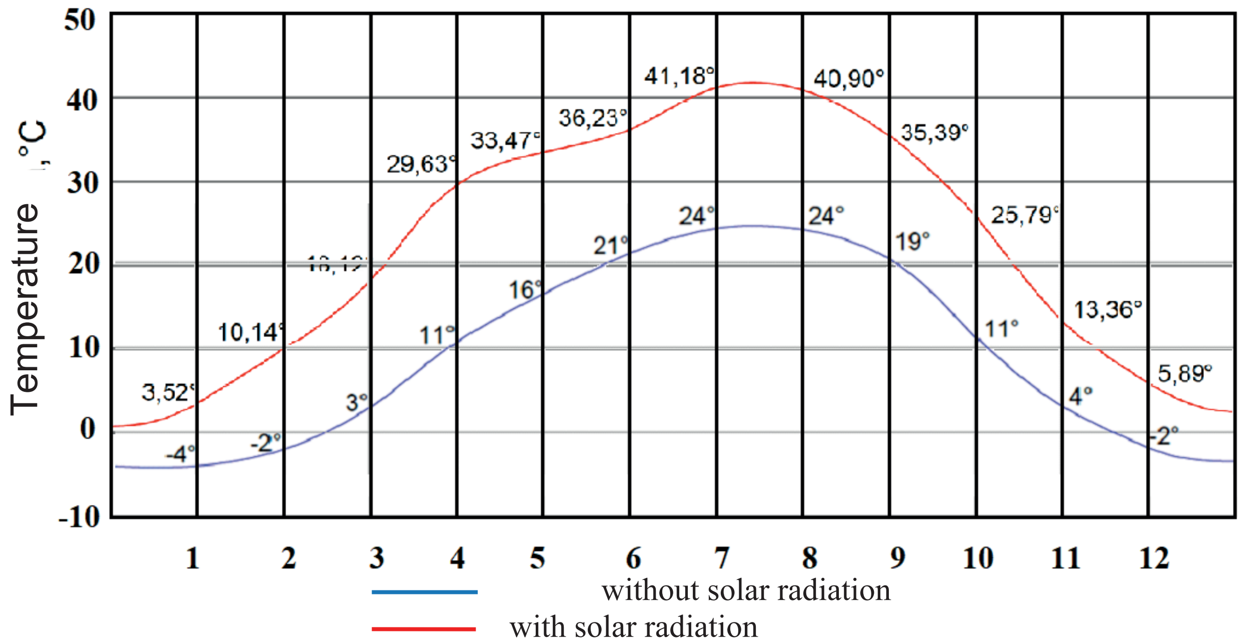


Figure 1. Graph of changes in in the average monthly air temperature in the construction area

The climate in the dam site area is characterized by a large number of sunny days in the year – 250. Therefore, solar radiation was considered as one of the factors influencing the formation of temperature regime of the construction.

The issue of solar radiation effect on the temperature regime of concrete dams in construction and operational periods and the development of a methodology for accounting for this effect has received relatively little attention to date. The works of domestic researchers [1,5-6,8-9,12] contain a number of indications on the need to take into account solar radiation when calculating the temperature regime of concrete constructions. The usual approach, used in hydrotechnical practice is usually to increase the temperature on the construction surface exposed to sunlight using the dependence [22-24]:

$$t_n = t_в + R/\alpha_n, \tag{6}$$

where $t_в$ – air temperature, R – amount of radiant hear absorbed by a unit surface per unit time; α_n – coefficient of heat transfer at the contact of the structure with air.

For the climatic conditions in Russia the average daily value of the surface temperature due to solar radiation R/α_n varies within (4-10) °C [22-24].

The papers [22-24] propose to use some average parameters of thermal heating from solar radiation S_0, $kJ/(m^2 \cdot h)$ depending on the latitude of the considered point of the Earth and the month of the year, obtained on the basis of meteorological observation data.

The value of heating from solar radiation for a day with variable cloudiness can be determined from the dependence:

$$S = S_0 \cdot (1 - k_1 \cdot n), \tag{7}$$

where S – the amount of solar radiation heat on a day with variable cloudiness; S_0 - the amount of heat of solar radiation on a sunny day; n – the cloudiness coefficient; k_1 – coefficient taking into account the latitude.

One of the first objects where much attention was paid to the study of the solar radiation influence was the high concrete dam of the Toktogul hydroelectric power station in the Republic of Kyrgyzstan, where the summer period is characterized by high solar activity.

The determination of solar radiation effect on the temperature regime of the dam on this site was carried out on the basis of data from field actinometric observations directly at the construction site. At the same time, the impact of the scattered solar radiation was assumed to be directly proportional to the impact of direct solar radiation, which led to a decrease in accuracy of the assessment results.

The study of this issue was actively carried out by Chinese researchers in relation to transport facilities [22-24]. In particular, an issue of solar radiation's impact on the temperature regime of bridge supports was considered. However, such facilities are not as massive as concrete dams, which results in more intensive cooling of the structure due to convective heat transfer. The ability of the surfaces of concrete masses to absorb solar energy also needs additional study.

The solar radiation impact will be especially significant for the high gravity dam of rolled concrete considered in this paper. In this case due to the intensive rate of concreting and erecting the structure in fairly thin layers (from 0,5 to 1,5 m) the degree of solar radiation impact on the formation of the temperature regime increases.

The modern approach to assessing the impact of solar radiation, conducted in this paper, allows to take data from both field and satellite observations into account as well as determine the amount of absorbed solar energy and heating of concrete mass connected to it according to seasonality and the terrain around the building site.

The radiation regime of the surfaces under consideration when erecting the dam made of low-cement concrete (the surface of the pressure and downstream faces, the horizontal face of the laid layer) is formed by radiant energy flows. The total solar radiation affecting during the day on a horizontal surface is determined by the formula (8):

$$G = J \cdot sinh_0 + D, \tag{8}$$

where J – intensity of direct solar radiation, W/m^2, determined by means of satellite/field actinometric observations [1]; D – diffused solar radiation, W/m^2, h_0 – angular height of the sun, degrees, determined by the dependence (9):

$$sinh_0 = sin\varphi \cdot sin\delta + cos\varphi \cdot cost \cdot cos\delta, \tag{9}$$

where $\varphi -$ the latitude of the construction area; $\delta -$ declination of the sun, deg; $t -$ hour angle, deg.;

The calculation of the characteristics of solar radiation was conducted taking into account the peculiarities of the location of the hydroelectric complex and the terrain around the site selected specifically for the construction. On Fig. 2 below is a graph for determining the angular height of the sun above the horizon and the solar azimuth, built taking into account the terrain.

As the result the temperatures on the concrete surface of the gravity dam under construction were determined, considering its increase from solar radiation effects by months of the year.

The obtained results are presented on Fig. 2 and Table 1. A significant increase in temperature on the surface due to solar radiation can be noted: for example, it is 17,2 ºC in July.

Data obtained as a result of calculating solar radiation impact temperatures on the surface of concrete structure by months were used in calculating the temperature regime at the next stage.

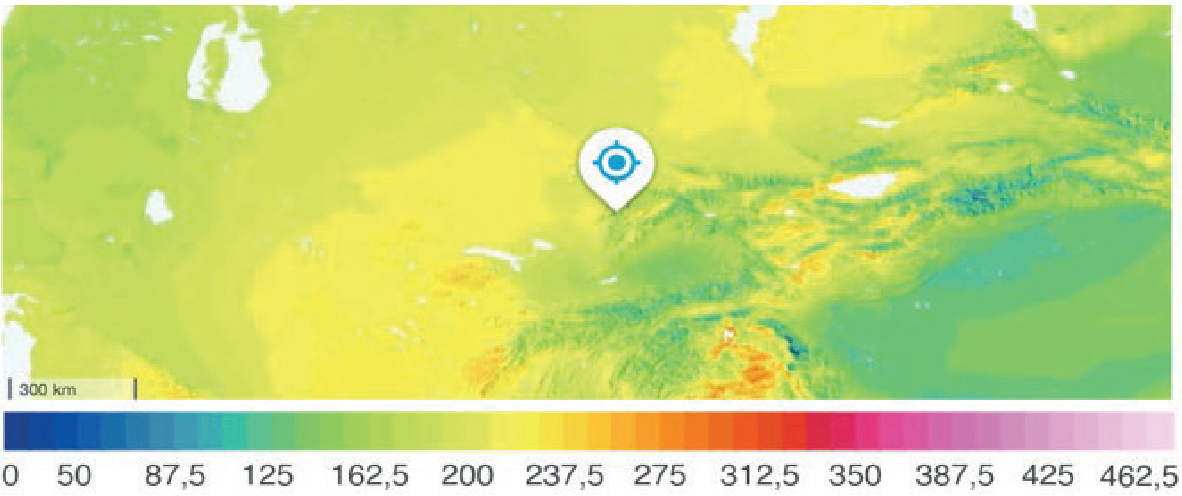


Figure 2. Map of the intensity impact of direct solar radiation, kW/m² in the construction area of the Pskem HPP

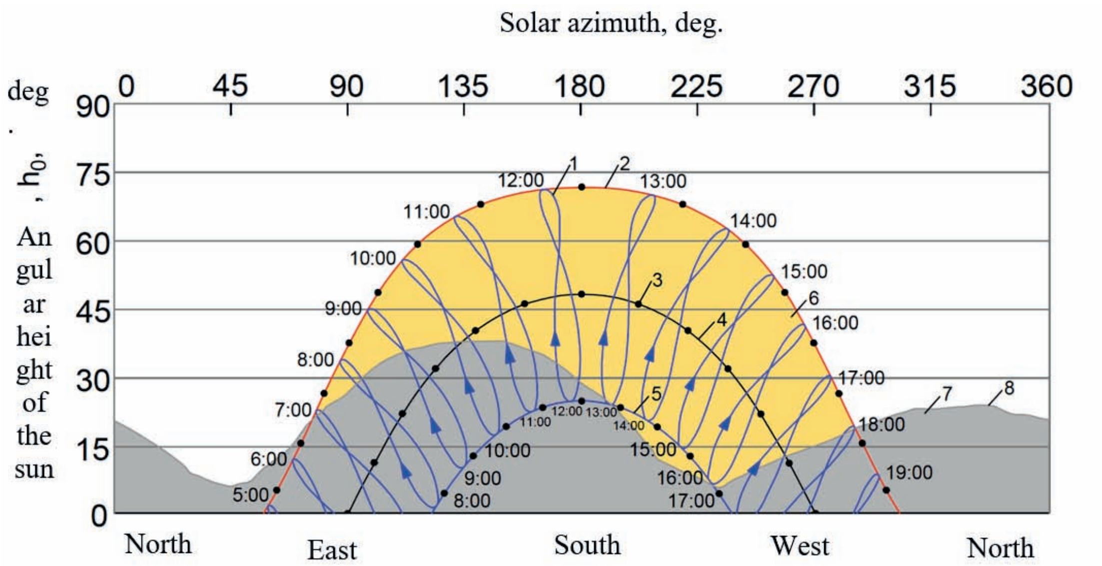


Figure 3. Graph of the change in the angular height h_0 and solar azimuth, where: 1 – local time in the construction area (time zone of Tashkent, Uzbekistan, UTC+05:00); 2 – the movement of the sun on the summer solstice day on 21.06.2021; 3 – true solar time; 4 – the movement of the sun on the spring/autumn equinox day; 5 – the movement of the sun on the winter solstice day on 21.12.2021; 6 – zone of active solar impact; 7 – shading caused by the surrounding terrain; 8 – the contour of the surrounding terrain at the construction site

2.2. Statement of studies using factor analysis.

The main task of studying the temperature regime of a low-cement concrete dam, the results of which are presented in this paper, is to analyze the degree of influence of the selected factors, to assess their favorable or unfavorable effect on the structure. Based on the obtained mathematical model of the temperature regime, recommendations will be developed to achieve a favorable temperature distribution in the structure and a combination of acting factors will be determined to ensure the optimal solution. It must be optimal technologically and economically and meet the stated requirements for the reliability and structural safety. The issues of predictive modeling of the temperature regime and the thermally stressed state of concrete gravity dams were considered in a number of works performed at NRU MGSU, JSC "VNIIG named after B.E. Vedeneev", in the branch of JSC "Institute Hydroproject" – "NIIES" and other organizations [1-12,16-17,22-24]. Within the framework of this work, numerical studies were performed using the ANSYS software package using the finite element method [15-24]. The result of the work is a mathematical model of the structure, which makes it possible to predict the thermally stressed state of the structure and ensures maximum project efficiency. The analysis of the degree of influence of the selected factors on the temperature regime and the thermally stressed state of the low-cement concrete dam was carried out using the factor analysis technique [13-14]. Several possible scenarios are considered for accounting and assessing the degree of influence of various factors on the stress-strain state of a structure. The calculations were carried out taking into account seasonality (2 seasons: autumn-winter including the September – February period; spring-summer including the March to August period). The effect of solar radiation on the temperature regime is considered in detail. The calculations were carried out for two options: with and without additional heating from exposure to solar radiation.

As an object of study, a gravity dam made of rolled low-cement concrete with a height of 197 m was considered. Fig. 4 presents the cross-section with the position of control points intended to establish temperature values. The formation process of the temperature regime in the process of layer-by-layer construction, filling the reservoir and the start of the operational period (the first year after the completion of construction) was considered.

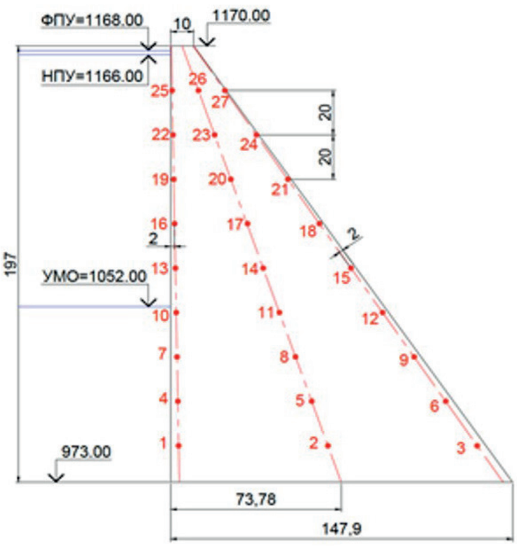


Figure 4. Cross-section of the dam with indication of control points

To create a predictive model for the temperature regime of a gravity dam made of rolled concrete, we used the experimental planning technique [13-14]. To carry out computational studies, the following factors were chosen that affect the formation of the temperature regime: cement consumption (X_1); thickness of the laid-out layer (X_2); heat generation of cement (X_3), temperature of the laid-out concrete mixture (X_4). The selected intervals of factor variation are presented in Table 2.

Table 2. Intervals of factor variation

	Factors of variation	*Factor designation*	*Values*	
			Minimum	*Maximum*
1.	Consumption of cement in the mixture (kg/m^3)	X_1	70	150
2.	Thickness of the laid-out concrete layer (m)	X_2	0,5	1,5
3.	Heat generation of cement (KJ/kg) Q_{28}/Q_{max}	X_3	293/339	335/388
4.	Concrete placement temperature (°C)	X_4	10	30

The heat emission rate of cement was chosen for the most widely used types in the manufacture of low-cement concrete mixes. This choice is associated with a faster build-up of strength, which allows one to speed up the construction of the structure. Calculations in accordance with the compiled planning matrices for the selected factors were performed for the following options:

1. Depending on the month of commencement of construction works: May or October with the corresponding ambient temperatures;
2. Depending on the consideration of solar radiation, the variable temperature of the concrete surface was assumed to be equal to the temperature or the ambient temperature. The following values obtained during the entire considered time period were selected as responses:
    1. Absolute maximum temperature in the concrete array (with indication of the location of the corresponding point), □C;
    2. Maximum temperatures at characteristic points No. 2, No. 8, No. 14, No. 20, No. 26 (Fig. 4), □C.
    3. Maximum temperature gradient between a point in the center of the array and a point on the surface of the pressure face, indicating the corresponding points, □C.

3. RESULTS OF THE STUDY

Let us consider some of the obtained equations and analyze the results obtained from the solution of the temperature problem.

Option 1. Beginning of concreting in May without taking solar radiation into account.

$$y_{i(T_{max})} = 34{,}544 + 4{,}33 \cdot x_1 - 0{,}818 \cdot x_2 + 0{,}787 \cdot x_3 + 2{,}707 \cdot x_4 - \\ -0{,}067 \cdot x_1 \cdot x_2 + 0{,}312 \cdot x_1 \cdot x_3 + 1{,}782 \cdot x_2 \cdot x_4 \qquad (10)$$

Option 2. Beginning of concreting in October without taking solar radiation into account.

$$y_{i(T_{max})} = 34{,}541 + 4{,}334 \cdot x_1 - 0{,}821 \cdot x_2 + 0{,}79 \cdot x_3 + 2{,}71 \cdot x_4 - \\ -0{,}064 \cdot x_1 \cdot x_2 + 0{,}307 \cdot x_1 \cdot x_3 + 1{,}785 \cdot x_2 \cdot x_4 \qquad (11)$$

Option 3. Beginning of concreting in May, taking solar radiation into account.

$$y_{i(T_{max})} = 47{,}9 + 3{,}396 \cdot x_1 - 2{,}987 \cdot x_2 + 0{,}695 \cdot x_3 + 1{,}619 \cdot x_4 - \\ -0{,}876 \cdot x_1 \cdot x_2 + 0{,}317 \cdot x_1 \cdot x_3 + 0{,}845 \cdot x_1 \cdot x_4 - 0{,}105 \cdot x_2 \cdot x_3 + 0{,}919 \cdot x_2 \cdot x_4 + \\ +0{,}089 \cdot x_3 \cdot x_4 + 0{,}855 \cdot x_1 \cdot x_2 \cdot x_4 + 0{,}101 \cdot x_2 \cdot x_3 \cdot x_4 \qquad (12)$$

Option 4. Beginning of concreting in October, taking solar radiation into account.

$$y_{i(T_{max})} = 47{,}9 + 3{,}376 \cdot x_1 - 2{,}976 \cdot x_2 + 0{,}695 \cdot x_3 + 1{,}62 \cdot x_4 - \\ -0{,}884 \cdot x_1 \cdot x_2 + 0{,}313 \cdot x_1 \cdot x_3 + 0{,}865 \cdot x_1 \cdot x_4 - 0{,}092 \cdot x_2 \cdot x_3 + 0{,}908 \cdot x_2 \cdot x_4 + \\ +0{,}089 \cdot x_3 \cdot x_4 + 0{,}863 \cdot x_1 \cdot x_2 \cdot x_4 + 0{,}089 \cdot x_2 \cdot x_3 \cdot x_4 \qquad (13)$$

Analyzing the equations obtained from the solution of the temperature problem, we can draw the following conclusions:

– All the selected factors have a significant effect on the maximum temperatures at the selected points. This is most influenced by the cement consumption (factor X_1), the thickness of the laid concrete layer (X_2) and the temperature of the concrete mix (X_4). An increase in cement consumption up to 150 kg/m^3 (the maximum value of factor X_1) leads to an increase in the temperature in the concrete array by ~ (8-12) □C compared to the minimum considered consumption of 70 kg/m^3.

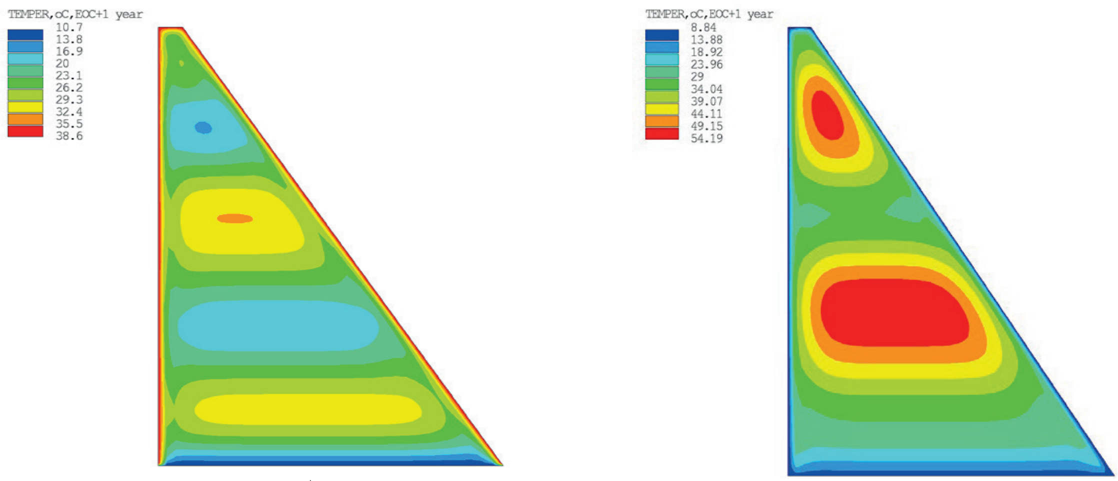
– The degree and sign of the influence of the factor X_2 (thickness of the laid-out concrete layer) has a different effect depending on the laying zone, the seasonality of laying and whether solar radiation is taken into account. In the case when solar radiation is not taken into account and the concreting is begun in May (option 1), in the massive zones of the dam, with an increase in the thickness of the layer of laid concrete, the temperature of the concrete array decreases (the coefficients of the regression equation with a X_2 are negative). However, for this case, the result changes in the near-ridge zone (point 26), where the reverse result is obtained: with an increase in the layer thickness, the temperature increases. At the beginning of concreting in October (option 2), the result is reversed: in the lower massive part of the dam, an increase in the layer thickness leads to an increase in temperature, and vice versa in the zone near the crest.

– For options with taking solar radiation into account (options 3, 4), in most areas of the dam, with an increase in the thickness of the layer, the temperature of the array decreases, which is explained by a decrease in the degree of solar heating for thick layers. An exception here is the zone near the base (point 26) for option 4, which is explained by the influence of low air temperature in the autumn-winter period of the year, when this zone is concreted. When laying out in thin layers, the concrete is intensively cooled by cold air.

– For the considered climatic conditions, taking into account solar radiation makes a significant contribution to the increase in the temperature heating of the structure during its construction. The impact of solar radiation causes an increase in temperature in the concrete array at a maximum of (15-16) □C□

– The choice of the start of dam construction (the options for starting work in May and October are considered) determines the formation of the temperature regime in the most problematic zone of the structures, that is, the one near the contact of the dam with the foundation. Thus, the start of concreting in May leads to an increase in temperature in the area of the dam close to the base by ~ (16-17) □C compared to the option of starting concreting in October.

Based on the results obtained, the worst and the best-case scenarios were determined in terms of the temperature regime of the structure. The degree of heating of the concrete array was considered as an evaluation criterion. The least favorable is the option with the following values of the factors and conditions of construction: cement consumption – 150 kg/m^3, layer thickness – 0,5 m, heat release is increased, initial temperature of the concrete mixture +30 □C, start of work in October, solar radiation is taken into account. The most favorable option corresponds to the following values of the factors: cement consumption – 70 kg/m^3, layer thickness – 1,5 m, heat release is moderate, initial temperature of the concrete mixture +10 □C, with the start of work in May and taking solar radiation into account. The temperature distribution for these options is shown in Fig. 5.



a) *b)*

Figure 5. The results of calculating the maximum temperature in the concrete array: a) the most favorable design case; b) the least favorable design case

The resulting mathematical model of the temperature regime of a gravity dam made of rolled concrete can be used to predict the temperature regime of similar structures and to select the optimal combination of the considered factors. At the next stage of research, the results of solving temperature problems were used to calculate the stress-strain state.

4. CONCLUSIONS AND DISCUSSION

We have presented the practical application of the technique for determining the effect of solar radiation on the temperature regime of the low-cement concrete dam of the Pskem hydroelectric power plant, taking into account the shading of the terrain. Such an impact increases the average annual temperature of the concrete surface by 13,98 ºC or by 147,16%, which is a significant factor that must be taken into account when designing such structures in similar climatic conditions. In the considered example solar radiation causes an increase in temperature in the concrete array, depending on the considered point, by 53,72% – 89,5% (from 8,46 □C – 16,14 □C). Based on the results of variational calculations, the most and least favorable design cases were determined in terms of the temperature regime of the dam. The worst case is the one with the following values of the factors: cement consumption – 150 kg/m^3, layer thickness – 0,5 m, heat release is increased, initial temperature of the concrete mix +30 □C, start of work in October. The most favorable is the case with the following values: cement consumption – 70 kg/m^3, layer thickness – 1,5 m, heat release is moderate, initial temperature of the concrete mixture +10 □C, work begins in May.

Based on the results of the calculations, regression equations were obtained that make it possible to determine the values of the desired indicators at the points under consideration. The equations are applicable to any massive low-cement concrete dams with a base width of at least 40 m in any climatic conditions.

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Aniskin Nikolai Alekseevich, doctor of Technical Sciences, Professor, National Research Moscow State University of Civil Engineering, 129337, 26, Yaroislavskoye Shosse, Moscow, Russia. e-mail aniskin@mgsu.ru; phone +79104377227.

Shaytanov Aleksey Mihaylovich, graduate student, National Research Moscow State University of Civil Engineering, 129337, 26, Yaroislavskoye Shosse, Moscow, Russia. e-mail shaytanov.alexey@mail.ru; phone +79689887119.

*Shaytanov Mikhail Vladimirovich***,** PhD, Deputy General Director, Lengiprorechtrans Company, 29A, Ivana Chernykh, Saint Petersburg, 198095, e-mail shaytanov-sm@mail.ru; phone +79689887119

Анискин Николай Алексеевич – доктор технических наук, профессор; директор института гидротехнического и энергетического строительства, Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, г. Москва, Ярославское шоссе, д. 26; e-mail aniskin@mgsu.ru; тел. +79104377227.

Шайтанов Алексей Михайлович, аспирант, Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, г. Москва, Ярославское шоссе, д. 26; e-mail shaytanov.alexey@mail.ru; тел. +79104377227

Шайтанов Михаил Владимирович, заместитель генерального директора, Проектно-изыскательский институт «Ленгипроречтранс»; 198095, Санкт-Петербург, ул. Ивана Черных, д. 29, литер А, e-mail shaytanov-sm@mail.ru; тел. +79689887119