Prediction of thermal stress in a concrete gravity dam

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Abstract. Temperature is one of the main factors affecting gravity concrete dams. The effects of many temperature factors on the gravity concrete dam cause additional deformations and tensile stress, as a result, thermal cracks appear. In order to determine the predictive model of temperature regime and thermal stress states in gravity concrete dams is a difficult problem. Because there are a large number of factors that influence temperature regime and thermal stress in the dam during construction and operation. This paper presents the results of numerical modeling of the temperature regime and thermal stress state of the Ban Lai roller-compacted concrete gravity dam (Lang Son province, Vietnam) 56 m high. The model was created using the Midas software package and can evaluate the work of the structure under the influence of temperature during construction and operation phases. The results obtained were taken into account when designing the structure and can make appropriate recommendations.

1. Introduction

The issues of creating predictive models about the temperature field and stress state are considered in the works of many scientists [1-9]. As a rule, they consider specific structures and construction conditions. Different cases of the construction schedule of the concrete dam of the Bureyskaya HPP and their effects on the temperature regime were considered [10].

The mathematical models of the temperature in mass concrete structures during construction were considered in works [6, 7, 11, 12] and performed at the Department of Hydraulics and Hydraulic Engineering (NRU MGSU). The layer-by-layer construction of mass concrete using the technologies of “rolled” and “vibrated” concrete was considered in relation to climatic conditions with air temperatures of 20°C (summer period of laying) and 5°C (winter period of laying). The method of factor analysis was used. Factors that affect the maximum temperature value in mass concrete blocks during construction as cement consumption and its maximum heat release, the thickness of the layer to be laid, the initial temperature of the concrete mixture, and the construction schedule (the construction schedule of mass concrete according to height). The response functions were obtained in the form of regression equations for the maximum temperature at the center of the mass concrete. Numerical studies were carried out in a two-dimensional setting using a calculation program based on the FEM, compiled at the Department of Hydraulics and Hydraulic Engineering (NRU MGSU).

Assessing the risk of thermal cracking is based on the forecast of the temperature regime in mass concrete structures. When the temperature difference between the center and the surface of the concrete block exceeds 20°C, thermal cracks can appear [4]. However, the temperature model does not take into account some of the operating factors: strength properties of concrete, changing over time, the influence of the base, and its rigidity. This leads to the emergence of models that predict thermal stress states. As an example, in works [10, 13, 14] of the Hydro project, the influence of some...
parameters on the thermal stress state in mass concrete with pipe cooling system during construction in the area of the Toktogul HPP was considered. We considered the technology of laying concrete, called the Toktogul method (a prototype of modern rolled concrete technology). The following conditions and parameters were changed: season to pour concrete, breaks time during the placement of the concrete adjacent, the length, and height of the blocks, the pouring temperature of the concrete. The composition and characteristics of concrete for all cases were taken to be the same. Calculations of all cases are performed using a calculation program based on the theory of thermal conductivity, elasticity, and creep in a plane setting using the finite difference method. As a result of the calculations, general graphs of the dependence of the maximum tensile stresses on the factors considered were constructed. The analysis of the results obtained made it possible to recommend a set of measures to ensure the solidity of the mass concrete.

In the paper, the calculations have been carried out with the continuation and development of the previous research direction. We have done in contrast to previous studies with the use of 3D modeling in «Midas civil» software. The results obtained are the mathematical models to predict the thermal stress state in gravity concrete dams under the climatic conditions of northern Vietnam. The air temperature during concreting was taken: $T_{\text{air}} = 26.5\,^\circ\text{C}$ for the summer period; $T_{\text{air}} = 17\,^\circ\text{C}$ for winter and $T_{\text{air}} = 5\,^\circ\text{C}$ for winter conditions in mountainous areas. Because several hydropower projects are being built in this area [15-17].

2. Materials and methods

In this study, to create a mathematical model that predicts the thermal stress regime in a concrete pillar on the base is considered and shown in Fig. 1.

The average monthly the construction schedule of the dam concreting (the rate of erection in height) in the calculations was taken $V = 0.3\,\text{m/day}$ (the most common in the modern practice of hydraulic engineering) [6, 18].

![Figure 1. Fragment of the design scheme](image)

The formation of temperature fields in gravity concrete dams during construction and operation depends on many factors such as climate and technology. In this work, in order to create a mathematical model for the thermal stress, the experiment planning technique was used [7, 19, 20]. The following factors and the intervals of their changes were considered (which were taken on the basis of the analysis of data from field observations of the parameters of the technology of dam construction in the northern part of Vietnam) [21]: $X_1 (C)$ - cement consumption, kg/m$^3$ (range of variation from 50 to 200); $X_2 (\Delta)$ - the thickness of each poured concrete layer, m (range of variation from 0.3 to 1.5); $X_3 (E_{\text{max}})$ - maximum heat release from cement, kJ/kg (range of variation from 120 to 350); $X_4 (L_m)$ - block length, m (range of variation from 10 to 40); $X_5 (t_{\text{mix}})$ - the pouring temperature of the concrete, $^\circ\text{C}$ (range of change from 10.0 to 25.0). As a reaction, the maximum tensile stress that occurs in the concrete mass during construction was considered.

To create a simulation mathematical model, the method of factor analysis was used [7, 11,12]. As a response, the maximum tensile stress that occurs at the center of the concrete mass was considered.
When determining the temperature field and thermal stress in mass concrete blocks at the construction stage, the heat release of concrete was determined by the formula (1) [7]:

$$Q(\tau) = Q_{\text{max}} \left[1 - (1 + A_{20}\tau)^{-n}\right],$$  \hspace{1cm} (1)

where: $Q_{\text{max}} = qC$ - heat release by the end of hydration; $C$ - the amount of cement per unit volume (cement consumption); $A_{20}$ - coefficient of the growth rate of heat release related to the hardening temperature of 20°C ($A_{20} = 0.012$ - 0.015 h$^{-1}$); $n$ - depending on the properties of the cement: for Portland cement $n = 0.83$.

The change in the modulus of elasticity of concrete ($E$), depending on time and was taken into account by the formula (2) [7]:

$$E(\tau) = E_0(1 - \xi e^{-\beta\tau}),$$  \hspace{1cm} (2)

where: $E(\tau)$ - elastic modulus of concrete at time $\tau$; $E_0$ - the limiting value of the modulus of elasticity, depends on the grade of concrete (for the grade of concrete M250 $E_0 = 2.5 \times 10^{10}$ N/m$^2$); $\xi, \beta$ - parameters selected on the basis of laboratory tests of concrete, accepted $\xi = 1, \beta = 0.0086$ h$^{-1} = 0.2064$ day$^{-1}$ [7]; $\tau$ - time, day.

An experimental plan was created in relation to the factors under consideration. With the help of the software complex "Midas civil" for all experiments of the plan, at each time step, the temperature regime and thermal stress state in mass concrete due to the action of temperature and self-weight were calculated. The values of the maximum stresses were estimated, the time and place of their occurrence were recorded.

3. Results and Discussion

The regression equations are obtained (after removing insignificant terms of the equation) for the three cases with the influence of outside temperature (air temperature) and presented by Eqs. 3-5.

- during construction in northern Vietnam in the summer (with an average air temperature of 26.5°C).

$$\sigma_{\text{max}} = 1.30 + 0.21X_1 + 0.07X_2 + 0.15X_3 + 0.13X_4 + 0.14X_5 + 0.06X_6X_7 + 0.10X_8X_9$$  \hspace{1cm} (3)

- during construction in northern Vietnam in the winter (with an average air temperature of 17°C).

$$\sigma_{\text{max}} = 1.16 + 0.15X_1 + 0.04X_2 + 0.12X_3 + 0.08X_4 + 0.10X_5 + 0.07X_8X_9$$  \hspace{1cm} (4)

- during construction in the conditions of mountainous Vietnam (with an average air temperature of 5°C).

$$\sigma_{\text{max}} = 1.11 + 0.13X_1 + 0.04X_2 + 0.11X_3 + 0.09X_4 + 0.04X_5 + 0.03X_6X_7 + 0.06X_8X_9$$  \hspace{1cm} (5)

Analyzing the results obtained, the following can be noted. The factors $X_1$ (cement consumption) and $X_3$ (maximum heat release of cement) affect the greatest extent on maximum tensile stress for all construction cases (different climatic conditions). Further, in descending order of the factors affecting maximum tensile stress are $X_4$ (length of the concreting block), $X_5$ (the pouring temperature of the concrete), and $X_2$ (the thickness of each poured concrete layer).

As time and construction conditions are considered, maximum tensile stresses form in the area near the concrete's contact with the base - in its lower layer or near it. Depending on each case, tensile stress may occur at the center or edge of the mass concrete. The time of occurrence of maximum tensile stresses is in a fairly wide range from 504 to 1360 hours (from 21 to 57 days) after the first concrete layer is placed. To preliminary assess the possibility of forming thermal cracks, the resulting tensile stress is compared with the allowable tensile stress at 672 hours (28 days).

In accordance with Russian standards (SP 41.13330.2012, Table 3 - page 7), concrete of class B5, B7.5, B10, B12.5, B15, B17.5, B20 is used to prepare a concrete mix for rolled concrete technology. According to similar recommendations like hydrotechnical construction in Vietnam, for rolled concrete dams, as a rule, concrete of class B10-B20 (M150-M250) is used [23].
For these classes of concrete, in accordance with the standards, the maximum permissible compressive strength for the limiting states of concrete of the second group is \((7.5-14.9)\) MPa. The permissible tensile strength for the 2nd limit state is \((0.78-1.38)\) MPa.

Based on the theory of nomography combined with regression equations, nomograms were constructed to determine the maximum tensile stress for the given values of the factors. Nomograms during construction from roller compacted concrete for three construction cases with different ambient temperatures are shown in Figs. 2-4. The binary fields of the nomograms \((X_4, \sigma_{\text{max}})\) show the boundaries corresponding to the permissible values of the maximum tensile stresses for rolled concrete classes B10-B20 in accordance with SP 41. 13330.2012 [23]. Therefore, the areas are divided on the nomograms (in Figs. 2-4, they are highlighted with different shading).

- **zone 1** – the maximum tensile stress value less than allowable value of \(0.78\) MPa for concrete type B10, ensure no cracking occurs;
- **zone 2** - the maximum tensile stress value to exceed value \(0.78\) MPa for grade B10 concrete and not to exceed value \(1.38\) MPa for grade B20 concrete. Temperature cracks for this area occur if the value of the maximum tensile stress obtained from the nomogram is greater than the permissible value for concrete of the accepted class;
- **zone 3** - maximum tensile stress value exceeds value \(1.38\) MPa for grade B20, thermal cracking occurs in concrete block.

![Figure 2. Nomogram for determining the maximum stress of a concrete block during construction in summer \((T_{\text{air}} = 26.5^\circ\text{C})\)](image-url)
Based on the performed numerical studies, predictive models of the temperature regime and the thermally stressed state in mass concrete by roller compacting technology during construction were obtained for the climatic conditions of North Vietnam or similar. From the obtained regression equations and based on factor analysis, the nomograms have been built. The nomograms allow preliminary assessment and a reasonable selection of concrete mix and construction technology. This will help to regulate the temperature regime of the concrete gravity dam during construction and minimize the appearance of thermal cracks.

Considering the temperature field and thermal stress state of the Ban Lai roller-compacted concrete gravity dam (Lang Son) 56 m high, which built in the North of Vietnam [22]. The dam cross-section and base are shown in Fig. 5, a. The average air temperature in northern Vietnam ranges from 15.0°C in winter to 26.5°C in summer [22]. The starting time of placing concrete was March 10. The construction of Ban Lai concrete dam is considered with two different the average construction schedule cases as follows: \( V = 0.3 \) m/day for case 1 and \( V = 0.4 \) m/day for case 2. The time step between the laying of adjacent concrete layers \( \Delta t \) was taken equal to 24 hours for case 1 and 18 hours.
for case 2. The thickness of each poured concrete layer is assumed 0.3m. The binder composition of the M150 roller compacted concrete mix consists of 85 kg/m$^3$ cement + 145 kg/m$^3$ of pozzolanic were used in the construction of the Ban Lai dam.

![Figure 5](image)

**Figure 5.** Ban Lai rolled concrete dam (Vietnam): a – the dam cross-section and base, b – fragment of finite element model

In order to determine the temperature field and thermal stresses in the Ban Lai dam during construction and operation, the software package "Midas civil" was used. Fig. 5, b shows a 3D model and finite element for the dam and the base.

Maximum temperature, thermal gradient, and thermal stress at different points in time were obtained using «Midas civil» software [1-3]. The thermal stress change over time of the 6 nodes (6 nodes selected in Fig.5b) is shown in Fig.6. From the comparison results obtained, we can note the following: when the temperature at the center in mass concrete during construction increases, the thermal stress values also increase. In particular, the average construction schedule of the second case is greater than the average construction schedule of the first case, so the thermal stress of the second case will be greater. Presents the results of comparing the values of the maximum temperatures and stresses for 2 cases are shown in Table 1.

![Figure 6](image)

**Figure 6.** Graph of changes in maximum thermal stress at 6 dam nodes over time: a) $V = 0.30$ m/day; b) $V = 0.40$ m/day
Table 1. Influence of construction schedule on the temperature field and thermal stress in dam

| Case | V, m/day | $T_{\text{max}}, ^\circ\text{C}$ | $\sigma_{\text{max}}, \text{MPa}$ | $\sigma_{\text{min}}, \text{MPa}$ |
|------|----------|----------------------------------|----------------------------------|----------------------------------|
| 1    | 0.3      | 40.04                            | 1.17                             | 1.55                             |
| 2    | 0.4      | 44.07                            | 1.48                             | 1.83                             |

From the results in Table 1, we can note the following: As the average construction schedule increases, the temperature field and thermal stress also increase. Specifically, when the average construction schedule increased from 0.3 m/day to 0.4 m/day, the maximum temperature in the dam body increased from 40.04°C to 44.04°C while the maximum tensile stress increased from 1.17 MPa to 1.48 MPa.

Thermal stress prediction models are obtained to assess the crack risk of gravity concrete dams. The maximum tensile stresses for this case are observed near the edge of the mass of the near-contact zone of the dam and base. The model obtained a value equal to 1.14 MPa (for the average construction schedule $V = 0.3 \text{ m/day}$). The obtained value is not dangerous from the point of view of cracking, because $\sigma = 1.14 \text{ MPa} \approx R_p = 1.10 \text{ MPa}$, where $R_p = 1.10 \text{ MPa}$ is the standard tensile stress for concrete of class B15.

After the completion of the calculations for the construction period, studies were carried out on the temperature field and thermal stresses in the dam at the construction period. At the same time, the changes in the air temperature, the water level of the reservoir, and the change in water temperature with depth over time are considered. It can be noted that after filling the reservoir with water for 6 months, the temperature in the body of the dam quickly dropped from 39.55°C to 35.89°C ($\approx 4°C$). Then, every 6 months, the maximum temperature in the dam body decreases (1.5-0.5)°C. After 15 years in operation of the dam, the temperature reduction in the dam body is finished.

To analyze the stress-strain state (SSS) of the dam for the main combination, we have solved the problem of determining the stress-strain state with loads such as temperature, static load (hydrostatic pressure of water, filtration and weighing backpressure, own weight of the dam) starting from the moment of filling the reservoir. At each time step, detailed pictures of the distribution of stress components in the computational domain were obtained, some of which are shown in Fig. 7.

Figure 7. Distribution of vertical stress $\sigma_z$ a - after 6 months (01/5/2020, $T_{\text{air}} = 25.5°C$), $\sigma_{z\text{max}} = 1.15 \text{ MPa}$; $\sigma_{z\text{min}} = -2.04 \text{ MPa}$; b - after 1 year (01/11/2020, $T_{\text{air}} = 19.0°C$), $\sigma_{z\text{max}} = +0.94 \text{ MPa}$; $\sigma_{z\text{min}} = -1.85 \text{ MPa}$; c - after 2 years (01/11/2021, $T_{\text{air}} = 19.0°C$), $\sigma_{z\text{max}} = +0.91 \text{ MPa}$; $\sigma_{z\text{min}} = -1.92 \text{ MPa}$

The insignificant tensile stresses that occur in the contact section of the dam do not exceed the permissible value and decrease over time.

4. Conclusions

Based on the research results obtained, the main conclusions are presented as follows:
(1) Based on the analysis of the factors and the obtained regression equations, nomograms were built to allow the evaluation and selection of the appropriate parameters of the concrete mix and concrete pouring technology.

(2) The temperature field and thermal stress state in the dam are determined from the prediction model in accordance with the observed data in the field. This shows that the obtained prediction models are validated.

(3) The average construction schedule increased from 0.3m/day to 0.4m/day, the maximum temperature in the dam body increased from 40.04°C to 44.04°C while the maximum tensile stress increased from 1.17MPa to 1.48MPa.

(4) The method of generating mathematical models to predict the temperature field and thermal stress in gravity concrete dams could be applied for other similar projects.

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