Temperature regime of massive concrete dams in the zone of contact with the base

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Abstract: In construction of mass concrete dams the main effect on the structure are temperature impacts. Heat release in cement hydration and the effect of many factors may result in considerable temperature gradients and cracks. The most dangerous here is the zone near the structure contact with the foundation bed. This manuscript gives analysis of dependence of the temperature regime and thermally stressed state of the zone near the structure contact with the foundation bed on the operating factors, preparation of recommendations on optimization of the construction procedure.

1. Introduction

The mass concrete structures most often are encountered in hydraulic engineering. First of all these are mass concrete dams which may include gravity and mass head buttress dams. They are widely used in modern hydraulic construction. One of the essential effects on such structures is temperature effect causing a change in stress-strain state of the structure both in construction and in operation periods.

The temperature regime of the dam concrete massif during its construction is formed under effect of many factors. Prominence is given to external temperature effects: air temperature, foundation bed temperature, insolation effect, availability of wind and its direction. The main operating factor during construction is cement exothermic. The value of exothermic heating is affected by concrete mix composition: cement consumption and its heat release.

Besides, the temperature field formation is affected by many technological factors: the concreting flow sheet, temperature of concrete placing, thickness of placed concrete lifts, concreting rate, use of artificial cooling of the concrete massif, etc. During the massif construction and cement intensive heat release a considerable heating of the massif zone occurs. This may result in great temperature differences which cause considerable tensile stresses and result in cracking [1, 2, 3, 4].

According to construction practice of mass concrete dams depending on «pinching» conditions and block location in the dam body (fig.1) the emergence of temperature cracks is connected with temperature differences [5, 6]:

- for blocks in the «pinching» zone (fig. 1, b), located near the foundation bed (the zone of the height roughly equal to the block length l_{bd}), the main reason for cracking is the difference between the averaged temperature in the block in the exothermic period and the averaged temperature in the block during the operation period ΔT_{2} (fig. 1, d);
- for blocks in the «free» zone (fig. 1, b) the decisive factors is the difference between the temperature in the block center and on its external surface ΔT_{1} (fig. 1, g).
Investigation of temperature regime of mass concrete dams is described in a big number of papers performed using modern methods [7, 8, 9, 10, 11]. In this paper the author made an attempt at creation of a mathematical prediction model of temperature regime of lin-lifts placement of concrete massif depending on the main operating factors. Use of such model will permit to make rational decisions on the concrete composition (cement consumption and its heat release) and the flow sheet of construction of concrete dams (rate of dam construction in height, thickness of the concrete lift placed).

Figure 1. Flow sheets of mass concrete dams concreting and temperature differences. 

a – flow sheet of placement by one-layer long blocks (procedure of «rolled compacted» concrete)(RCC); b – flow sheet of columnar concrete placement (procedure of «vibrated» concrete); c – curve of temperature difference in the block and the dangerous temperature difference in «free» zone; d – curve of temperature difference in the block and dangerous temperature difference in the «pinched» zone.

Attempts at creation of similar mathematical models were made before, however they considered specific projects and conditions of construction and a limited number of factors affecting the process [12]. Under consideration there are two most often used in dam construction schemes and flow sheets of construction: the placement flow sheet by one-lift long blocks (the flow sheet of «rolled compacted» concrete) (fig. 1, a) and the flow sheet of columnar concrete placement (the flow sheet of «vibrated » concrete)(fig. 1, b).

2. Methods
To determine the dependence of the temperature of the exothermical heating of the concrete massif on several elected factors use was made of methods of the experiment planning [13, 14, 15], permitting to obtain the wanted result with minimum number of solutions. Also these methods are called the factor analysis since with a certain number of varying factors affecting the sought function it is possible to
determine the contribution of each of them. This work considers a full-factor experiment, for which the response function (for the case of 5 factors) or the regression equation assumes the following form [13]:

\[ Y_i = \beta_0 + \sum_{j=1}^{n} \beta_j X_j + \sum_{j=1}^{n} \sum_{k=j+1}^{n} \beta_{jk} X_j X_k + \sum_{j=1}^{n} \sum_{k=j+1}^{n} \sum_{l=k+1}^{n} \beta_{jkl} X_j X_k X_l + \ \ldots \]

where: \( Y_i \) – response sought function; \( X_1, \ldots X_n \) – investigated factors; \( \beta_0, \beta_j, \beta_{jk}, \beta_{jkl} \) – coefficients of regression equation.

On the basis of factor space methods the analysis of some factors dependence on the massif temperature regime was performed. There were considered two most used in modern dams construction flow sheets of cutting the massive structure into concreting blocks:

- flow sheet of cutting by long one-lift blocks (using the flow sheet of «rolled» compacted» concrete or RCC) (fig. 1, a);
- flow sheet of columnar cutting (using the flow sheet of «vibrated» concrete) (fig. 1, b).

As factors, consideration was given to the following intervals of change:

- \( X_1 (C) \) – cement consumption (kg/ m³) (there are accepted the change boundaries from 50 to 170 for rolled compacted concrete and from 200 to 350 for vibrated concrete);
- \( X_2 (H) \) – thickness of the lift placed (m) (there are accepted the change boundaries from 0,3 to 1,0 for the rolled compacted concrete and from 1.0 to 3.0 for vibrated concrete);
- \( X_3 (t) \) – temperature of concrete placed (°C) (there are accepted change boundaries for both variants of placement from 10.0 to 22.0);
- \( X_4 (Q) \) – cement maximum heat release (KJ/kg) (there are accepted change boundaries from 120 to 350 for the rolled compacted concrete and from 350 to 500 for vibrated concrete);
- \( X_5 (V) \) – concreting rate (the massif construction velocity in height, m/day) (there are accepted change boundaries for both variants of placement from 0.1 to 0.6).

As response, consideration was given to maximum temperature arising in the massif under construction \( t_{max} (°C) \).

There was made a plan of full-factor experiment including 32 calculations with all possible variants of factors with their minimum and maximum values. For checking the adequateness of the obtained solution there was performed one more experiment at zeroth levels of factors (equal to average values of factors between their minimum and maximum values).

Solution of the temperature problem is based on the solution of the main differential equation of the thermal conductivity:

\[ \frac{\partial}{\partial t} \left( \rho \frac{\partial \theta}{\partial t} \right) + \frac{\partial}{\partial x} \left( a_x \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left( a_y \frac{\partial \theta}{\partial y} \right) + \frac{\partial}{\partial z} \left( a_z \frac{\partial \theta}{\partial z} \right) + C \frac{\partial H}{\partial t} = \varphi \frac{\partial \theta}{\partial t} \]  

(2)

Where \( t = t(x, y, z, \tau) \) – the sought temperature function; \( a_x, a_y, a_z \) – material temperature conductivity in direction of coordinate axes \( X, Y, Z \); \( \tau \) – time; \( c \) – concrete specific heat; \( \rho \) – concrete density; \( H \) – concrete heat release; \( C \) – cement consumption (kg) per 1 m³ of concrete.

As known [11], the solution of differential equation (2) is reduced to minimization of the following 3D integral:

\[ \Phi = \iiint \left[ \frac{1}{2} \left( a_x \left( \frac{\partial \theta}{\partial x} \right)^2 + a_y \left( \frac{\partial \theta}{\partial y} \right)^2 + a_z \left( \frac{\partial \theta}{\partial z} \right)^2 \right) + \left( \frac{\partial \theta}{\partial t} - \frac{C \partial H}{\partial \theta} \right) \right] dx \cdot dy \cdot dz \]  

(3)

If the outline of the area under study has boundary conditions of 2 and 3 orders, the functional (3) includes additional members and assumes form [16]:

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\[ \Phi = \iiint \left( \frac{1}{2} a_x \left( \frac{\partial^2}{\partial x^2} \right)^2 + a_y \left( \frac{\partial^2}{\partial y^2} \right)^2 + a_z \left( \frac{\partial^2}{\partial z^2} \right)^2 \right) \right) \] 

\[ + \int_{\Omega_1} q \, dt \, d\Omega + \int_{\Omega_2} \frac{1}{2} \beta (t - t_c) \, d\Omega, \]  

(4)

Where \( \beta \) – coefficient of heat exchange on the surface structure; \( t_c \) – ambient temperature; \( \lambda \) - coefficient of concrete thermal conductivity, \( q \) – specific heat flow, \( \Omega_1, \Omega_2 \) – surfaces of the design area where there are fulfilled boundary conditions of 2 and 3 orders respectively.

Minimization of functional (4) was performed in software system «TERMIC», based on the method of finite elements in locally varying setting [16].

The concrete heat release calculation in the studied time moment was made by the formula with regard to the temperature effect on concrete heat release [17]:

\[ Q_c = Q_{\text{max}} \left[ 1 - (1 + A_{20}) \int_0^\tau \frac{t(t-20)}{e} \, d\tau \right]^{-0.833}, \]  

(5)

where \( Q_c \) - cement heat release in the studied time moment \( \tau \); \( Q_{\text{max}} \) - maximum (full) cement heat release; \( A_{20} \) - coefficient of the rate of concrete heat release at the hardening constant temperature \( t = 20 \, ^\circ C \), \( A_{20} = 0.014 \,(\text{W} \cdot \text{m}^2 \cdot \text{K}) \) (by recommendations [17]); \( e \) - characteristic temperature difference, normally accepted equal to 10\(^\circ\)C [17].

3. Investigation results

For all experiments of the plan there were performed the calculations of the temperature regime of the concrete massif under construction by the finite elements method using the software systems «TERMIC» and «ANSYS» [18]. Simulation covered the in-lifts construction of the concrete massif on the foundation bed. Calculations were carried out for two cases of temperature impact of environment. In the first case the air temperature was accepted constant and equal to 20\(^\circ\)C (which roughly corresponds to the summer time concreting). In the second case the air temperature was accepted constant and equal to 5\(^\circ\)C (which corresponds to the winter time concreting protected by heated shelters in severe climatic regions).

The following thermal-physical concrete characteristics were set: coefficient of thermal conductivity \( \lambda = 2.33 \, \text{W} / (\text{m} \cdot \text{K}) \) (2 large calories/m·hr·°C); coefficient of thermal conductivity \( a = 0.0042 \, (\text{m}^2/\text{K}) \). The same foundation bed characteristics were accepted.

For the variant of the concrete massif placement by one-lift blocks there were obtained the following dependences of maximum temperature in the center of the concrete massif under construction on the selected factors which after exclusion of little-significant members have the following form::

- at the external air temperature 5\(^\circ\)C (winter time concreting):
  \[ t_{\text{max}} = 27.29 + 2.95X_1 + 1.33X_2 + 5.41X_3 + 2.64X_4 + 2.30X_5 + 1.71X_6 \]  

(6)

- at the external air temperature 20\(^\circ\)C (summer time concreting):
  \[ t_{\text{max}} = 34.7 + 2.58X_1 + 5.22X_2 + 1.98X_3 - 0.56X_4X_5 - 0.23X_2X_4 - 0.23X_1X_3 + 0.52X_2X_5 + 0.21X_2X_7 + 0.37X_3X_8 + 0.37X_3X_9 \]  

(7)

The adequateness checking of the obtained equation shows good convergence (errors in equations 6, 7 make 0.64% and 0.22% respectively). On the basis of the obtained dependences there were constructed the nomographs [19, 20], permitting to give a quick evaluation of the temperature regime of the massif under construction and to solve the inverse problem: by the wanted temperature in the concrete massif to determine possible values of the studied factors. Fig. 2, 3 show the nomographs for determining the maximum temperature of the concrete massif heating.
After consideration of the functions of responses (equations 7 -8), it is possible to point out the following. All the considered factors exert a rather great effect on the value of the concrete massif maximum temperature. The greatest effect is exerted by the value of temperature of the mix placed \( (X_3) \), which is natural since it is the concrete initial temperature on which the effect of the remaining factors «is superimposed».

**Figure 2.** The nomograph for determining the maximum temperature in block center \( (t_{air} = 5^\circ C, \) cement consumption 50-170 kg/m\(^3\), thickness of the lift placed 0,3 m – 1,0 m, temperature of concrete placed 10\(^\circ\)C -22\(^\circ\)C, \( Q_{max} \) 120-350 kJ/kg, concreting rate 0,1m/day – 0,6m/day).

**Figure 3.** The nomograph for determining the maximum temperature in block center \( (t_{air} = 20^\circ C, \) cement consumption 50-170 kg/m\(^3\), thickness of lift placed 0,3 m – 1,0 m, temperature of concrete placed 10\(^\circ\)C -22\(^\circ\)C, \( Q_{max} \) 120-350 kJ/kg, concreting rate 0,1m/day – 0,6m/day).
However in this case no regard would have been given to the effect of temperature on the value of the exothermic heating (see formula 5). Besides for preliminary evaluation of possible cracking it is necessary to know the differences between the temperature inside the massif and that on its surface (for evaluation of cracking in the «free» zone, fig. 1, g) or (the averaged temperature in the block during operation, fig. 1. d). Many modern investigations were devoted to the problem of investigation of the mechanism of emergence of temperature cracks during construction and their prevention.

During construction of the concrete structure the main temperature effect is the cement exothermia directly depending in our case on two factors: cement consumption \((X_i)\) and its maximum heat release \((X_i)\). These two factors directly and through the members of equations 7-8 with regard to their interaction \((X_iX_j)\) in the greatest extent effect on the value of maximum temperature in concrete massif. Another significant factor – the concreting rate \((X_3)\), whose increase results in higher exothermic heating of the concrete massif.

In greater extent the rate affects in winter time concreting (dependence Maximum difference in temperatures at maximum \((0.6\ m/day)\) and minimum \((0.1\ m/day)\) rates can in this case roughly attain 4.6°C. In summer concreting this difference drops to \(-2.7°C\). The lowest effect on the value of maximum temperature is exerted by factor \(X_2\) – thickness of the lift of concrete placed. Also in greater extent it affects in winter time concreting causing the maximum possible temperature difference \(-2.7°C\) (as against \(-0.9°C\) in summer time concreting).

With selected intervals of the considered factors the concrete heating in winter concreting may change from 44.8°C to 14.8°C (the difference is \(-30.0°C\)). In case of summer concreting – from \(-48.0°C\) to \(-24.2°C\) (the difference is \(-23.8°C\)).

For the variant of the concrete massif placement by the flow sheet of columnar cutting the investigations were performed for three variants of the block width: \(L_{l/i}=10\ m\), \(L_{l/i}=15\ m\) и \(L_{l/i}=20\ m\). After exclusion of little-significant members there are obtained the following dependences of maximum temperature in the center of the concrete massif under construction on the selected factors (the results are given for variant \(L_{l/i}=10\ m\)):

- at external air temperature 5°C

\[
t_{\text{max}} = 53.70 + 10.15X_1 + 1.99X_2 + 5.26X_3 + 7.41X_5 + 3.20X_5 + 0.55X_2X_5 + \\
+ 0.85X_2X_5 - 0.83X_1X_2X_5 - 0.83X_1X_5; 
\]

(8)

- at external air temperature 20°C

\[
t_{\text{max}} = 57.79 + 9.81X_1 + 5.18X_2 + 6.66X_3 + 3.34X_5 - 0.72X_1X_2X_5 - 0.72X_1X_5; 
\]

(9)

The adequateness checking of the obtained equations shows good convergence (the errors of equations 9, 10 are 0.37% and 0.17% respectively). On the basis of the obtained dependences there were constructed the nomographs permitting to give a quick evaluation of the temperature regime of the massif under construction or to solve the inverse problem: for the wanted temperature in the concrete massif to determine possible value of the considered factors. Fig. 5,6 show the nomographs for the column 10 m wide.

After consideration of responses for the given case (equations 9 -10), the following can be pointed out. In comparison to the variant of the rolled-compact concrete (equations 8-9) there was a considerable increase in the effect of factors \(X_1\) and \(X_4\) (cement consumption and its maximum heat release), which naturally is connected with the composition of vibrated concretes. The lesser significant factor – concreting rate \((X_3)\), whose increase results in higher exothermic heating of the concrete massif. However as distinct from the rolled-compact concrete this factor roughly equally affects the maximum temperature in the winter and summer concreting.

Maximum difference in temperatures at maximum \((0.6\ m/day)\) and minimum \((0.1\ m/day)\) rates can roughly attain in both cases \(-6,4°C\). Also the least significant factor is factor \(X_2\) – thickness of the concrete lift placed. In a bit greater extent it influences in winter concreting causing the maximum possible temperature difference \(-4,0°C\) (as against \(-2,8°C\) in summer concreting). With the selected
intervals of the considered factors (table 1) the concrete heating in winter concreting can vary from 82.3°C to 29.6°C (the difference is ~52.7°C). In case of summer concreting – from ~85.8°C to ~34.0°C (the difference is ~51.8°C).

4. Conclusions

4.1 On the basis of the methods of the factor analysis using the numerical solution of the temperature regime problem of the in-lifts construction of concrete massif there was performed the
analysis of effect of the main affecting factors on the value of maximum temperature in the concrete massif center.

4.2. Consideration was given to the most used in modern dam construction the flow sheets of cutting the massive structure into the concreting blocks: the flow sheets of cutting by long one-lift blocks (using the procedure of the «rolled-compacted» concrete); the flow sheet of columnar cutting (using vibrated concrete).

4.3. The obtained dependences of the concrete massif maximum temperature on the selected factors and the nomographs can be used for preliminary engineering estimations of maximum heating of the concrete massif under construction. On the basis of the obtained results there is a possibility of a rough estimation of possible temperature cracks.

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