A Numerical Model for the Temperature Regime of a Concrete Gravity Dam in the Climatic Conditions of Northern Vietnam

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Abstract. One of the main impacts on concrete gravity dams is the temperature factor. The effect of temperature factor on concrete dams will create additional deformation and stress, which can lead to tensile stresses and so gives rise to the thermal cracking. So, forecasting the thermal regime and thermal stress state in concrete gravity dams is a difficult task because taking into account a large number of influencing factors. This paper presents numerical modeling results on the temperature regime of the Bannong (Son La Province, Vietnam) concrete gravity dam with a height of 45m. The model has created by the MIDAS software package and can assess the influence of temperature factors on the dam structure during construction and operation period. The results obtained may be used when designing and making appropriate recommendations.

1. Introduction

In recent years, the construction of waterworks in Vietnam has been developing quite fast. Some hydraulic structures were built using concrete gravity dams as water-supporting structures. For example, the Son La hydropower plant (dam height 138 m), Lai Chau hydropower plant (dam height 137 m), and others were built in northern Vietnam [1, 2]. In Vietnam, although the climate is relatively favorable (average air temperature of the month does vary significantly), the effect of temperature on mass concrete structures needs to be considered. During the construction period, the temperature increased significantly inside the concrete block due to the hydration of cement, but it gradually decreased over time. Due to the temperature difference between the center and the surface of concrete blocks, tensile stresses and thermal cracks may occur on the concrete structure [3,4, 5]. The influence of factors during operation can also worsen the stress of concrete gravity dams [6].

In recent years, an approximate estimation of the temperature regime and thermal stress state in the mass concrete structure has been developed by using numerical methods and factor analysis techniques [7, 8, 9]. A more accurate prediction can be obtained from the system of modern software based on the finite element principle taking into account the full range of influencing factors such as construction technology and temperature conditions. Therefore, the results of this work are presented in this paper. The calculation of thermal regime and stress-strain state in a concrete gravity dam was built in Vietnamese climatic conditions using the Midas software program (finite element method principle) [10].

2. Materials and Methods

2.1. Object of study
This paper presents the results of numerical simulations of the temperature regime and thermal stress state for a Bangmong concrete gravity dam (Son La Province, Vietnam) with a height of 45 m. Formation of a temperature regime in the concrete structures at the time immediately after placing the first layer of concrete until the steady-state temperature is reached during operation. The thermal stress state of concrete was also determined for construction and operational conditions. The cross-section of the dam with the maximum height is shown in Figure 1a. This dam was built in northern Vietnam. The climate of this region is characterized by monthly average temperature changes from 15 °C (in winter) to 26.5 °C (in summer) [11, 12, 13, 14, 15]. The values of average monthly air temperatures are given in Table 1.

The dam is constructed from concrete using conventional vibrated concrete technology. Concrete blocks are laid in layers of 1.5 m with a schedule of 1 layer/day and with interruptions in the concreting of layers for 4 days. Therefore, the average construction schedule (construction schedule according to the height) of the dam is $V = 0.3 \text{ m/day}$. The construction schedule of the dam is shown in Figure 2. The initial temperature of the concrete to be laid is 25°C and the soil temperature is 20°C.

| Month | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|
| 1  | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
| 2  | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 |
| 3  | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 |
| 4  | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 |
| 5  | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 |
| 6  | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |
| 7  | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |100 |
| 8  | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |100 |105 |
| 9  | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |100 |105 |110 |
| 10 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |100 |105 |110 |115 |
| 11 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |100 |105 |110 |115 |120 |
| 12 | 70 | 75 | 80 | 85 | 90 | 95 |100 |105 |110 |115 |120 |125 |
When calculating the temperature regime in concrete structures, the effect of reservoir temperature was taken into account. After completion of the dam construction, reservoir filling was modeled. After filling along the depth of the reservoir, the temperature change in time was set. The temperature of water drops gradually with depth and was determined according to Chinese standards (because the northern region of Vietnam is adjacent to the border with China). The adopted changes in the water temperature of the reservoir are presented in Table 2.

### Table 2. The temperature of water drops gradually with depth.

| M.  | 1     | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-----|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|     | +663  |     |     |     |     |     |     |     |     |     |     |     |
|     | 16.0  | 16.0| 18.1| 21.8| 25.9| 29.7| 31.8| 31.8| 29.8| 26.2| 21.9| 18.1|
|     | +658  |     |     |     |     |     |     |     |     |     |     |     |
|     | 14.4  | 14.3| 16.1| 19.3| 23.3| 26.6| 28.7| 28.7| 27.0| 23.7| 19.8| 16.5|
|     | +653  |     |     |     |     |     |     |     |     |     |     |     |
|     | 13.2  | 12.9| 14.5| 17.5| 22.9| 24.2| 26.0| 26.3| 24.7| 21.7| 18.2| 15.2|
|     | +648  |     |     |     |     |     |     |     |     |     |     |     |
|     | 11.9  | 11.9| 13.3| 16.0| 19.2| 22.1| 23.9| 24.1| 22.7| 20.2| 16.9| 14.0|
|     | +643  |     |     |     |     |     |     |     |     |     |     |     |
|     | 11.4  | 11.2| 12.4| 14.8| 17.8| 20.4| 22.0| 22.3| 21.1| 18.7| 15.8| 13.1|
|     | +638  |     |     |     |     |     |     |     |     |     |     |     |
|     | 10.8  | 10.6| 11.6| 13.8| 16.5| 18.9| 20.5| 20.8| 19.8| 17.6| 14.9| 12.4|
|     | +633  |     |     |     |     |     |     |     |     |     |     |     |
|     | 10.6  | 9.1  | 11.1| 13.0| 15.3| 17.7| 19.1| 19.5| 18.6| 16.6| 14.3| 11.9|
|     | +625  |     |     |     |     |     |     |     |     |     |     |     |
|     | 9.9   | 9.0  | 11.0| 13.0| 15.3| 17.2| 18.9| 19.0| 18.0| 16.1| 14.0| 11.8|

The following sequence diagram of the construction of a concrete dam is adopted. The lower third of the dam to the level of 640.0 m was built according to the “seam-dressing” scheme with a layer height of 1.5 m. The next section of the dam is constructed in the form of long blocks with a height of 1.5 m.

The physical characteristics of concrete and the foundation of the dam accepted in the calculations are given in Table 3. For the construction of the dam used concrete grade $M150$ with the appropriate composition of the concrete mixture and presented in Table 4.

### Table 3. Physical characteristics of concrete and foundation.

| No | Physical characteristic                      | Concrete   | Foundation |
|----|---------------------------------------------|------------|------------|
| 1  | The coefficient of thermal conductivity, W/(m·°C) | 2.91       | 3.60       |
| 2  | Specific heat, kJ/(kg·°C)                   | 0.95       | 0.85       |
| 3  | The density of the material, kg/m$^3$       | 2350       | 2100       |
| 4  | Modulus of elasticity, MPa                  | 19.5×10$^3$| 20×10$^3$  |
| 5  | The coefficient of convective heat transfer, W/m$^2$·°C | 13.95      | 14.00      |
| 6  | The coefficient of linear expansion, 1/°C   | 1.0×10$^{-5}$| 1.0×10$^{-5}$|
| 7  | Poisson’s ratio                             | 0.20       | 0.25       |

### Table 4. Composition of concrete mix design M150 for dam construction.

| Water/cement | Cement (kg/m$^3$) | Sand (m$^3$) | Stone (m$^3$) | Water (l) |
|--------------|-------------------|-------------|--------------|-----------|
| 0.5          | 166               | 0.53        | 0.93         | 85        |
Figure 3. Curve of heat intensity of cement.

Table 5. Change of compressive strength, tensile strength, and elastic modulus of concrete.

| Age, days | 7  | 28 | 90 |
|-----------|----|----|----|
| Rc, MPa   | 6.5| 8.5| 10.8|
| Rp, MPa   | 0.83| 0.95| 1.21|
| E, GPa    | 16.1| 19.5| 21.0|

As originally reported, the heat emission curve of the concrete mixture was obtained by the results of laboratory tests and is shown in Figure 3. Also, based on laboratory tests, strength characteristics such as limits of the compressive, tensile strength and the modulus of elasticity of concrete were determined to take into account their time variation (see Table 5).

To solve the problems of temperature regime and thermal stress state for concrete gravity dams, the finite element method was used through the Midas software. Figure 4 shows the finite element mesh of the concrete gravity dam and part of the foundation. A section of a concrete gravity dam 15.0 m wide was considered.

The numerical solution of the problem is based on the solution of the differential equation of the theory of thermal conductivity [13, 14]:

\[
\frac{\partial}{\partial t} \left( k_x \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial \theta}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial \theta}{\partial z} \right) + q_v = \rho c \frac{\partial \theta}{\partial t}
\]

(1)

where: \( k_x, k_y, k_z \) are thermal diffusivity of the material in the direction of the coordinate axes \( ox, oy, oz \) \((k_x = k_y = k_z = \lambda/c \rho)\), m\(^2\)/s; \( q_v \) is the amount of heat generated by internal sources at a given point in time (for example, during the process of cement hydration, W/m\(^3\)); \( c \) is specific heat, kJ/kg°C; \( \rho \) is concrete density, kg/m\(^3\); \( \tau \) is concrete hardening time, day.

When solving equations (1), one needs to know the initial and boundary conditions of the computational model [15]. The following boundary conditions are used as the initial boundary conditions for the next time step: the initial temperature of the foundation nodes is set by the average annual temperature of 20°C; the temperature of the concrete layers is set as the initial temperature of 25°C concrete mixture.
When solving the temperature regime and thermal stress state problem, the following boundary conditions are used.

Temperature regime: the following boundary conditions were set on the surfaces of the computational domain. On the surfaces of the mass concrete and the foundation at the contact with air, the boundary condition of the third kind was used (condition of heat exchange with the environment) [16]:

\[ \lambda \frac{\partial t}{\partial n} = h(t_s - t_a) \]  

where: \( n \) is external normal; \( h \) is heat transfer coefficient, \( W/(m^2^\circ C) \); \( t_s \) is the concrete surface temperature, \( ^\circ C \); \( t_a \) is the ambient temperature, \( ^\circ C \).

On the surfaces of the computational domain in contact with water during the operational period, boundary conditions of the first kind were used. The temperature in the nodes on the surface was assumed to be equal to the temperature of the water.

On the vertical surface of the base, boundary conditions with no heat transfer were modeled (equivalent to the absolute surface insulation). In special cases, the third boundary condition is used as a formula (2).

Thermal stress state: on the surface of the foundation, limited in the calculation domain, conditions that limit the displacement in the directions are used. The free boundary condition is assigned to the calculated domain of the concrete dam.

3. Results and Discussion

3.1. The temperature regime of the Bangmong concrete gravity dam (Son La Province)

The breakdown of the concrete gravity dam and part of the foundation into finite elements in a three-dimensional model is presented in Figure 4. With the help of Midas software, the temperature regime of the calculation area was determined.

Dam construction period: the results of temperature calculations for some moments during the construction period are presented in Figure 5. It should be noted that, in the central area of the dam, the maximum temperature increases significantly due to the generation of cement hydration. The maximum temperature in the dam is about 47\(^\circ\)C and almost during the dam’s construction.
The air temperature in the construction area varies throughout the year in the range from 15.0 °C to 26.5 °C. Therefore, the temperature difference between the center and the surface of the dam always exceeds 20 °C following recommendations of TCVN305: 2004 «Mass Concrete - code of practice of construction and acceptance», and other Russian and international standards [17, 18, 19]. This shows that the probability of cracking is very high.

The maximum temperature obtained following the prediction results is made based on the mathematical prediction program [20]. Accordingly with the parameters of the input is accepted such as concrete composition, construction technology, the ambient temperature the maximum temperature in the dam body reaches is 47.4 °C.

Operational Period: after the construction of the dam to the top of the dam, and the filling of the reservoir was modeled. The temperature problem was solved taking into account the effect of water temperature (see Table 2) and air temperature (see Table 1) on the dam crest and downstream dam slope. The task was considered with a time step of 15 days until a steady-state temperature regime was obtained. The length of time for the temperature regime to reach a steady-state is equal to the decay time of the temperature changes due to cement hydration in the construction period. Some results of the temperature regime in the dam body during the operating period are shown in Figure 6.
Figure 6 shows the temperature field of the dam and the foundation at times after 0.5, 1.0, 1.5, and 2 years from the start of the operation period of the dam.

The cooling process of the dam body is relatively fast during operation. During 2 years of operation of the dam, the maximum temperature in concrete blocks has decreased from 47 °C (see Fig. 5d) to 31.2 °C (see Fig. 6d).

Figure 7 shows graphs of temperature changes for the node located in the center of the dam at different elevations. The locations of the nodes on the dam body are shown in Figure 4. It is seen that the cooling of the upper part of the dam occurs much more intensively due to the small thickness of the structure. At the upper levels, the effect of seasonal temperature changes is also noticeable.

3.2. Thermal stress state of the Bangmong concrete gravity dam during the construction period

The thermal stress state under the effect of thermal load, self-weight in the construction period has determined by using Midas software. The distribution of the maximum stresses at various points in the dam body during construction is shown in Figure 8.

It can be noted that tensile stresses arise in the zone close to the contact with the foundation. To assess the stresses arising from the point of view of the possibility of cracking, the cracking criterion according to Russian SP41.13330.2012 standard was used [18 – 27]. Table 6 presents a comparison of the calculated maximum tensile stresses with acceptable values determined by the standard used. The contact area is considered at the instantaneous point corresponding to the dam construction stages as shown in Figure 8. Besides, Figure 8 shows the maximum stress values appear in the points such as...
center, the upstream, and downstream of the section. It should be noted that the vectors of maximum
tensile stress different directions at each point.

The results show that for every stage of construction, the tensile stress at the center of the contact
section does not exceed the allowable value. This indicates that the thermal cracking in the center of
the contact area does not appear. At the same time, the upstream and downstream sides of the contact
section during construction at an elevation of + 644.5 m, + 655.0 m, and 670.0 m have maximum
tensile stress exceeding the allowed value. Besides, because the tensile stress in this area exceeds the
allowable stress is not large. So, the length of the crack is supposed to be insignificant.

![Figures](image)

**Figure 8.** Distribution of maximum stresses in the concrete mass of the dam
during the construction period.

| El., m | σ(τ) – Thermal stress in the contact section at time τ, MPa | Cracking criteria (SP41.13330.2012), MPa | Providing crack resistance |
|--------|----------------------------------------------------------|----------------------------------------|--------------------------|
| 635.5  | 1.33 1.30 1.33                                        | 1.88                                   | OK                       |
| 644.5  | 1.55 1.81 1.96                                        | 1.88                                   | NO                       |
| 655.0  | 1.64 2.23 2.51                                        | 1.88                                   | NO                       |
| 670.0  | 1.84 2.25 2.76                                        | 1.88                                   | NO                       |

It should be noted that to assess the actual stress state in the concrete dam structure during
operation, it is necessary to take into account the effects of the main load combination such as
hydrostatic water pressure, pressure uplift, etc.

4. Conclusions
Based on the results of the present study support the following conclusions:

1. The results of the temperature calculations of the Banmong concrete gravity dam (northern Vietnam) for the construction and operational periods allow us to conclude that the temperature difference between the center and surface of a concrete dam (in the range from 22 °C to 32 °C depending on the season) exceeds the allowed value. That shows the possibility of thermal cracks appearing in the concrete dam.

2. From the results of the thermal stress state of the dam during the construction period, tensile stresses appear in the upstream and downstream sides of the contact section. It is necessary to conduct additional studies of the stress-strain state, taking into account such basic loads of the operational period such as hydrostatic water pressure, pressure uplift, etc.

3. In order to improve the temperature regime and reduce the risk of thermal cracking of massive concrete, it is possible to change the main acting factors such as reducing cement content, using low-heat cement, reducing construction schedule, or using technological measures like using cooling pipe systems or formwork with insulation.

References

[1] Thermal stress analysis of the RCC dam 2010 Lai Chau Hydropower Project Technical Design (Vietnam) p 61
[2] Nguyen Canh Tinh 2008 Studying the influence of factors on thermal stress state in concrete dam (Se San 3 dam Vietnam) Master thesis Thuy Loi University p 130
[3] Japan Concrete Institute 2017 Guidelines for control of cracking of mass concrete 2016 (Tokyo Japan) p 302
[4] Korea Concrete Institute 2010 Thermal crack control of mass concrete (concrete practices Manual Korea)
[5] Bushmanova A V Videnkov N V Semenov K V Barabanshchikov Yu G Dernakova A V Korovina V K 2017 The thermo-stressed state in massive concrete structures Magazine of Civil Engineering 71(3) pp 51-60 DOI: 10.18720/MCE.71.6
[6] Nguyen C T Aniskin N A 2019 Temperature regime during the construction massive concrete with pipe cooling Magazine of Civil Engineering 89(5) pp 156-166 DOI: 10.18720/MCE.89.13
[7] Muneer K S Muhammad K R Mohammed H B Lutf A T 2020 Cracking in concrete water tank due to restrained shrinkage and heat of hydration: field investigations and 3D finite element simulation Journal of Performance of Constructed Facilities 34(1) p 12 DOI: 10.1061/(ASCE)CF.1943-5599.0001356
[8] Zhu H Hu Y Li Q Ma R 2020 Restrained cracking failure behavior of concrete due to temperature and shrinkage Construction and Building Materials 224 118318 https://doi.org/10.1016/j.conbuildmat.2020.118318
[9] Arifjanov A M Otaxonov M Samiev L Akmalov Sh 2019 Hydraulic calculation of horizontal open drainages «Construction the formation of living environment 2019 (FORM-2019)» XXII International scientific conference E3S Web of Conferences 97 05039
[10] Arifjanov A M Akmalov Sh Akhmedov I Atakulov D 2019 Evaluation of deformation procedure in waterbed of rivers XII International Scientific Conference on Agricultural Machinery Industry IOP Conf. Series Earth and Environmental Science 403 012155
[11] Dimo Dimov Fabian Löw Johannes H Uhl Shavkat Kenjabaev Olena Dubovyk Mirzahayot Ibrakhimov 2019 Chandrashekar Biradar “Framework for agricultural performance assessment based on MODIS multitemporal data” J Appl Remote Sens 13(2) 025501 doi: 10.1117/1.JRS.13.025501
[12] Amanov B T Gadaev N N Ahmedjonov D G Zhaparkulovala E 2020 Mathematical calculations of water saving during furrow irrigation of cotton using a screen from an interpolymer complex Journal of Physics: Conference Series Volume 1425 Modelling and Methods of Structural Analysis 13–15 November 2019 (Moscow Russian Federation Journal of Physics: Conference Series) Volume 1425 Issue 1 8 January Number state 012120
[13] Jurík Ľ. Zeleneáková M, Kaletová T, Arifjanov A M 2019 Small Water Reservoirs: Sources of Water for Irrigation The handbook of environmental Chemistry Volume 69 pp 115-131

[14] Arifjanov A M, Samiev L, Apakhdajeva T, Akmalov Sh 2019 Distribution of river sediment in channels XII International Scientific Conference on Agricultural Machinery Industry IOP Conf. Series: Earth and Environmental Science 403 012153

[15] Arifjanov A M, Rakhimov K, Abduraimova D, Akmalov Sh 2019 Transportation of river sediments in cylindrical pipeline XII International Scientific Conference on Agricultural Machinery Industry IOP Conf Series: Earth and Environmental Science 403 012154

[16] Laktayev N T 1978 Watering the cotton (Moscow Kolos) pp 43-46

[17] Arifjanov A M, Samiev L, Akmalov Sh 2019 Dependence of Fractional Structure of River Sediments on Chemical Composition International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075 Volume-9 Issue-1 November

[18] Fatxulloyev A M, Gafarova A I, Hamraqulov J 2019 The importance of mobile applications in the use of standard water measurements International conference on information science and communications technologies (ICISCT 2019) Tashkent, Uzbekistan 27 February pp 1-3

[19] Arifjanov A M, Fatxulloyev A M 2020 Natural Studies for Forming Stable Channel Sections. Volume 1425, Issue 1, 8 January 2020, 012025. International Scientific Conference on Modeling and Methods of Structural Analysis 2019, (MMSA 2019); Moscow; Russian Federation; 13-15 November. Code 156713. (2019). Fatxulloyev A.M, Gafarova A.I. Study of the process of cultivation in soil fertile irrigation channels. «Construction the formation of living environment 2019 (FORM-2019)» XXII International scientific conference. E3S Web of Conferences 97, 05025. https://doi.org/10.1051/e3sconf/20199705025.

[20] Ergashev R, Artikbekova F, Jumabaeva G, and Uljayev F 2019 Problems of water lifting machine systems control in the republic of Uzbekistan with new innovation technology E3S Web of Conferences 97 05037

[21] Khidirov S, Berdiev M, Norkulov B, Rakhimov N, and Rainova I 2019 Management exploitation condition of Amu-Bukhara machine channel E3S Web of Conferences 97 05038

[22] Kan E, Ikramov N, and Muxammadiev M 2019 The change in the efficiency factor of the pumping unit with a frequency converter E3S Web of Conferences 97 05010

[23] Ikramov N, Kan E, Mirzoev M, and Majidov T 2019 Effect of parallel connection of pumping units on operating costs of pumping station E3S Web of Conferences 97 05014

[24] Shaazizov F, Badalov A, Ergashev A, and Shukurov D 2019 Studies of rational methods of water selection in water intake areas of hydroelectric power plants E3S Web of Conferences 97 05041

[25] Shaazizov F, Uralov B, Shukurov E, and Nasrulin A 2019 Development of the computerized decision-making support system for the prevention and revealing of dangerous zones of flooding E3S Web of Conferences 97 05040

[26] Bazarov D, Shodieev B, Kurbanova U, and Ashirov B 2019 Aspects of the extension of forty exploitation of bulk reservoirs for irrigation and hydropower purposes E3S Web of Conferences 97 05008

[27] Krutov A, Bazarov D, Norkulov B, Obidov B, and Nazarov B 2019 Experience of employment of computational models for water quality modeling E3S Web of Conferences 97 05008