Mathematical model of temperature regime and thermal stress state of roller-compacted concrete gravity dam

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Abstract. This paper presents a mathematical model about the temperature regime and thermal stress state of Ban Lai roller-compacted concrete gravity dam, built in the climatic conditions of northern Vietnam. The model is made on the basis of the finite element method using the software complex Midas Civil. The three cases of dam construction were considered: The first was construction progress with 0.3 m/day, the second was construction process with 0.4 m/day and the last was actual construction progress. The results obtained from the mathematical model compared to the field measurements are reliable. This allows us to recommend the use of the proposed methodology with similar objects. The obtained values of maximum temperatures and thermal stresses indicate a low probability of temperature cracks.

1. Introduction
In the world, one of the most widely used types of dam construction is a gravity dam with a large amount of material. In the process of placing mass concrete with the hydration of cement, a sufficiently large amount of heat is released [1]. This phenomenon leads to the fact that the temperature inside the mass concrete is significantly different from the surface temperature [2]. As a result, the temperature gradient between the central zone and the surface, thermal deformation, and thermal stress occur in concrete structures. In addition, stresses due to other loads, thermal stresses can cause tensile stress and thermal cracks, which reduce the water resistance, durability, and safety of the structure. After many years of practicing in design of concrete gravity dams, many measures have been developed in order to reduce the temperature due to the hydrothermal cement. One of them is to reduce the consumption of cement in concrete mix design process. The development of this event led to the use of so-called low cement content concrete and the emergence of new technology is placing concrete by roller compaction. A new type of concrete gravity dams has appeared called roller-compacted concrete. It is being widely used and has improved over the past 20 years [3].

The studies about roller-compacted concrete dams at the beginning of the application are the physical and mechanical properties of the material and its placement technology. For the first time, the problem of temperature cracking in concrete structures was highlighted by Stefan T.B. and Schrader E.K. [4-6]. After that, scientists and engineers began to pay more attention to controlling the temperature regime and thermal stress during construction. As the practice of construction of the roller-compacted concrete dam shows, cracks occur in most structures under construction process [7-10], especially with those built under extreme climatic conditions [11]. However, the countries with a
fairly mild climate (for example, Vietnam), control and prevention of crack formation in the dam during construction progress are necessary.

At the design stage of the construction technology of roller-compacted concrete dam, which is important to correctly predict the temperature regime and thermal stress state in the concrete dam during construction. This will allow you to choose the right method for controlling the temperature regime and minimize cracking. In recent years, predictions of mathematical models for temperature regime and thermal stress states have been created by many researchers [12]. The complexity of creating predictive mathematical models is the change many times in the size of the structure and many other influencing factors [13-16]. These factors include external temperature effects, heat generation due to cement hydration. In addition, many technological factors affecting temperature regime such as the intensity of concreting, the thickness and length of the laid concrete layer, the interval between their successive placements, the temperature of the laid concrete, the season of laying concrete blocks, the use of cooling pipe system, etc.

This paper presents the results about mathematical modeling of temperature regime and thermal stress state of Ban Lai roller-compacted concrete gravity dam (Vietnam) during construction period by using Midas Civil Software [17].

2. Materials and methods

2.1. Subject of study

The object of research in this work is the Ban Lai concrete gravity dam (Lang Son) with a height of 56.0 m in the northern part of Vietnam. The cross section of the dam and the process of its construction are presented in Figure 1. The climate of this region is characterized by temperature fluctuations from 15.0°C in winter to 26.5°C in summer. The values of average monthly ambient air temperature is shown in Table 1.

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|
| T<sub>air</sub> °C | 15.0 | 17.5 | 20.0 | 23.5 | 25.5 | 26.5 | 26.0 | 25.8 | 24.8 | 22.7 | 19.0 | 15.9 |

The beginning of laying concrete in the dam body is March 10. Two proposed cases for the construction of the dam has been considered as with an average monthly construction schedule equal 0.3 m/day (case 1) and 0.4 m/day (case 2). Figure 2 shows the height schedules of the dam for these two cases and for the actual construction schedule is implemented (case 3). The time intervals between each cast are Δt was assumed to be 24 hours for case 1 and 18 hours for case 2. The thickness of the layer to be laid is 0.3 m in 1 day. The graph also shows the construction schedule implemented in reality during the construction of the dam.

The concrete mixture consists of 85 kg of Portland cement and 145 kg of pozzolanic plasticizing additive per cubic metre of roller-compacted concrete.

![Dam construction process](image1)

(a) - dam construction process

![Dam cross section](image2)

(b) - dam cross section

Figure 1. Ban Lai roller-compacted concrete gravity dam (Vietnam)
The initial temperature of the concrete to be laid is 23°C, base rock temperature is 20°C. The calculated characteristics of the concrete and dam base are shown in Table 2.

### Table 2. Characteristics of concrete and rock foundation

| Thermophysical characteristics                  | Concrete | Rock  |
|------------------------------------------------|----------|-------|
| Heat conductivity coefficient, W/(m.°C)        | 2.15     | 2.63  |
| Specific heat, kJ/(kg.°C)                      | 1.00     | 1.05  |
| Density, kg/m³                                  | 2400     | 2700  |
| Heat transfer coefficient, W/(m².°C)           | 13.35    | 14.00 |
| The coefficient of linear thermal expansion, 1/°C | 0.9×10⁻⁵ | 0.8×10⁻⁵ |
| Poisson’s ratio                                 | 0.20     | 0.30  |

The time-varying elastic modulus of concrete, compressive strength, and tensile strengths were obtained experimentally in the laboratory of the Institute of Hydrotechnical Materials (Vietnam) and is presented in Tables 3 [18]. According to experimental studies, a heat release curve was also obtained due to the cement hydration heat in Vietnam is shown in Figure 3.

### Table 3. Variation of concrete strength, tensile strength, and elastic modulus over time

| Time, day | R_c, MPa | R_p, MPa | E, GPa |
|-----------|----------|----------|--------|
| 7         | 3.9      | 0.3      | 9.4    |
| 14        | 6.9      | 0.5      | 14.8   |
| 28        | 10.4     | 0.7      | 20.2   |
| 56        | 14.3     | 0.9      | 25.0   |
| 90        | 16.9     | 1.1      | 27.8   |
2.2. Finite element method for solving the temperature problem

Today, numerical models are widely used to create predictive models of the temperature regime in massive concrete dams [19]. These models allow you to evaluate the temperature regime and thermal stress before building a concrete structure and provide the necessary measures to obtain the desired result. Today, the finite element method is the most widely used method for this purpose [20, 21]. In this work, in order to determine the temperature field and thermal stress in the Ban Lai dam during its construction by Midas civil software [22, 23].

Figure 4 shows a three-dimensional finite element mesh for the computational domain. To reduce the size of the model, the symmetry of the structure with respect to the vertical plane passing through the center of the dam section was used. Therefore, half the width of the section 12.5 m long was used in the calculations [24, 25].

Figure 5 shows the boundary conditions for the temperature problem. An 8-node solid element with one degree of freedom at each node was used for temperature analysis. Figure 6 shows the boundary conditions for structural analysis, which used an 8-node solid element with three degrees of freedom (x, y, z) at each node [24, 25]. As a result of calculations using the Midas civil complex, temperature distribution, maximum temperatures, gradient temperature, and thermal stress in the mass concrete at different times were obtained [26].

2.3. Observation of the temperature regime in the dam at the construction site

During the construction of the dam with the help of instrumentation, temperature regime was observed at the construction site. Temperature measuring devices were placed inside the dam body during construction. The temperature measuring device used (model 4200/Geokon-USA) (Figure 7) has the following technical characteristics: measuring range: (-80 ÷ + 150)°C; sensitivity: 0.5°C; accuracy: ±0.5% FSR. The sensor measuring head is connected to the multiplexer (CL) by a wired data cable.
(cable type 02-187V3 - Geokon). The process of installing the devices in order to the temperature in a dam during construction is shown in Figure 8.

Figure 7. Equipment in order to measure temperature in mass concrete (temperature sensor - model 4200- Geokon - USA)

Figure 8. Installation of temperature sensors in order to measure temperature during the construction

Using the temperature measurement results in the dam body at the construction site allows us to evaluate the reliability of the results of the mathematical models created.

3. Results and Discussion
The results of solving the unsteady temperature problem at different times during the construction of the dam are shown in Figure 9 (case 1) and Figure 10 (case 2).

Figure 9. The temperature regime of the concrete dam during construction for case 1-V = 0.3 m/day

At each calculated step in time, the problem of determining the stress state in the mass structure during construction taking into account the temperature effects and deadweight of the structure was also solved. Details of the maximum thermal stress state over time for six selected nodes are shown in Figure 11 (the position of the selected nodes is shown in Figure 4).

Comparing the results, it can be noted that the maximum temperature in the center of the dam and the maximum tensile stress increase when the construction schedule increases (case 2). The results of
comparing the maximum temperature, tensile stress and compressive stress of two construction cases are given in Table 4.

Figures 10. The temperature regime of the concrete dam during construction for case 2-V = 0.4 m/day

Figures 11. The tensile stress variation process of six points in the dam over time

Table 4. The effect of the construction schedule on the maximum temperature and the thermal stress state in the dam

| Case            | $T_{\text{max}}$, °C | $\sigma_{\text{max}}$, MPa | $\sigma_{\text{min}}$, MPa |
|-----------------|----------------------|----------------------------|--------------------------|
| No. 1, V = 0.3 m/day | 40.04                | 1.17                       | -1.55                    |
| No. 2, V = 0.4 m/day | 44.07                | 1.48                       | -1.83                    |

Thus, with an increase in the construction schedule from 0.3 m/day to 0.4 m/day, the maximum temperature inside the dam increases from 40°C to 44°C, while the maximum tensile stresses increase from 1.17MPa up to 1.48MPa.

**Compare the results of the mathematical model with in situ measurements.** According to the results of the mathematical model obtained from the two cases of dam construction, case 1 was selected more favorably about the temperature regime during construction. However, the actual construction schedule differs from the schedule for case 1 (Figure 2). Disruptions during the construction of the dam and some deviations in the construction schedule are accepted due to building dam corridors, rainy weather, and insufficient finance. This increased the overall construction time but during the construction of the dam, the construction schedule was approximate with the theoretical value and equal to V = 0.3 m/day (Figure 2). Based on the actual construction schedule (Figure 2), the mathematical model was created to determine the temperature regime, the thermal stress state in the dam during construction. Table 5 shows the comparison between the maximum temperature obtained from the temperature sensors in the center of the profile and the maximum temperature obtained from the mathematical model at the same time and at the same level.
Table 5. Compare the results of mathematical models in situ measurements

| At elevation, m | Maximum temperature in mass concrete, °C | Error, % |
|----------------|------------------------------------------|----------|
|                | FEM                                      | Field measurements |            |
| +270.20        | $T_{\text{max}} = 41.65$                 | $T_{\text{max}} = 42.50$ | 2.0       |
| +274.70        | $T_{\text{max}} = 39.99$                 | $T_{\text{max}} = 43.30$ | 7.6       |
| +283.70        | $T_{\text{max}} = 40.45$                 | $T_{\text{max}} = 40.40$ | 0.1       |
| +288.20        | $T_{\text{max}} = 39.26$                 | $T_{\text{max}} = 40.70$ | 3.5       |

Figure 12 shows the results of modeling the temperature regime in the dam body at the time of construction to elevation shown in Table 5.

(a) - at elevation 270.20 m, $T_{\text{max}} = 41.65$°C

(b) - at elevation 274.70 m, $T_{\text{max}} = 39.99$°C

(c) - at elevation 283.70 m, $T_{\text{max}} = 40.45$°C

(d) - at elevation 288.20 m, $T_{\text{max}} = 39.26$°C

Figure 12. The results of temperature modeling according to the actual construction schedule

From the temperature results shown, the simulation results are in good agreement with the values of field measurements. The maximum discrepancy is 7.6%, the minimum is -0.1% (Table 6). Thus, we can say that the mathematical simulation model adequately describes the temperature regime in the dam during the construction of the dam and can be used to predict the temperature regime in similar structures.

Figure 13. The tensile stress variation process of six points in the dam over time (for actual construction schedule)
Figure 13 shows the change of maximum thermal stress at selected nodes (Figure 2). It can be noted that the maximum stresses arising during concrete hardening due to the effect of temperature reach values of tension 1.14MPa and compression 1.55MPa. Comparing the obtained stress values with the allowable stress shows that the occurrence of thermal cracks during construction progress of dams is not possible.

4. Conclusions
Based on the results of the study, the following main conclusions can be drawn:

(1) Using Midas civil software based on the finite element principle to do the mathematical model of temperature regime and thermal stress state of 56m high roller-compacted concrete dam built under Vietnamese conditions.

(2) The result of calculating the temperature regime and thermal stress state are in accordance with the data of field observations, which indicates its adequacy.

(3) The results are obtained in the form of distribution in the calculated region of temperature regime: the maximum temperature in the central zone of the dam is \( T_{\text{max}} = 40.04^\circ C \) (when the construction progress according to height \( V = 0.3 \text{ m/day} \)) and \( T_{\text{max}} = 44.07^\circ C \) (when the construction progress according to height \( V = 0.4 \text{ m/day} \)).

(4) The maximum tensile stresses are observed near the contact zone of the dam. However, thermal stress value is equal to 1.17 MPa (for the accepted the construction schedule according to height \( V = 0.3 \text{ m/day} \)) is not dangerous from the point of view of cracking.

(5) The method of creating a mathematical model for temperature regime and thermal stress state of roller-compacted concrete gravity dam can be used for other similar objects.

References
[1] Wen Yi Zheng, Peng Pan, Lie Ping Ye 2012 Applied Mechanics and Materials 212-213 912-916 https://doi.org/10.4028/www.scientific.net/AMM.212-213.912.
[2] Birhane Gebreyohannes Hagos, Siva Parvathi I, Praveen T V 2019 Journal of Structural Engineering 45(6) 447-485.
[3] Warren T, Denoyer A, and Ulas A 2011 Power and Dam Construction 63(7) 20-23.
[4] Abdallah I H M, Saad A M, Tony J Q 2003 Journal of Performance of Constructed Facilities 17(4) 177-187 DOI:10.1061/(ASCE)0887-3828(2003)17:4(177).
[5] Aniskin N A, Nguyen H 2014 Scientific and Engineering Journal for Construction and Architecture 8 165-178.
[6] Dadiani N Z 2018 Hydraulic engineering 6 49-54.
[7] Aniskin N A, Nguyen T C 2018 MATEC Web of Conferences 196 04059 https://doi.org/10.1051/matecconf/201819604059.
[8] Li B, Wang Z, Jiang Y, Zhu Z 2018 Advances in Mechanical Engineering 10(1) 1-15 https://doi.org/10.1177/1687814017752480.
[9] Bushmanova A V, Videnkov N V, Semenov K V, Barabanschikov Yu G, Dernakova A V, Korovina V K 2017 Magazine of Civil Engineering 3 51-60.
[10] Tressa K, Kavitha P E, Bennet K 2013 American Journal of Engineering Research (AJER) 1 26-31.
[11] Tatro S, Schrader E 1992 Roller Compacted Concrete III. New York : ASCE 389-406.
[12] Ezzeldin Y Sayed-Ahmed, Amr A A, Rana A E 2018 Dams and Reservoirs 28(1) 12-30 DOI:10.1680/jdare.16.00055.
[13] Aniskin N A, Nguyen T C 2019 E3S Web of Conferences 97 https://doi.org/10.1051/e3sconf/20199705021.
[14] ACI Committee 207 Mass and thermally controlled concrete (Reported by ACI committee 2017).
[15] Vladan K, Ljubodrag S, Nikola M 2015 Faculty of Mechanical Engineering 43(1) 30-34 DOI:10.5937/fmet1501030K.
[16] Nguyen T C, Aniskin N A 2019 *Magazine of Civil Engineering* 5(89) 156-166 https://DOI: 10.18720/MCE.89.13.

[17] Nguyen T C, Huynh T P, Tang V L 2019 *Asian Journal of Civil Engineering* 20 1101-1107 https://doi.org/10.1007/s42107-019-00175-5.

[18] Thermal Stress Analysis Report of Ban Lai roller-compacted concrete gravity dam 2018 *Vietnam Ministry of Construction* (Publishing Construction. Hanoi).

[19] Parveen K, Aeid A A, Bijan S, Khaled G 2015 *Journal of Thermal Stresses* 38(6) 591-609 https://doi.org/10.1080/01495739.2015.1015862.

[20] Nailde de A C, Lineu J P 2018 *Third International Dam World Conference* 3 10.

[21] Husein Malkawi A I, Aufleger M, Strobl Th, Conrad M, Mutasher S, Al-Jammal M 2004 *International Journal on Hydropower & Dams* 11 (4) 86-95.

[22] MIDAS Information Technology 2011 *Heat of Hydration - Analysis Analysis Manual*.

[23] Aniskin N A, Nguyen T C, Hoang Q L 2018 *MATEC Web of Conferences* 251 02014 https://doi.org/10.1051/matecconf/201825102014.

[24] 7th ICOLD benchmark workshop on numerical analysis of dams 2003

[25] Chen Y, Wang C, Li S, Wang R, He J 2011 *Advances in Engineering Software* 32(9) 667-682 https://doi.org/10.1016/S0965-9978(01)00025-4.

[26] Jaafar M S, Bayagoob K H, Noorzaei J, Waleed A M 2007 *Advances in Engineering Software* 38(11-12) 886-895 https://doi.org/10.1016/j.advengsoft.2006.08.040.