Simulation analysis of temperature control on RCC arch dam of hydropower station

Shi-fa XIA
State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, 100044, China
302676581@qq.com

Abstract. The temperature analysis of roller compacted concrete (RCC) dam plays an important role in their design and construction. Based on three-dimensional finite element method, in the computation of temperature field, many cases are included, such as air temperature, elevated temperature by cement hydration heat, concrete temperature during placing, the influence of water in the reservoir, and boundary temperature. According to the corresponding parameters of RCC arch dam, the analysis of temperature field and stress field during the period of construction and operation is performed. The study demonstrates that detailed thermal stress analysis should be performed for RCC dams to provide a basis to minimize and control the occurrence of thermal cracking.

1. Introduction
In RCC dams, the concrete temperature rising from the heat of hydration, within the quick construction process and the low conductivity of concrete can cause a high thermal gradient in the interior mass and exterior surface of the dam. Through the evolution of temperature distribution in the dam, with time, and the resulting thermal stress, depends on the temperature analysis parameters, such as environmental conditions, properties of concrete, the thickness of the lift, temperature and concrete pouring process. There are many technical reports in the document for the designers to assess the thermal performance, construction requirements and configuration of RCC dams. These techniques include complex three-dimensional finite element analysis methods and numerical calculations.

In this paper, the determination of the thermal and structural stresses and temperature control requirements is described for the 90 m high Sanglang RCC Arch Dam in China. Temperature distribution with time, concrete placement temperature limits, and joint spacing requirements to minimize cracking are also discussed.

2. Mathematical modeling
The general partial differential equation governing heat flow in 3D solid is expressed as:

$$\alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\partial \theta}{\partial \tau} = \frac{\partial T}{\partial \tau}$$

(1)

The numerical solution scheme used in this study is based on the Taylor–Galerkin method. Upon applying this method, the following system of differential equations is obtained:

$$[K][\Delta \delta_n] = \{\Delta P_n\} + \{\Delta P_c\} + [\Delta P^f_{\tau}] + [\Delta P^R_{\tau}]$$

(2)
Where: \( \overline{D_n} = E_n [Q]^{-1}; \overline{E_n} = \frac{E(t_n)}{1 + E(t_n) C(t_n - \tau_n)} \)

Where: \( [K] \) is global stiffness matrix; \( \{ \Delta P_n \}, \{ \Delta P^r \}, \{ \Delta P^e \} \) are load increment.

Creep degree calculation: \( C(t_n, \tau_n) = \sum_j \psi_j \left( \tau \right) \left[ 1 - e^{-\tau_j (t - \tau)} \right]; \{ \eta_n \} = \sum_j \left( 1 - e^{-\tau_j \Delta \tau_n} \right) \{ \omega_j \} \)

Get the stress as follows: \( \{ \sigma_n \} = \{ \Delta \sigma_1 \} + \{ \Delta \sigma_2 \} + \cdots + \{ \Delta \sigma_n \} = \sum_{j=1}^{n} \{ \Delta \sigma_j \} \)

3. Description of Dam
The Sanglang Dam located in Guizhou Province, China. It is a RCC arch dam, approximately 90 m high; this hydraulic project will play important roles in flood prevention, sedimentation reduction, irrigation, water supply, power generation and so on. The Sanglang Dam is constructed of high paste content RCC, placed in 300 mm thick layers with a facing made of grout enriched roller compacted concrete.

3.1. Temperature Control Requirements
Obvious thermal caused stresses are appeared as a result of the heat of hydration of the cement in RCC dams. The temperature distribution through the dam and its evolution with time depend on several factors.

3.2. Material Properties and Environmental Conditions
Model attributes are evaluated using existing data and typical RCC attributes. Table 1 shows Poisson ratio, modulus, specific heat, density and thermal conductivity. The convection coefficient of air is analyzed, which is consistent with the moderate wind speed. Heat generation rates adopted for the 125 kg/m$^3$ cement +75 kg/m$^3$ flyash mixture.

| Property                                      | dam                 | foundation          |
|-----------------------------------------------|---------------------|---------------------|
| Thermal diffusivity \( \alpha \) (m$^2$/d)    | 0.1                 | 0.1                 |
| Heat conductivity coefficient \( \lambda \)  (kJ/d·m$^{-1}$·K$^{-1}$) | 216                 | 243                 |
| Specific heat \( C \) (kJ/kg·K$^{-1}$)       | 0.9                 | 0.9                 |
| Heat exchange coefficient \( \beta \) (kJ/m$^2$·d·K$^{-1}$) | 1200                | 1200                |
| Coefficient of linear expansion \( \alpha \times 10^{-6}$/°C | 9                   | 10                  |
| Adiabatic temperature rise \( \theta \) (°C) | \( \theta = 18\tau / (2 + \tau) \) | -                   |
| Density \( \rho \) (kg/m$^3$)                | 2400                | 2700                |
| Poisson ratio \( \nu \)                      | 0.167               | 0.3                 |

4. Three-Dimensional Model Analysis
The height of the arch dam is 90 m. The width of the wave crest in valley is 150m. The origin of the intersection point is the crown part, the upstream dam face line, the direction of the axial direction is downstream, and the y axis is the left bridge indicating from the right shoulder, perpendicular to the flow direction. The positive direction of the z axis is going up. The boundary of the water is the water's solid water convection, but the boundary above the water surface is still in the condition of the solid space boundary. Solid-air boundary can be treated as the third boundary, and the solid water boundary can be treated as the first boundary (figure 1).
5. Finite-Element Results

5.1. Temperature distribution
The predicted temperatures calculated by three dimension finite element method are shown in figure 2. It is clear from these plots that the predicted temperatures obtained from the code that was appeared are in good. Higher-temperature zones are formed at the upper of dam. This may be due to the use of higher RCC placing temperatures combined with the higher insulating property of this region due its massive volume compared with the other locations.

5.2. Stress analysis
After completion of the temperature analysis of every construction stage, stress analysis is performed meanwhile and the fracture parameter is calculated. So, the dam can be considered to be safe against cracking when the fracture parameter is greater than 1. Figure 3 and figure 4 show the variation in the fracture parameters with time for two levels across the dam’s width. It is clear from the fracture parameters that the variation presented in Figs. 3 and 4 that the dam is safe against cracking for level 4m and 10.5m, even though the fracture parameters at the elevation of 1.5 m drops below the allowable limit, but in this period the concrete can still be considered to be young concrete, where its age is below 30 days.
6. Summary
The results are very sensitive to the time of the year, the temperature, the crushing temperature and the hydration heat rate. According to the calculation results, the following conclusions are drawn:

(1) The finite element code appeared for this study is capable of simulating the thermal response of RCC dams reasonably well.

(2) The actual thermal response of RCC dam can be determined accurately by using the recorded environment temperature, material properties and actual RCC lay out schedule. In addition, you can implement any new RCC models available.

(3) The fracture parameters variation can give a good indication of the probability of a crack occurring.

References
[1] Thanoon WA, Jaafar MS, Bayagoob KH, Amini R. Effect of placementschedule on the thermal and structural response of RCC dams, using finiteelement analysis. In: Proceeding of advances in geotechnical engineering with emphasis on dams, highway materials, and soil improvement. Jordan:ASCE; 2004. p. 94–104.
[2] Malkawi AIH, Mutasher S. A direct tensile strength for roller compacted (RCC) gravity dams. In: Proceedings of the fourth international symposium on roller compacted concrete (RCC) dams. 2003. p. 645–9.
[3] American Concrete Institute. Roller-compacted mass concrete. ACI manual of concrete practice, Part 1. ACI 207.5R-99, USA; 2004.
[4] Noorzaei J, Bayagoob KH, Thanoon WA, Jaafar MS. Thermal and stress analysis of Kinta RCC dam. Eng Struct 2006(11):1795–802.
[5] Noorzaeii, Jamaloddin, Jafaar, Saleh Mohd, Thanoon, Waleed A, Bayagoob, Khaled H. Temperature analysis of roller-compacted concrete dam during construction. Indian Concrete J 2005(5):23–8.
[6] Xie Hongwei, Chen Yaolong. Determination of the type and thickness for impervious layer in RCC dam. Adv Eng Softw 2005(8):561–6.
[7] Li, Shouyi, Ren, Jinke, Wu, Zhongming, Zhao, Lijuan. Simulation of temperature field – RCC arch dam. Int Water Power Dam Construct 2008(4):16–8.