STUDY ON TEMPERATURE DISTRIBUTION DUE TO FREEZING AND THAWING AT THE FENGMAN CONCRETE GRAVITY DAM

by

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Freezing and thawing damage is one of the major problems of the Fengman concrete dam. Based on the temperature records of the dam, appropriate heat transfer boundary conditions in the dam body are suggested. A three-dimensional finite element model is used to determine annual variation of temperature field of the dam as a case study. The deterioration problem of concrete dam owing to freezing and thawing effect is investigated.

Key words: *freezing and thawing, concrete dam, temperature field, deterioration*

Introduction

Thermal analysis of massive concrete structures is a common topic in many massive concrete publications. Temperature variation must be evaluated to define initial loading conditions for development of a defensive measure in dam safety analysis. The temperature distribution through the dam and its evaluation with time depend on some thermal parameters such as concrete properties, ambient conditions, concrete placing temperature *etc* [1]. In recent years, numerous analytical and experimental researches have been performed on the prediction of thermal field in mass concrete structures. Zhu proposed a useful analytical formula for prediction of water temperature in the deep reservoir as a prescribed boundary condition of heat transfer analysis in concrete dams [2]. Jaafar *et al*. developed a finite element based computer code for the determination of temperatures within the dam body. Based on the results obtained, it could be concluded that for a given roller compacted concrete dam, changing the placing schedule can optimize the locations of maximum temperature zones [3]. Thermal analysis of Kinta RCC dam was researched by Noorzaei *et al*.[4]. The actual climatic conditions and thermal properties of the materials were considered in the analysis. The predicted temperatures obtained from the finite element code that was developed are found to be in good agreement with actual temperatures measured in the field using thermocouples installed within the dam body [4]. Dechaumphai presented finite element

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analysis procedures for predicting temperature. Results demonstrate the efficiency of the method for the analysis of heated products that have complex geometries [5].

This paper focuses on the behaviors of Fengman concrete dam temperature under the environmental impact for 70 years by using finite element method. Aim at portraying the temperature levels, incurred as the temperature varies over time. The reasons of the cracking of the concrete dam owing to freezing and thawing deterioration will be investigated.

Approximation of atmospheric temperature and water temperature

In this paper, the thermal behaviors of Fengman dam is investigated by a three dimensional model, assuming a uniform distribution of the thermal properties and boundary conditions along the longitudinal axis. Figure 1 depicts basic model of dam and rock foundation for computing thermal transfer.

The daily temperature records are obtained from direct sight measurement, they may be approximated by the following sinusoidal function [1]:

$$T(\tau) = B\cos\omega(\tau + e_0) + b_0 \tag{1}$$

where B is the amplitude of atmospheric temperature, B = 20.0 °C; ω – the circle frequency, $\omega = \pi/12$; τ – the time, month; ε_0 – the phase angle, ε_0 = –6.5 months; b_0 – the compensation factor of the atmospheric temperature, b_0 = 2.0 °C. Figure 2 shows air temperature in the Fengman dam location *vs*. seasons from 1980 to 1981.

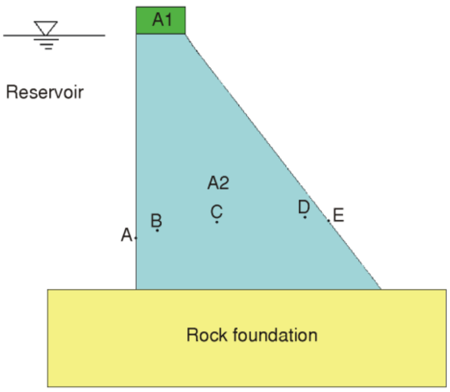

Figure 1. Basic model of dam and rock foundation for computing thermal transfer

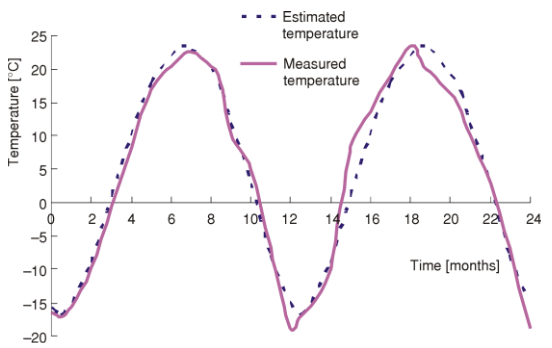

Figure 2. Air temperature in Fengman dam location *vs*. seasons from 1980 to 1981

It is necessary to predict the water temperature at various depths of the reservoir as a prescribed boundary condition for heat transfer equilibrium equation in concrete. According to a vast amount of observed data, an experimental–analytical formula for prediction of water temperature in the deep reservoir located in a different climate is proposed by Zhu. Based on the observed data for many years at the Fengman reservoir, the water temperature at different water depth can be expressed as follows [2]:

$$T(y,\tau) = T_\mathrm{m}(y) + A(y)\cos\omega(\tau - \tau_0 - \varepsilon) \tag{2}$$

$$T_m(y) = c + (b - c)\exp(-\alpha y) \tag{3}$$

$$A(y) = A_0 \exp(-\beta y) \tag{4}$$

$$\varepsilon = d - f\exp(-\gamma y) \tag{5}$$

where $T(y,\tau)$ is the water temperature; y – the water depth, m; τ is the time, month; $T_m(y)$ – the yearly average temperature when water depth is y; $A(y)$ – the amplitude of annual variation of water temperature when water depth is y; ε is the phase angle of annual variation of water temperature and air temperature, ω – the circular frequency of temperature variation. Other constants as show as follows: $c = 5.67$, $b = 11.1$, $A_0 = 13.4$, $\beta = 0.013$, $\alpha = -0.04$, $d = 2.15$, $f = 1.30$, $\gamma = 0.085$, $\tau_0 = 6.5$. Figure 3 shows design water temperature of the Fengman dam reservoir.

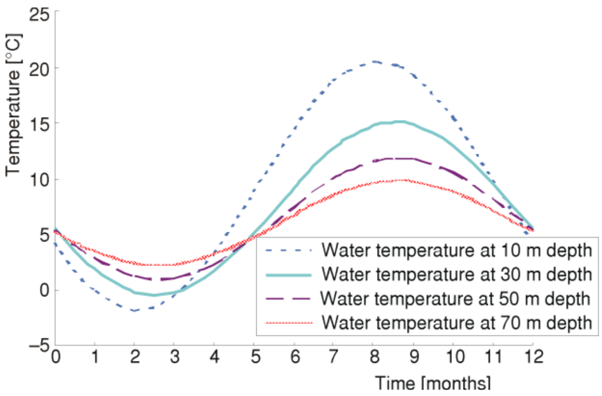

Figure 3. Water temperature of the Fengman dam reservoir

Thermal analysis of the Fengman concrete dam

Transient heat conduction in three dimensional heat transfer problem is governed by the following differential equation

$$-\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right) + Q = \rho c \frac{\partial T}{\partial t} \tag{6}$$

where q_x, q_y and q_z are conduction heat fluxes in the x, y and z-directions, respectively, c is the specific heat, ρ is the specific mass, Q is internal heat generation rate per unit volume and T is the temperature that varies with the coordinates as well as the time t. The conduction heat fluxes can be written in the form of temperature using Fourier's law. Assuming constant and uniform thermal properties, the relations are:

$$q_x = -k_x \frac{\partial T}{\partial x} \quad q_y = -k_y \frac{\partial T}{\partial y} \quad q_z = -k_z \frac{\partial T}{\partial z} \tag{7}$$

where k_x, k_y and k_z are thermal conductivity in the x, y and z-directions, respectively. Heat transfer boundary conditions consist of several heat transfer modes that can be written in different forms. The boundary conditions frequently encountered are as follows [6, 7]:

$$T_s = T_1(x, y, z, t) \tag{8}$$

$$-q_s = h(T_s - T_\infty) \tag{9}$$

where T_1 is the specified surface temperature; q_s – the specified surface heat flux (positive into surface); h – the convective heat transfer coefficient; T_s – the unknown surface temperature, and T_∞ – the convective exchange temperature. To determine the temperature field as initial time to start the transient computations, a steady state thermal transfer problem is carried out by applying the average annual air, water, and foundation temperature directly at the boundaries of the system. For the purpose of temperature distribution analysis of concrete dams during operation, the temperature of the concrete varying in the relative narrow region and the temperature dependence of thermal properties of concrete are negligible. The conductivity of concrete is assumed isotropic. In this period the heat transfer process will not be affected by the latent heat effects during phase change. The effect of solar radiation is taken into account by increasing the average annual temperature of the concrete-air interface about the average air temperature. Therefore, in this study the mechanical and thermal properties of concrete are assumed constant, isotropic, and temperature independent and the phase change phenomena is not taken into consideration.

The Fengman concrete gravity dam is situated in the southeast, about 24 km away from the center of Jilin City and is across the second Songhua river. The altitude of the dam top is 267.7 m. The storage capacity of the reservoir is 8770 million cubic meters and the total waterhead to the machine house is 41.5 m. The dam has a crest length of 1080 m and consists of 60 blocks of 18 m breadth. The largest block in the middle of the valley is 92.2 m high. Table 1 lists thermal parameters of Fengman concrete gravity dam and rock foundation [8]. The temperature distributions of transverse section of Fengman concrete gravity dam in January, February, July and August are shown in figs. 4 and 5.

Table 1. Thermal parameters of Fengman concrete gravity dam and rock foundation

Material parameters	Thermal conductivity [$Jm^{-1}s^{-1}°C^{-1}$]	Specific heat coefficient [$Jkg^{-1}·°C^{-1}$]	Specific mass [kgm^{-3}]
Concrete dam	2.9	1047	2350
Rock foundation	2.3	1172	2640

As shown in figs. 4 and 5, the minimum temperature of Fengman dam is –17.3 °C in January, and the maximum temperature of Fengman dam is 20.8 °C in August. Comparing with the figs. 4 and 5, the variation of atmospheric temperature and water temperature has a significant effect on the temperature of Fengman dam, and the temperature of Fengman dam varies in the relative narrow region in the vicinity of the concrete-air interface and the concrete-water interface.

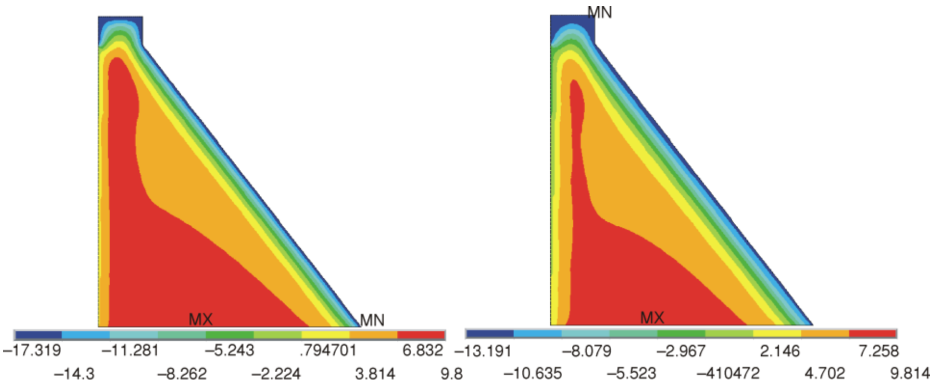

Figure 4. Temperature distribution of transverse section of the Fengman dam in January and February (unit: °C) (color image see on our web site)

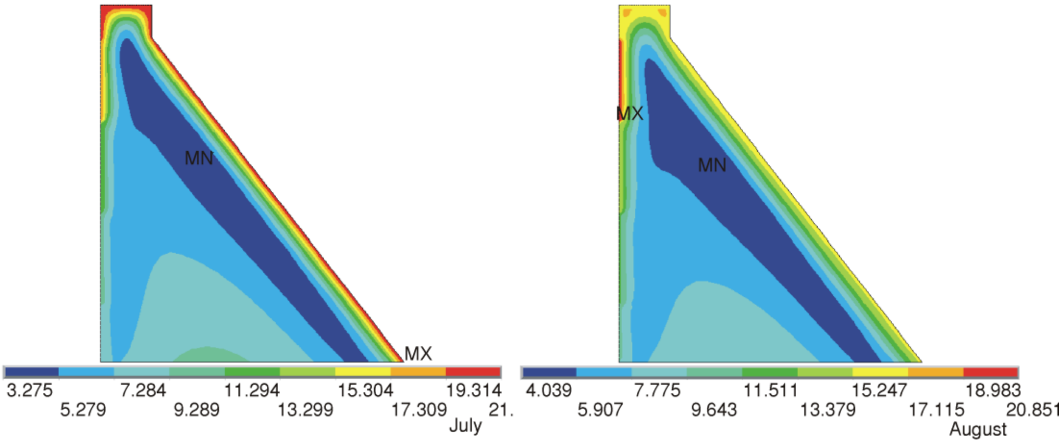

Figure 5. Temperature distribution of transverse section of the Fengman dam in July and August (unit: °C) (color image see on our web site)

Conclusions

Temperature distribution of concrete gravity dam is influenced by many factors. Based on the study carried out in this investigation, in severe cold area, seasonal thermal variation play a significant role in temperature distribution of Fengman concrete gravity dam, the dam is subjected to surface temperature variations exceeding 35 °C from winter to summer condition. Repeated freezing-thawing cycles can give some contribution to strength and stiffness degradation. Such severe conditions usually induce important thermal loads that jeopardize the intended durability of Fengman concrete gravity dam. January is the critical month, in this month the vast area of downstream may be cracked.

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