Numerical Simulation Analysis of Temperature Control of Large Volume Concrete Aqueduct

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Abstract. The Equivalent Heat Transfer Coefficient Method (EHTCM) is extended to the simulation of transient heat transfer problems for Large-scale concrete aqueducts in the construction process. The present EHTCM consists of the following ingredients: (1) a novel cell death and birth technique is proposed to deal with the existence or nonexistence of the concrete insulation layers, and hence the construction process of aqueducts can be easily simulated; (2) a simplified formula for specific heat transfer is implemented to improve the efficiency of transient computations. Several typical models and examples are selected to verify the performance of this method. On the basis of the weakened weak formulation, the EHTCM is spatially stable and convergent to the exact solution. The EHTCM can achieve the same results in accuracy and convergence rate, in comparison with the actual model method.

1. Introduction

Large-scale concrete aqueducts have been built all over the world. For example, in China alone, there are Wulunguhe aqueduct, wanlong aqueduct, caohe aqueduct, and diaohe aqueduct. These huge hydraulic projects play a great role in the clean water supply for drinking or irrigation. The safety and stability of such a large-scale structure is very important in the process of construction and service. Among the problems with technique that hydraulic engineers face, concrete cracks can be one of the toughest, especially the temperature cracks on the surface or through the aqueduct body[1-5]. In addition to the damage and fracture mechanism of concrete material, the temperature load during construction is very complicated and should be treated carefully and adequately. In engineering practices, the concrete aqueducts are constructed by two layers, and many measures are taken to reduce the maximum temperature and the temperature gradient. These measures include optimization of composite mixture, pre-cooling of aggregate, surface protection and water pipe cooling. All these measures are chosen and controlled according to the prediction of the temperature field. Before the popularization of computers, the temperature prediction was primarily carried out by analytical methods or semi-analytical semi-empirical methods. With the development of numerical methods such as finite element method (FEM) and finite difference method (FDM), significant progress has been made in the accuracy and efficiency of the computational prediction of temperature and stress field, which greatly advances the concrete construction technology[6-10]. To achieve more accurate results for those parts of concern such as the surfaces and interfaces between layers, very small time steps and
very fine mesh should be used in the simulation of transient temperature field during aqueducts construction. Also, if the concrete cracks, the cracking process should be considered and the adaptive technique used to capture the nonlinear distributions of great temperature gradient or strain gradient. Therefore, the computational efficiency of FEM could be reduced evidently[11]. The EHTCM model without insulation, which is surface protection, but it can achieve the same accuracy but more efficiency than the actual model with insulation.

This paper extends EHTCM to the transient temperature field simulation for massive concrete structures such as aqueducts during the construction period. The formulations of EHTCM are briefly introduced. To simulate the construction process of large-scale concrete aqueducts, a novel background cell death and birth technique is proposed. Then the validity, accuracy and computational efficiency of the proposed method are discussed with a typical concrete aqueduct example during a thermal shock. In the end, the EHTCM is applied on the temperature field simulation of a practical aqueduct during its construction period.

2. The calculation theory and analysis of numerical simulation

2.1. Basic formulations and solution approach of temperature field

Based on the energy balance principle, the general partial differential equation governing heat flow in a 3-D solid medium is expressed as[12]:

\[
c\rho \frac{\partial T}{\partial \tau} \int \int \int dxdydz = \left[ \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{dQ}{d\tau} \right] \int \int \int dxdydz
\]

(1)

Where \( T \) is concrete temperature, \( \lambda \) are heat conductivity coefficient, \( \rho \) is the material density, \( c \) is the material’s specific heat, \( Q \) is the adiabatic temperature rise of the concrete, \( \tau \) is time, and \( x, y, z \) are the three directions of cartesian coordinates.

The initial transient temperature and the two main boundary conditions at the external surfaces are represented as:

\[
T(x, y, z, 0) = T_0(x, y, z)
\]

(2)

\[
T(\tau) = f(\tau)
\]

(3)

\[
\lambda_x \frac{\partial T}{\partial x} n_x + \lambda_y \frac{\partial T}{\partial y} n_y + \lambda_z \frac{\partial T}{\partial z} n_z + R = -\beta(T - T_a)
\]

(4)

In which \( f(\tau) \) are the known temperature values on some boundaries; \( R \) is the heat flowing from the surface; \( \beta \) is the heat transfer coefficient; \( T_a \) is the ambient temperature; \( \lambda_x, \lambda_y, \lambda_z \) are heat conductivity coefficients in \( x, y, z \) directions; respectively, \( n_x, n_y \) and \( n_z \) are the direction cosines of the outward normal to the surface.

2.2. Cell death and birth technique

This paper introduces a cell death and birth technique for EHTCM while the cell status changes between “existence” and “nonexistence”. This technique has a similar function to the element death and birth technique used in the FEM. When some structure layer is constructed, the relevant background cells are then activated, and their edges and nodes are involved in the construction of
smoothing domains and field approximation. Details of the three probable situations in the implementation process are as follows: first, if only one side layer of the interface is activated, the active cells around the interface are considered as boundary cells; second, if the material property changes between the two active layers, material discontinuity should be considered; and in the last case, the cells along the interface are considered as boundary cells, and the attached smoothing domains are constructed within the same material[13]. With this death and birth technique, the installation and dismantling of insulation layer during the construction process of concrete aqueduct can be easily simulated.

2.3. Simulation of the temperature with Insulation

Figure 1. Three-Dimensional network model

The diaohe aqueduct is the first phase of the south-to-north water diversion project built on the diao river in henan province of China. The diaohe aqueduct is a large pre-stressed concrete aqueduct with a total length of 350m, and the maximum span of the aqueduct simply supported at bottom is 40m length. The top width is 15 m, and the bottom width is 15.1 m, the Three-Dimensional network model is shown in Figure 1. In the entire FE model, both concrete and insulation are simulated by 3-D solid element. The shared nodes of the insulation solid element and the concrete solid element are used to simulate the convection heat of insulation and concrete.

The main factors of insulation material affect the temperature field of aqueduct structure are the thickness, thermal conductivity and specific heat[12]. Thus the study mainly focus on the three factors. The adiabatic temperature rise of concrete is given by:

\[ T(\tau) = T_{\text{max}}(1 - \exp(-m\tau)) \]  

where \( T_{\text{max}} \) is the maximum temperature of concrete under adiabatic conditions, \( T_{\text{max}} = 58.1^\circ\text{C} \); \( \tau \) is the concrete age in days; and \( m \) is the model parameter that represent the heat generation rate, \( m = 0.759 \). The transient temperature is computed for the aqueduct during the construction period. The concrete pouring temperature takes 20°C and ambient temperature takes 20°C. The material properties for concrete, insulation and relevant coefficients are taken as follows:

| \( \lambda_{\text{concrete}} \) (J/(m×h×°C)) | \( c_{\text{concrete}} \) (J/(kg×°C)) | \( \rho_{\text{concrete}} \) (kg/m³) | \( \lambda_{\text{insulation}} \) (J/(m×h×°C)) | \( c_{\text{insulation}} \) (J/(kg×°C)) | \( \rho_{\text{insulation}} \) (kg/m³) | \( \beta_{\text{air}} \) (J/(m²×h×°C)) |
|---|---|---|---|---|---|---|
| 9000 | 1046.5 | 2549 | 125.6 | 1300 | 100 | 82200 |

3. The calculation results discussion

3.1. The influence of insulation thickness

For analysis the influence of the insulation’s thickness on the temperature field of aqueduct structure, the concrete pouring temperature takes 20°C and ambient temperature takes 20°C, the material properties for insulation are shown in table 1.
Figure 2. Comparison of temperature histories for some thickness

Figure 2 shows a comparison of temperature histories for the six insulation thickness at point A, and as can be seen, the peak temperatures for the points located at A are gradually increased and delayed along with the increase in thickness of the insulation layer.

3.2. The influence of thermal conductivity of insulation

For analysis the influence of the thermal conductivity to the temperature field of aqueduct structure, the concrete pouring temperature takes 20°C and ambient temperature takes 20°C. The material properties for insulation are $c_{\text{insulation}} = 1300 \text{ J/(kg°C)}$ and $\rho_{\text{insulation}} = 24 \text{ kg/m}^3$ respectively.

The thermal coefficient of the insulation board commonly used in engineering is between 0.12 to 0.92 kJ/(m²·h·°C). So the scope between 0.12 to 0.92 kJ/(m²·h·°C) are taken to be analyzed.

Figure 3. Comparison of temperature histories for some values of thermal coefficient

Figure 3 shows a comparison of temperature histories for some values of thermal coefficient at point A; As can be seen, the peak temperatures for the point located at A are gradually decreasing and advanced with the increase in thermal coefficient of the insulation layer.

3.3. The influence of specific heat of insulation

For analysis the influence of the specific heat of insulation on the temperature field of aqueduct structure, the concrete pouring temperature takes 20°C and ambient temperature takes 20°C. The material properties for insulation can be seen in table 1, while the $\rho_{\text{insulation}} = 24 \text{ kg/m}^3$.

Figure 4. Comparison of temperature histories for some values of specific heat
Figure 4 shows a comparison of temperature histories for some values of specific heat at point A. As can be seen, the specific heat of insulation has such an influence that first increases and then decreases as the age increase on the temperature field of concrete aqueduct, also shows that the more larger of the value of specific heat the more obvious of the influence. However, because of the value of specific heat is very little, it has a little of influence on the insulation performance.

3.4. The influence of the equivalent heat transfer coefficient

The insulation effect of the insulation materials to the concrete aqueduct can be achieved by changing the heat transfer coefficient between the concrete and the air[13], which is called the equivalent heat transfer coefficient method. This method can get the same reliable results with less workload and less computing time, which depends on the accuracy of the values of the equivalent heat transfer coefficient. In practical engineering, the equivalent heat transfer coefficient $\beta_c$ can calculated as the follow formula:

$$\beta_c = \frac{1}{\beta_{air} + \sum \left( h_i / \lambda_i \right)}$$

Where $h_i$ is the thickness of i-th layer of insulation; $\lambda_i$ is the thermal conductivity coefficient of i-th layer of insulation; and $\beta_{air}$ is the heat transfer coefficient of the concrete in the air.

For analysis the validity, accuracy and computational efficiency of the proposed formula, one example is computed with actual model and equivalent heat transfer coefficient model. During the computing, the concrete pouring temperature takes 20℃ and ambient temperature takes 20℃, The material properties for concrete and insulation as well as relevant coefficients can be seen in table 1.

Figure 5 shows a comparison of temperature histories for two models at point A. As can be seen, the equivalent heat transfer coefficient model can achieve the same results in accuracy and convergence rate compared with the actual model method, and the EHTCM is spatially stable and convergent to the exact solution. However the EHTCM finished the calculation need less time (84.5 seconds) than the actual model method (145.6 seconds).

4. Conclusions

Based on the above study, the following conclusions can be drawn:

(1) Equivalent heat transfer coefficient method is introduced to perform the thermal analysis of insulation measures in large-scale concrete aqueducts. The numerical results were compared directly to two theoretical models. It is found that the proposed method is highly accurate.
(2) The simulation of the temperature field by the EHTCM can reflect the influence of the insulation, and the cell death and birth technique can achieve the installation and dismantling of insulation on temperature distributions. Moreover, the computational results are in good agreement with the actual model method, which shows that this method is generally effective and is excellent for temperature simulation and forecasting.

(3) The simulation of the temperature field by the EHTCM cell death and birth technique shows that the removal time of insulation layer has a greater influence on the temperature field of the concrete aqueduct. Along with the time for insulation removed extended the temperature difference between inside and outside of concrete aqueduct is gradually reduced.

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References
[1] Xia, S. F., Lu, Y. H., Li, X. L., Geng, Y. S. (2012) Numerical Simulation of Temperature Control and Anti-cracking Measures for the Ming River Aqueduct of the South-to-North Water Diversion Project. S-to-N.W. Div. W. Sci. tech., 10(4): 1-6.
[2] Wang, Z. H., Zhu, Y. M., Yu, S. P. (2007) Study on temperature control and crack prevention of thin-walled concrete structures during the construction period. J. Xi.an. Univ. Arch. Tech. (N. S. E.), 39(6): 773-778.
[3] Zhang, P., Tian, B., Liu, D. (2008) Real time temperature simulation of Caohhe River landing rectangular aqueduct for Project during construction period. Eng. J. Wuh. Univ., 41(3): 38-42.
[4] Chen, Y. Y., Huang, D. H. (2011) Techniques and development trends of temperature control and crack prevention of large-scale concrete aqueducts. Adv. Sci. Tech. W. Res., 31(2): 16-22
[5] Tian, Y., Jin, X. Y., Jin, N. G. (2013) Thermal cracking analysis of concrete with cement Hydration model and equivalent age method. J. Computers and Concrete., 11(4): 271-289.
[6] Wu, X., Mu, C. L., Zhang, L. L., Wang, C. (2010) Research on Concrete Hydration Heat in Raft Foundation and Numerical Simulation. J. Nor-east Uni. (N.S.), 31(2): 285-288.
[7] Zhu, B. F. (1999) Effect of cooling by water flowing in nonmetal pipes embedded in mass concrete. J. Constr. Eng. Manage., 125(1): 61-68.
[8] Luna, R., and Wu, Y. (2000) Simulation of temperature and stress fields during RCC dam construction. J. Constr. Eng. Manage., 126(5): 381-388.
[9] Li, Y., Nie, L., Wang, B. (2014) A numerical simulation of the temperature cracking propagation process when pouring mass concrete. J. Automation in Construction., 203-210.
[10] Liu, X. H., Zhuang, C., Chang, X. L., Zhou, W., Cheng, Y. G., Duan, Y. (2015) Precise simulation analysis of the thermal field in mass concrete with a pipe water cooling system. J. Applied Thermal Engineering., 78(5): 449-459.
[11] Zienkiewicz, O. C., and Taylor, R. L. (2005) The finite element method(V1: The basis), 6th Ed., Butterworth-Heinemann, Oxford, England.
[12] Zhu, B. F. (1998) Thermal stresses and temperature control of mass concrete, China Electric Power Press, Beijing.
[13] Zhu, B. F. (1991) Equivalent equation of heat conduction in mass concrete considering the effect of pipe cooling. J. Hydraul. Eng., (3): 28-34.