Water Science and Engineering 2017, 10(2): 107−114

HOSTED BY ELSEVIER

Available online at www.sciencedirect.com

Water Science and Engineering

journal homepage: http://www.waterjournal.cn

Thermal field in water pipe cooling concrete hydrostructures simulated with singular boundary method

Yong-xing Hong [a,b], Wen Chen [a,b], Ji Lin [a,b,*], Jian Gong [a,b], Hong-da Cheng [c]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[b] College of Mechanics and Materials, Hohai University, Nanjing 211100, China
[c] School of Engineering, University of Mississippi, Mississippi 38677, USA

Received 14 November 2016; accepted 13 February 2017
Available online 23 June 2017

Abstract

The embedded water pipe system is often used as a standard cooling technique during the construction of large-scale mass concrete hydrostructures. The prediction of the temperature distribution considering the cooling effects of embedded pipes plays an essential role in the design of the structure and its cooling system. In this study, the singular boundary method, a semi-analytical meshless technique, was employed to analyze the temperature distribution. A numerical algorithm solved the transient temperature field with consideration of the effects of cooling pipe specification, isolation of heat of hydration, and ambient temperature. Numerical results are verified through comparison with those of the finite element method, demonstrating that the proposed approach is accurate in the simulation of the thermal field in concrete structures with a water cooling pipe.
© 2017 Hohai University. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Keywords: Thermal field; Singular boundary method; Semi-analytical method; Water cooling pipe; Concrete hydrostructure

1. Introduction

Concrete hydrostructures such as dams, foundations, and pumping stations suffer from crack problems due to the hydration heat, especially at the early stages of concrete solidification (Kogan, 1980). A water pipe cooling system is considered an efficient technology for cooling the interior temperature in mass concrete and consequently mitigating thermal stress cracks and resultant structural weakness (Qiang et al., 2015). As stated in Hauser et al. (2000), the flowing water along the pipe not only absorbs the heat from the concrete, but also upgrades the thermal storage capacity and decreases hydration heat (Kim et al., 2001), furnishing a strategy for better thermal removal.

Since the first successful application of the cooling pipe system in the Hoover Dam (Kwak et al., 2014), the prediction of the temperature history and distribution in massive concrete structures with a pipe cooling system has attracted much attention from engineering and science communities. Several major factors affecting cracks, such as the temperature (Ding and Chen, 2013), the thermal gradient (Sato et al., 2005), the structure restraint, and the material thermal stability (Zhang et al., 2004), have been taken into account. The equivalent equation of heat conduction in a concrete structure with a cooling pipe, proposed by Zhu (1991) without consideration of the thermal gradient, describes the average temperature:

$$\frac{\partial T}{\partial t} = a\nabla^2 T + (T_0 - T_{\mathrm{w}})\frac{\partial \phi}{\partial t} + \frac{\partial \theta}{\partial t} \tag{1}$$

where T is the temperature of concrete, T_0 is the initial temperature of concrete close to the water pipe, T_{w} is the cooling water temperature, ϕ is a given function associated with the

This work was supported by the National Natural Science Foundation of China (Grants No. 11572111 and 11372097) and the 111 Project (Grant No. B12122).
* Corresponding author.
E-mail address: linji861103@126.com (Ji Lin).
Peer review under responsibility of Hohai University.

http://dx.doi.org/10.1016/j.wse.2017.06.004
1674-2370/© 2017 Hohai University. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

heat flux from concrete to water, a is the thermal diffusivity of concrete, and θ is the adiabatic temperature raise of concrete at a certain time instance t. Three boundary conditions for measuring the thermal gradient on the boundary (Zhu, 1999) are as follows:

$$T = T(t) \tag{2}$$

$$\eta\frac{\partial T}{\partial \boldsymbol{n}} = \beta(T_{\mathrm{w}} - T) \tag{3}$$

$$\frac{\partial T}{\partial \boldsymbol{n}} = 0 \tag{4}$$

where $T(t)$ is a prescribed temperature process, η represents the coefficient of heat convection, $\boldsymbol{n}$ is the unit outward normal vector on the boundary of the computational domain, and β is a rational number. This system of equations can also be well utilized in the formulation of casting processes of mass concrete containing double-layer staggered heterogeneous cooling pipes, as reported in Yang et al. (2012).

As mentioned above, the equivalent equation of heat conduction in the concrete-pipe system has been studied using the finite element method (FEM) (Chen et al., 2011). In the FEM, the structures are discretized into small elements, and a final system of equations is made up of approximations in each sub-element, which can be arduous, time consuming, and computationally expensive, especially due to the fact that a considerable number of elements are needed to model the small pipes of a cooling system (Sasaki et al., 2014). In order to tackle this bottleneck, one alternative method is to neglect the practical sectional shape and size of cooling pipes for simulations (Liu et al., 2015). Although it can be used to approximate the equivalent temperature of the target structure efficiently, this method still lacks the capacity to model the thermal field surrounding the inner water pipes.

Instead of the FEM, the singular boundary method (SBM) was introduced in this study to solve the heat conduction problem with a water pipe. The SBM is a newly developed meshless method proposed by Chen (2009) for the simulation of boundary value problems (Chen and Gu, 2012). This method falls into the category of the boundary-type method with integration-free attributes, which can also be considered one type of ameliorative algorithm of the method of fundamental solutions (MFS) (Šarler, 2009). The SBM uses the fundamental solutions of the governing equations as the basis functions. To avoid the singularity of the fundamental solutions, the origin intensity factors are introduced (Li et al., 2016; Wei et al., 2015). Therefore, the SBM is a truly semi-analytical boundary-type meshless method.

The SBM has been widely used to deal with many engineering problems, such as wave propagation problems (Lin et al., 2014), steady-state heat conduction problems (Wei et al., 2016), and time-dependent problems (Wang and Chen, 2016). Moreover, the SBM, combined with the dual reciprocity method and inverse interpolation, is effective in solving non-homogeneous problems (Chen et al., 2014). For the problems considered in this study, only the information on the surface of the structure and pipe was required. Due to the use of the fundamental solution, the SBM is a semi-analytical technique and has great potential for the simulation of time-dependent problems.

This paper is organized as follows: in Section 2, the mathematical formulation of the SBM for the thermal field in a concrete structure with a water pipe cooling system is introduced; in Section 3, three benchmark examples are examined to show the effectiveness of the presented method; and, finally, some conclusions and remarks are provided in Section 4.

2. Numerical formulation of pipe water cooling system

In order to apply the SBM, the time-dependent problems can be transformed into a system of steady-state problems using the time difference method. In this study, the implicit Euler scheme was employed to discretize the time derivatives in Eq. (1) and transform the considered problems into a system of Helmholtz equations. The SBM could then be used to carry out the spatial discretization in the domain Ω of interest.

2.1. Time discretization

To begin with, the time interval $[0,\ t]$ is divided equally into M sub-intervals. Then, the time step is $\mathrm{d}t = t/M$, and $t_n = n\mathrm{d}t$, where $n = 0,\ 1,\ \cdots,\ M$. The implicit Euler scheme is used to discretize Eq. (1) as follows:

$$\left(\nabla^2 - \frac{1}{a\mathrm{d}t}\right)T_{n+1}(\boldsymbol{x}) = -\frac{1}{a\mathrm{d}t}T_n(\boldsymbol{x}) - \frac{1}{a}\left[(T_0 - T_{\mathrm{w}})\frac{\partial\phi_{n+1}}{\partial t} + \frac{\partial\theta_{n+1}}{\partial t}\right] \tag{5}$$

where T_n is the temperature of concrete at time t_n, ϕ_{n+1} is ϕ at time t_{n+1}, θ_{n+1} is θ at time t_{n+1}, and $\boldsymbol{x} = (x,\ y)$ for a two-dimensional problem. Using the notation $1/(a\mathrm{d}t) = \mu^2$, we come to the following system of Helmholtz equations, which can be solved by the proposed SBM:

$$(\nabla^2 - \mu^2)T_{n+1}(\boldsymbol{x}) = g_{n+1}(\boldsymbol{x}) \tag{6}$$

where
$g_{n+1}(\boldsymbol{x}) = -\mu^2 T_n(\boldsymbol{x}) - (T_0 - T_{\mathrm{w}})\partial\phi_{n+1}/(a\partial t) - \partial\theta_{n+1}/(a\partial t)$.

2.2. Singular boundary method

At first, using the dual reciprocity method (Chen and Gu, 2012), the solution to the non-homogeneous Helmholtz equation (Eq. (6)) can be approximated by the summation of $T^{\mathrm{p}}_{n+1}(\boldsymbol{x})$ and $T^{\mathrm{h}}_{n+1}(\boldsymbol{x})$, as follows:

$$T_{n+1}(\boldsymbol{x}) = T^{\mathrm{p}}_{n+1}(\boldsymbol{x}) + T^{\mathrm{h}}_{n+1}(\boldsymbol{x}) \tag{7}$$

where $T^{\mathrm{p}}_{n+1}(\boldsymbol{x})$ represents the particular solution and $T^{\mathrm{h}}_{n+1}(\boldsymbol{x})$ represents the homogeneous solution. The particular solution $T^{\mathrm{p}}_{n+1}(\boldsymbol{x})$ satisfies the non-homogeneous equation (Eq. (8)), but does not necessarily satisfy the boundary conditions, and $T^{\mathrm{h}}_{n+1}(\boldsymbol{x})$ satisfies the homogeneous equation as follows:

Download English Version:

https://daneshyari.com/en/article/4929456

Download Persian Version:

https://daneshyari.com/article/4929456

Daneshyari.com