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Research on Xiluodu Underground Engineering Flood Discharging Tunnel Longluowei Section Lining Concrete with Cooling Pipes

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Abstract: Cracks are often found at lining concrete of flood discharging tunnel during construction. Previous studies have shown that temperature stress is the main cause leading to cracks during construction. The cooling pipes method is one of the important measures to control temperature. The equivalent heat conduction Finite Element Method (FEM), because of its simple, is usually applied to simualte the temperature field. The FEM with cooling pipes which can simulate the temperature field accurately has rarely been reported. For this reason, the lining concrete of Xiluodu underground engineering flood discharging tunnel Longluowei section is simulated by FEM with cooling pipes. Good simulated results are obtained comparing with the experimental data and some very useful conclusions can be applied for site analysis to prevent cracks.

Key words: Lining concrete, cooling pipes, FEM, temperature, cracks

INTRODUCTION

Lining concrete belongs to the mass concrete which often has cracks during construction. Once the crack appears, it will lead to the cavitation erosion at runtime especially for the Longluowei section with high flow velocity.

Previous studies have shown that temperature stress is the main reason leading to cracks during construction if water conservation has been done at the surface of concrete (Duan *et al*., 2006; Chen and Duan, 2010; Zhang and Duan, 2011; Zou and Duan, 2013).

Temperature field of concrete with cooling pipes is very difficult to simulate accurately. The equivalent heat conduction FEM is usually applied (Zhu, 1999, 2003b) but it is a method for solving the temperature with an average sense which can't reflect the true temperature. In recent years, domestic scholars have done some researches on the FEM with cooling pipes (Huang and Zhou, 2009; Zhu, 2003a; Chen *et al*., 2012; Liu *et al*., 2009; Xie *et al*., 2011; Liu *et al*., 2012) but there are few researches on the underground engineering lining concrete. In order to simulate the temperature field accurately and get some valuable results, the lining concrete of Xiluodu underground engineering flood discharging tunnel Longluowei section is simulated by FEM with cooling pipes on this study.

COMPUTATIONAL METHOD FOR TEMPERATURE OF CONCRETE

According to heat balance principle, concrete in the Cartesian coordinate system is satisfied with the heat conduction equation as follows:

$$\frac{\partial T}{\partial \tau}=a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{\partial \theta}{\partial \tau} \tag{1}$$

In which a = λ. ρc, λ is thermal conductivity, kJ/(m•d•K), c is specific heat, kJ/(kg.K), c is density, kg m^{-3}, θ is adiabatic temperature rise, K, τ is time, d.

There are three main boundary conditions for the temperature calculation. The concrete surface temperature is known function which belongs to the first boundary condition that is $T(\tau) = \varphi(\tau)$. The concrete surface heat flow is known function which belongs to the second boundary condition that is $-\lambda\partial T/\partial n = \phi(\tau)$, n is the common normal of the exterior surface. The concrete exposed to air which belongs to the third boundary condition, it presumes the heat flow of concrete surface is proportional to the difference of the concrete surface temperature T and air temperature T_a that is:

$$-\lambda\frac{\partial T}{\partial n}=\beta(T-T_a)$$

β is surface heat transfer coefficient, kJ/(m^2.d.K).

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The unstable temperature field functional of space can be expressed as follows:

$$I=\iiint_R \frac{1}{2}\left[\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2\right]dxdydz$$

$$-\iiint_R \frac{1}{a}\left(\frac{\partial \theta}{\partial \tau}-\frac{\partial T}{\partial \tau}\right)dxdydz$$

$$+\iint_c \frac{1}{\lambda}\left[\frac{1}{2}\beta T^2-\beta T_a T\right]ds \quad (2)$$

After spatial discretization:

$$[H]\{T\}+[R]\left\{\frac{\partial T}{\partial \tau}\right\}=\{F\} \quad (3)$$

In which:

$$H_{ij}=\sum_e (h_{ij}^e+g_{ij}^e)$$

$$R_{ij}=\sum_e r_{ij}^e$$

$$F_i=\sum_e\left(f_i^e\frac{\partial \theta}{\partial \tau}+p_i^e T_a\right)$$

$$h_{ij}^e=\iiint_{\Delta R}\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x}+\frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y}+\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}\right)dxdydz$$

$$r_{ij}^e=\frac{1}{a}\iiint_{\Delta R} N_i N_j dxdydz$$

$$f_i^e=\frac{1}{a}\iiint_{\Delta R} N_i dxdydz$$

$$g_{ij}^e=\frac{1}{\beta}\iint_{\Delta C} N_i N_j ds$$

$$p_i^e=\frac{1}{\beta}\iint_{\Delta C} N_i ds$$

N is shape functions of element, R is solution domain, C is the third boundary.

After time discretization:

$$\left([H]+\frac{1}{\Delta\tau_n}[R]\right)\{T_{n+1}\}=\frac{1}{\Delta\tau_n}[R]\{T_n\}+\{F_{n+1}\} \quad (4)$$

According to the known quantity $\{F_{n+1}\}$ and $\{F_n\}$, the unknown quantity $\{T_{n+1}\}$ can be deduced by the linear equations.

When concrete contains cooling pipes, the temperature rise of water ΔT_w along the pipes' length should be considered. They can be calculated as follows (Zhu, 1999):

$$\Delta T_w=-\frac{\lambda}{c_w\rho_w q_w}\iint_\Gamma \frac{\partial T}{\partial n}ds \quad (5)$$

In which the integral on curve Γ is along the cooling pipes' edge and c_w is specific heat of water, ρ_w is density of water, ρ_w is flow of water.

The iterative calculation method assumes the integral:

$$\iint_\Gamma \frac{\partial T}{\partial n}ds$$

has linear variation along the cooling pipes' length from section i to i+1:

$$\Delta T_{wi}=-\frac{\lambda}{2c_w\rho_w q_w}\left[\left(\iint_\Gamma \frac{\partial T}{\partial n}dS\right)_\lambda+\left(\iint_\Gamma \frac{\partial T}{\partial n}dS\right)_{\lambda+1}\right] \quad (6)$$

$$\Delta T_{wi}=T_{w1}+\sum_{j=1}^{i-1}\Delta T_{wj}, i=2,3,... \quad (7)$$

The control standard for the parametric error is expressed as follows:

$$\max_i=\left|\frac{T_{wi}^k-T_{wi}^{k+1}}{T_{wi}^{k+1}}\right|\le\varepsilon \quad (8)$$

In which k is iterations, ε is a designated very small number.

NUMERICAL SIMULATIONS OF LINING CONCRETE

Characterization of model paremeters: The finite element model of Xiluodu underground engineering flood discharging tunnel Longluowei typical section is shown in Fig. 1. The side wall has thickness of 1 m, width of 9 m and height of 14.3 m. The cooling pipes place at the center of the thickness of side wall which has the diameters of 25 mm and the interval of 0.8 m. The elements near the pipes are shown in Fig. 2. The initial temperature of concrete and rock is 291.15 and 297.15 K, respectively. The environment temperature of air, water pipe injection temperature in Fig. 3. Water flow q_w is shown in Fig. 4. The adiabatic temperature rise can be expressed as θ (t) = 34t/(1.034+t)+2.73.15 with correlation coefficient

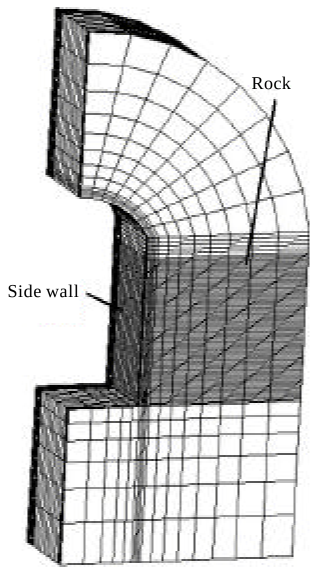

Fig. 1: Finite element model of lining concrete and sourrounding rock

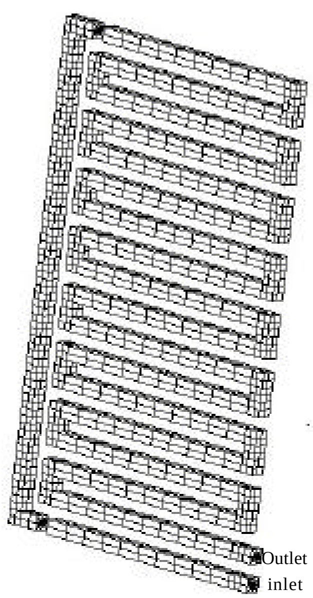

Fig. 2: Elements near the cooling pipes

of 0.998. The density of concrete is 2550 kg m^{-3}. The specific heat of concrete is 0.945 kJ kg^{-1} K. The thermal conductivity of concrete is 203.76 kJ/(m.d.K). The time which template removed from the surface of the side wall is 3 day after pouring and the surface water curing

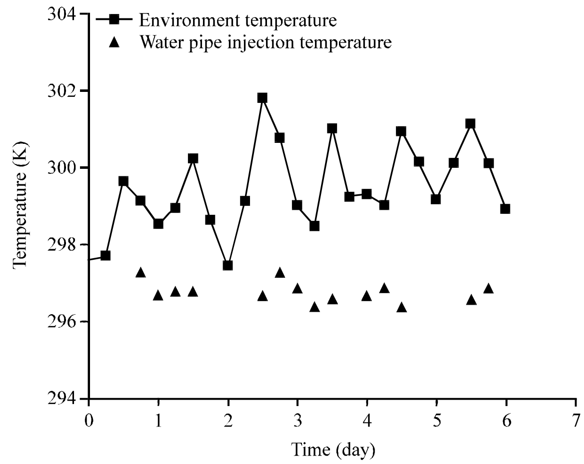

Fig. 3: Environment temperature and water pipe injection temperature

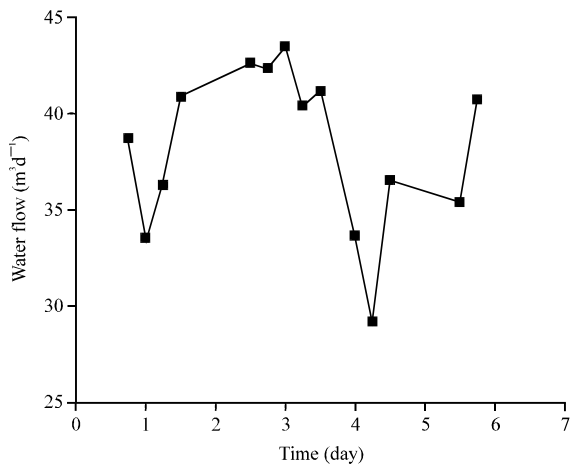

Fig. 4: Water flow of cooling pipes

time is 28 day. The surface heat transfer coefficient of the template and concrete is 447 kJ/(m^2.d.K) and 720 kJ/(m^2.d.K), respectively. The density of water is 1000 kg m^{-3}. The specific heat of water is 4.187 kJ kg^{-1} K. The boundary conditions are demonstrated in detail by Sun and Duan (2013). The typical point is at the center of thickness, width and height of side wall corresponding to the place which the thermometer buried.

RESULTS OF NUMERICAL SIMULATIONS AND ANALYSIS

The contour plots of the cross-section at the center of thickness of side wall are shown in Fig. 5 and 6. The duration curves of temperature of typical points are shown in Fig. 7.

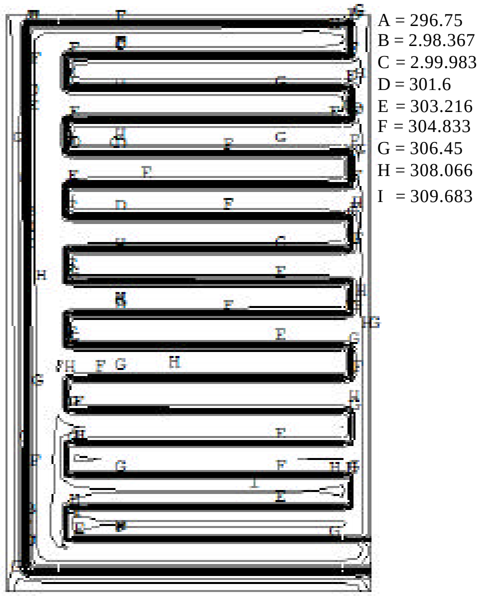

Fig. 5: Contour plots of the cross-section at the center of thickness of side wall after pouring 1.5 day

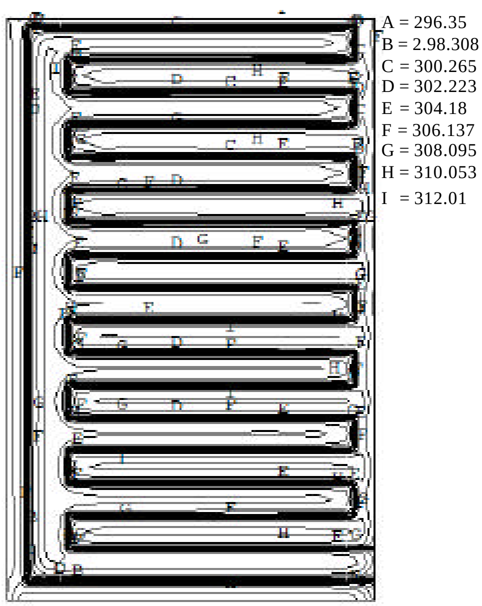

Fig. 6: Contour plots of the cross-section at the center of thickness of side wall after pouring 3 day, (a) Point at the center of thickness, width and height of side wall and (b) Point at the water outlet

From Fig. 5 and 6, The emerging location of the highest temperature is generally located in the middle of

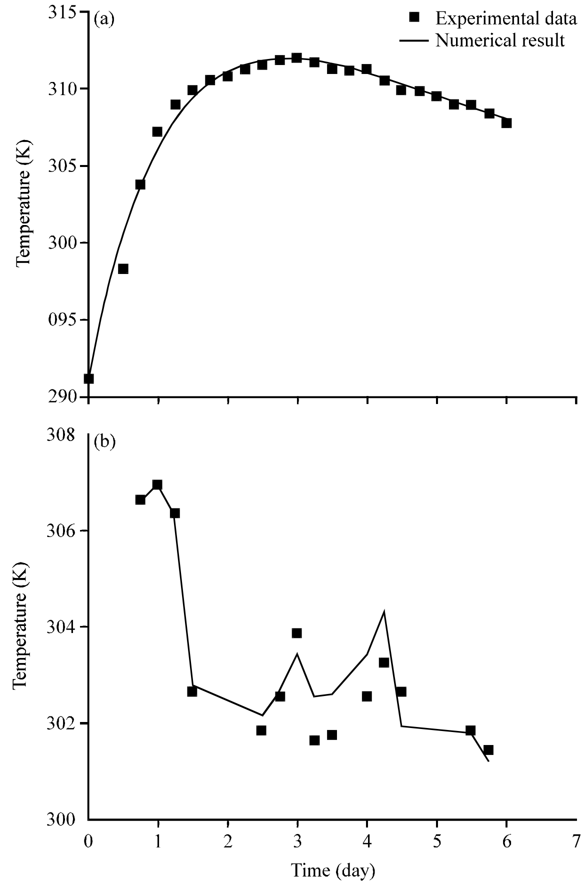

Fig. 7(a-b): Duration curves of temperature of each typical point (a) Good simulated temperature and (b) Uniform temperature

two pipes and below the center of height while the previous studies shows that the location above is at the center of height (Sun and Duan, 2013; Zou and Duan, 2013). The results also show that the differences between two methods (Huang and Zhou, 2009) are not only the regular of temperature but also the location prone to crack. Figure 7a shows good simulated temperature results are obtained when the points are far away from the pipes. The lining concrete reaches the highest temperature at 3 day after pouring. From the Fig. 7b, Uniform temperature regular pattern has been obtained comparing to the experimental data at the water outlet while the previous studies shows that the regular is simliar as Fig. 7a (Sun and Duan, 2013; Zou and Duan, 2013). There are some differences after 1.5 day. The reason could be the grid size (Zhu, 2003a), the work stopping of cooling pipes once in a while, the error of experimental data, the limitation of the numerical method and so on. Although new numerical methods have been introduced (Chen *et al*., 2012; Liu *et al*., 2009; Liu *et al*., 2012), it seems has not improved apparently. In fact, it is very difficult to simulate the temperature of the water outlet accurately. The study can also obtain that even if the temperature near the pipes varies quickly, the impact of temperature regular pattern of the points far away from the pipes turns out to be small.

CONCLUSION

In order to avoid cavitation erosion at runtime due to the crack during construction, the FEM with cooling pipes is adopted to simulate the temperature field of the Xiluodu underground engineering flood discharging tunnel Longluowei section lining concrete. The method avoids the disadvantages of equivalent heat conduction FEM. Calculation results show good precision of temperature comparing with the experimental data. The emerging position of the highest temperature is located in the middle of two pipes and below the center of height of side wall which is more prone to crack. The regular pattern of temperature development at the water outlet is the same as the construction site. Although the temperature curves at the water outlet varies quickly, it plays a minor role on the regular pattern of the points far away from the pipes. Calculation results can be better applied to site analysis and cracks preventing.

NOTATION

The following symbols are used in this study:

λ	=	Thermal conductivity
c	=	Specific heat
ρ	=	Density
θ	=	Adiabatic temperature rise
τ	=	Time
n	=	Common normal of the exterior surface
β	=	Surface heat transfer coefficient
N	=	Shape functions of element
R	=	Solution domain
C	=	The third boundary
ΔT_w	=	Temperature rise of water along the pipes' length
Γ	=	Curve integral along the cooling pipes' edge
c_w	=	Specific heat of water
ρ_w	=	Density of water
q_w	=	Flow of water
k	=	Iterations
ε	=	A designated very small number

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