Comparative Study on the Discrete Model and the Improved Embedded Model of Cooling Water Pipe

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Abstract. Lianghu pump station of a large-scale water conservancy project under construction is characterized by complex structure, large scale and large size of solid body pouring block, while the previous discrete model of cooling water pipe is difficult to be successfully arranged in the concrete grid and requires a large amount of computation. In this paper, the improved embedded model of cooling water pipe, which considers the change of the water temperature in the cooling water pipe, is adopted to simulate the temperature control of the large pump station during the construction period. The results show that, with the help of the measured data, although the error rate of the improved embedded model of cooling water pipe at the highest temperature is 5% higher than that of the discrete model, the calculation efficiency is increased by about 40% in comparison with the discrete model. The comprehensive profit is improved by nearly 35%. It is worth popularizing and applying in the simulation calculation of temperature field of large pump station structure during construction period. Finally, the results of the two pipe models are compared and the relevant suggestions are given.

1. Introduction

During the construction process of mass concrete structures, the hydration reaction of cement produces a lot of heat. A large number of engineering examples show that cooling water pipe has become an effective measure for temperature control and crack prevention of mass concrete. The accurate and rapid simulation of concrete temperature field during construction of mass concrete with cooling water pipe has always been a hot and difficult research topic.

Equivalent model algorithm and discrete model algorithm [1] of cooling water pipes are commonly used finite element algorithms in recent years. The former requires less memory for computers, but cannot accurately and truly simulate the temperature field distribution around cooling water pipes with a large temperature gradient. The latter has higher calculation accuracy, but it will greatly increase the number of elements in the whole model, and the calculation efficiency is low. In order to take efficiency into account, and more accurately reflect the real temperature field of concrete with cooling water pipe, many experts and scholars have made a lot of explorations, trying to find a better simulation algorithm. For example, composite method [2], adaptive accuracy method [3], direct algorithm [4], embedded element method [5], composite element algorithm [6], finite element substructure method [7], heat-fluid coupling method [8], a new composite element algorithm [9,10], an extended finite element method [11], a p-version embedded element method [12], and the algorithm based on heat flux integration [13] have been proposed one after another. The above algorithms have their own advantages, which further improve the calculation accuracy or efficiency. However, there
are also some problems that are not convenient for engineering application, such as the complicated calculation process, the complex programming, the error in the use process, or the unsatisfied comprehensive effect of calculation efficiency and accuracy.

The simulation object of this paper is Lianghu pump station in Shaoxing, Zhejiang Province of China. Lianghu pump station contains the drainage pump station with five connection holes and the diversion pump station with two connection holes, and their structure are different. The drainage pump station has the following characteristics. Firstly, the structure is complex, which leads to the poor regularity of finite element mesh element. The previous discrete model of cooling water pipe is difficult to be arranged successfully in the concrete mesh because the large scale of the structure leads to a large number of finite element model elements. Secondly, if the discrete pipe model is used, the number of elements will increase by several times, and the calculation time will also increase by several times, making it difficult to provide research results in time according to the project progress. Lastly, the casting block of solid body is large in size. In the previous similar large pump station, in order to save or reduce the temperature stress, holes were designed in some parts of the structure. Although it increased the degree of trouble in the construction, however the volume or size of the mass concrete pouring block is reduced, so the cooling water pipe may not be arranged or less arranged in these parts. The solid body structure of the pouring block in this pump station is large in size, almost all the pouring layers of pump stations need to arrange dense cooling water pipes. It leads to a large amount of work to arrange water pipe elements in the model before calculation, and the calculation of temperature field with cooling water pipes also increases significantly.

Based on the above characteristics of Lianghu pump station, the improved embedded model of cooling water pipe is used to simulate and calculate in the drainage pump station, while the traditional discrete model of water pipe is adopted in the diversion pump station. The advantage of the embedded element method [5] is that the cooling effect of water pipes on concrete can be considered without quadratic subdividing the existing models, but the variation of water temperature along the cooling water pipe and its influence on the temperature field are ignored. The obtained concrete temperature field is inaccurate. In this paper, an improved embedded element method of cooling water pipe [11] is adopted in the drainage pump station, which can consider the variation of water temperature along the distance in the cooling water pipe and its influence on the temperature field. The discrete pipe model [14,15] used in the diversion pump station has the characteristics of high precision but low calculation efficiency. Finally, the results of the two algorithms are compared and the relevant suggestions are given.

2. Numerical simulation model and parameter

2.1. Numerical simulation model

The finite element model of the drainage pump station is shown in Figure 1(a). The total number of elements is 86836 and the total number of nodes is 100637. The finite element model of the diversion pump station is shown in Figure 1(b). The total number of elements is 92824 and the total number of nodes is 106339. The coordinate origin is located in the inlet channel, the Z axis is vertical upward, the X axis is pointing to the direction of water flow, and the Y axis is pointing to the left bank according to the right hand spiral rule.
2.2. Discrete model and embedded model of cooling water pipe

Figure 4 is the cooling water pipe model arrangement of the drainage pump station and the diversion pump station. Although the corresponding structures of the two pipe models are different, however, the number of nodes and elements in the two pipe models is close in the simulation calculation of this paper, and there is still a certain contrast in the calculation efficiency. The total number of corresponding node elements is shown in Table 2. For the pouring block of drainage pump station, the embedded pipe model used in simulation is shown in Figure 4(a). For the pouring block of diversion pump station, the discrete pipe model used in simulation is shown in Figure 4(b). All the water pipes with diameter of 4.0 cm are used. In the finite element model, the arrangement of water pipes is affected by the size and shape of the elements. The local water pipes are slightly dense, the local water pipes are slightly sparse, and the density of different locations is different. The specific flow rate, time and temperature of cooling water pipe can be seen in each calculation case.

2.3. Numerical simulation parameter

The two models of cooling water pipe studied in this paper mainly affect the calculation accuracy and efficiency of the temperature field, so only the calculation parameters and boundary conditions related to the temperature field are provided. C25 concrete is used in the bottom of the pump station, and C30
concrete is used in the pile foundation and other structures of the pump station. The foundation material below the bottom plate is mainly silty clay.

Due to the lack of measured geothermal parameters, the main thermal parameters of concrete are obtained from laboratory tests by referring to the manual of geotechnical mechanical parameters. The specific thermal parameters of various materials are shown in Table 1.

### Table 1. The thermal parameters of materials.

| Category     | Thermal conductivity $\lambda$ (kJ·m$^{-1}$·h$^{-1}$·°C$^{-1}$) | Specific heat $c$ (kJ·kg$^{-1}$·°C$^{-1}$) | Thermal diffusivity $a$ (m$^2$·h$^{-1}$) | Adiabatic temperature rise final value $\theta_f (°C)$ |
|--------------|-------------------------------------------------|---------------------------------|---------------------------------|----------------------------------|
| C25          | 6.575                                           | 0.934                           | 0.00311                         | 46.70                            |
| C30          | 6.471                                           | 0.938                           | 0.00305                         | 55.16                            |
| Silty clay   | 2.41                                            | 1.91                            | 0.0012                          | /                                |

For the convenience of calculation, the average monthly temperature of many years in Shaoxing, Zhejiang Province of China is fitted into a cosine curve [1], and the fitted formula is shown in equation (1).

$$T_a (t) = 17.1 + 12 \times \cos \left(\frac{\pi}{6} (t - 7.2)\right)$$

(1)

Where $T_a$ is the air temperature (°C), $t$ is the time (month).

### 2.4. Boundary condition

In the simulation of the temperature field, the surrounding and bottom surface of the foundation are adiabatic boundaries, and the upper surface is the heat dissipation boundary. The symmetric surface of the structure is an adiabatic boundary. The construction temporary joint surface and the structure permanent joint surface are the heat dissipation boundaries when not covered, while the adiabatic boundaries when they are covered. The other surfaces are heat dissipation boundaries.

### 3. Calculation case and results analysis

A large number of cases were calculated during the research process. This paper merely lists the relatively optimal calculation cases of the drainage pump station structure and the diversion pump station structure.

### 3.1. Calculation case

The concrete block is poured according to the structure joints and the planned pouring schedule. The pouring temperature is increased by 3 °C on the basis of daily average temperature, and not more than 28 °C. The pouring time of the inlet passage was in September of that year.

The relatively optimal calculation case of the drainage pump station structure: based on calculation of the calculation cases without temperature control measures, the thermal insulation material is covered on the surface after concrete formworks are removed (the surface heat dissipation coefficient is 100 KJ·m$^2$·d$^{-1}$·°C$^{-1}$). The concrete structure is cooled by water pipes and cooling water is used for 15 days. The water temperature is controlled not more than 20 °C. The flow rate is 50 m$^3$·d$^{-1}$ before the temperature peak and 15 m$^3$·d$^{-1}$ after the temperature peak.

The relatively optimal calculation case of the diversion pump station structure: based on calculation of the calculation cases without temperature control measures, the pouring temperature is controlled not more than 20 °C. The pouring date of the top wall of the diversion pump station was postponed to November of that year, and the pouring date of the upstream and downstream runner connecting the wall was also postponed accordingly. The thermal insulation material is covered on the surface after concrete formworks are removed (the surface heat dissipation coefficient is 50 KJ·m$^2$·d$^{-1}$·°C$^{-1}$). The inlet passage and top wall are cooled by water pipes and cooling water is used for 15 days. The water temperature is controlled not more than 18 °C. The flow rate is 50 m$^3$·d$^{-1}$ before the temperature peak.
and 6 m$^3$·d$^{-1}$ after the temperature peak.

3.2. Analysis of calculation results

![Figure 5](image1.png)

Figure 5. Duration curve of temperature early age at feature points of the drainage pump station.

![Figure 6](image2.png)

Figure 6. Duration curve of temperature early age at feature points of the diversion pump station.

Figure 5 is a comparison curve between the measured and calculated temperature values of the drainage pump station structure. The calculated values are the temperature data of the relatively optimal calculation cases, and the measured values are from construction site. It can be seen from Figure 5 that before the temperature peak of points 1 and 2 is reached, the results calculated by the improved embedded element method are closer to the actual temperature, but there are some errors between the calculated and measured values in the peak and later period. The temperature peak calculated by feature point 1 is 54.1 °C, the measured temperature peak is 48.6 °C, and the difference between them is 5.5 °C. The temperature peak calculated by feature point 2 is 50.4 °C, the measured temperature peak is 47.9 °C, and the difference between them is 2.5 °C. Comparison between calculated and measured maximum temperature of feature points, the error rate (the ratio of the difference between the measured maximum temperature and the calculated maximum temperature to the measured maximum temperature) is about 10%. The main reason is that the essence of the improved embedded element method is calculating equivalently the cooling effect of the water pipe in the element through which it passes. That is to say, the temperature field inside the improved embedded element is equivalent to the temperature field with linear distribution, and the fitting calculation is carried out by using the first-order function, that is, the linear function. However, as a
concrete block with cooling pipe, the actual temperature gradient of concrete in the range of 30 cm around the pipe is large [10], and temperature changes nonlinearly. Therefore, if the size of the improved embedded element is large and the conventional linear element is used in the calculation, some errors are inevitable in the calculation of the temperature field around the water pipe.

Figure 6 is a comparison between the measured and calculated values of temperature collected from the diversion pump station structure. It can be seen from Figure 6 that the temperature peak calculated by feature point 1 is 51.1 °C, the measured temperature peak is 49.4 °C, and the difference between them is 1.7 °C. The temperature peak calculated by feature point 2 is 57.0 °C, the measured temperature peak is 54.2 °C, and the difference between them is 2.8 °C. The rules of the discrete pipe model feature points 1 and 2 before reaching the peak temperature are basically the same as those of the improved embedded pipe model. However, the error rate of calculated and measured values of discrete pipe model is lower than that of the improved embedded pipe model at the peak and the later stage, which is about 5%.

It can be seen from Table 2 that the total calculation time of the improved embedded model of cooling water pipe is obviously different from that of the discrete pipe model. Although the simulation calculation accuracy is lost about 10%, the improved embedded pipe model calculation efficiency is increased about 40% compared with that of the discrete pipe model.

Table 2. Comparison of calculation time-consuming between the two water pipe models.

| Category                             | Total number of nodes | Total number of elements | Computation total time-consuming (s) | Computation time-consuming difference | Calculation efficiency |
|--------------------------------------|-----------------------|--------------------------|-------------------------------------|---------------------------------------|------------------------|
|                                      | Without water pipe    | Containing water pipe    | Without water pipe                  | Containing water pipe                |                        |
| The discrete pipe model              | 106339                | 174115                   | 92824                               | 152791                                | 12034                 | 17074                 | 5040                  | Delay about 42%       |
| The improved embedded pipe model     | 100637                | 100637                   | 86836                               | 86836                                 | 8923                 | 9114                  | 191                   | Delay about 2%        |

4. Conclusions
(1) Under the combined temperature control measures of reasonable pouring temperature control, internal cooling water pipe and surface insulation, the error rate of the improved embedded model of cooling water pipe is 5% higher than that of the discrete pipe model at the highest temperature by comparing the calculated value of the simulated temperature field with the measured value. Although the accuracy of the improved embedded pipe model slightly decreases, the calculation efficiency is increased by about 40% in comparison with the discrete pipe model, and the comprehensive profit is improved by nearly 35%. It is worth popularizing and applying in the simulation calculation of temperature field of large pump station structure during construction period.

(2) The error of the improved embedded pipe model is caused by the homogenization of the temperature field in the elements. Therefore, if this model is adopted when setting temperature control index based on the calculation results, it is suggested that the maximum temperature in the calculation result be multiplied by the correction coefficient of 1.1 to obtain the maximum temperature index of the actual temperature control.

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