Finite element simulation and analysis of hydration heat in large-volume pile caps

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Abstract. To reveal influences of hydration heat in large-volume concrete, a large-volume concrete pile cap of a main bridge over a canal was taken as the engineering background. In the research, the finite element software, Madis civil, was used for simulation and analysis of hydration heat in the pile cap. Through finite element simulation, the temperature and stress fields were obtained and compared with the monitored data. Analysis results indicate that in the initial pouring stage of the pile cap, a large temperature difference occurs between the interior and surface of the pile cap; as the temperature difference enlarges, the temperature stress of the pile cap also increases correspondingly. The results of finite element analysis match well with the monitored data, which guarantees the construction quality in the field and verifies feasibility of the finite element software in simulation and analysis of hydration heat.

1. Introduction
As more extra-large bridges are built in China, more stringent requirements have been set on the construction of large-volume concrete pile caps which becomes increasingly important. Due to the large temperature gradient and difference between the interior and exterior of large-volume concrete during construction, temperature stress is generated inside the concrete, thus leading to cracking of the large-volume concrete. To guarantee the safe and stable operation of pile caps of bridges, it is of great significance to use finite element software to analyze large-volume concrete pile caps [1-3].

Taking a pile cap of an extra-large bridge over a canal as the engineering background, the finite element software Madis civil was used to carry out simulation and analysis on large-volume concrete [4-7]. Based on layout of cooling pipes in the pouring plan, the temperature and stress fields were obtained. Through result analysis, the change of hydration heat induced temperature of the large-volume concrete with time was revealed to verify the feasibility of layout of cooling pipes in the field construction plan. Arranging monitoring points appropriately in the field to compare with temperature data monitored in the field is conducive to ensuring field construction and maintenance quality.

2. Engineering profile
The extra-large bridge over the canal is a pre-stressed concrete continuous beam bridge, with spans of 50, 90, and 50 m. Pile caps under the bridge all share the dimensions of 12 m × 7.5 m × 3.5 m. They were constructed with C30 concrete that was prepared with cement, sand, gravel, water, and additive
(mixed with a ratio of 400:760:1052:168:7.2). The slump of the concrete was $160 \pm 20$ mm. Large steel molding plates were used and the pile caps were cast in one time and molding plates on four sides were wrapped with color band cloth for heat preservation while the top surface was covered with geotextiles for moisture preservation.

The layout of the cooling pipes is shown in Fig. 1. The cooling pipes were arranged in three layers with an interlayer spacing of 1 m and a distance of 0.75 m from the upper and lower boundaries. In each layer, the cooling pipes showed a spacing of 1 m and a distance of 0.75 m from the edges. Immediately after pouring of the concrete, water was injected in the cooling pipes. To avoid too large temperature differences in the concrete around the cooling pipes, a circulating water tank was placed beside the pile cap. In addition, valves were arranged at the inlet and the outlet to adjust the water flow, so as to regulate the cooling rate inside the concrete.

3. Finite element model

Madis civil was used for establishing the model of the 47# and 48# pile caps. Use of a 1/4-scale model for calculation can accelerate the modelling speed and shorten the analysis time, and also helps to visualize temperature distribution and stress condition in the concrete. The specific mesh generation of the model is shown in Fig. 2. The model contains 19,475 nodes and 17,136 elements. The ambient temperature was set as 20°C according to field measurement of temperature. The side walls of the pile cap were wrapped with color band cloth for heat preservation, under which the convection coefficient was a constant, $1.2 \times 10^{-5}$ kcal/mm²·hr·[°C]. Due to changes of concrete surface exposed to the atmosphere during the construction, the ambient temperature and convective boundary conditions were set for the defined convective boundaries 1, 2, and 3 of elements; the fixed temperature condition (20°C) was set for elements whose temperature did not change with time. According to the type of cement used in the field, and the amount of cement used per unit volume, it was calculated using the primitive function of heat that the maximum adiabatic temperature rise was 41°C. The cooling pipes were arranged according to above scheme, and continuous injection of circulating water lasted for 15 days for cooling the concrete. The injection of circulating water was stopped when the temperature at the center of the pile cap remained basically constant and showed a difference less than 25°C with the outside. Fourteen conditions were considered for the pile cap, namely, those at 10, 20, 30, 45, 60, 80, 100, 130, 170, 250, 350, 500, 700, and 1,000 h.
According to model calculation, the cement produces huge heat during the hydration after pouring of the concrete, so the temperature of concrete rises. On the condition, the concrete surface exchanges heat with the outside; while heat exchange inside is realized with the cooling pipes, which avoids occurrence of cracks on the concrete surface [6]. In the initial stage of concrete pouring, the temperature at the center of the pile cap is higher (Fig. 3). In the first 45 h, the temperature at the center of the pile cap rises rapidly and reaches the highest of 43.69℃ at 60 h (Fig. 4). At 10 h when water is still continuously injected in cooling pipes, the hydration heat induced temperature reduces obviously inside the concrete pile cap with the heat conduction of the circulating cooling water. As to the surface, the temperature rises slowly due to heat exchange with the outside and reaches the highest of 31.95℃ at 30 h. It is calculated that the largest temperature difference is at 60 h, being 14.08℃, which is much lower than the allowable temperature range of 25℃, conforming to the design requirement.
3.2. Calculation results of the stress field

As time goes on, a temperature difference is produced in the concrete due to the nonuniform temperature reduction at different positions. The temperature difference produces temperature stress in the pile cap and when the stress exceeds the allowable range, cracks will occur to the pile cap [7]. Therefore, it needs to analyze the stress in the pile cap through simulation. Through finite element simulation, it is found that the stress inside the pile cap does not exceed the maximum allowable value, so no tension crack occurs. Surface stress on the pile cap is shown in Fig. 5. Surface tensile stress gradually increases with time. Under the effect of cooling water, the stress reaches the maximum (0.63 MPa) at 60 h (Fig. 6), and then it gradually reduces with time.

According to the formula for the temperature crack index i,

\[
\text{Crack index (i)} = \frac{\text{Concrete tensile strength}}{\text{Temperature stress}}
\]  

Crack generation can be effectively avoided when \( i > 1.5 \); if \( i \) is in the range of 1.2–1.5, cracks will develop in the components while their generation will be inhibited; on condition that \( i \) ranges from 0.7 to 1.2, occurrence of harmful cracks in components will be limited. As the pile cap is built using C30 concrete, whose design tensile strength is 1.43 MPa, it is calculated that \( i=2.27 \), indicating that the pile cap is free of cracking risk.
Figure 5. Change of surface stress on the pile cap with time

Figure 6. The maximum surface stress on the pile cap at 60 h

4. Conclusion
1) The measured temperature change of the pile cap differed slightly from the temperature field calculated using the finite element software. By using the finite element software, the maximum
temperature difference of the pile cap was 14.08℃ at 60 h, while it was found to be 14.6℃ at 65 h according to field monitoring, lower than the maximum allowable temperature difference in codes.

2) The stress field of the pile cap was analyzed using the finite element software Madis civil. Stress in the pile cap reached the maximum (0.63 MPa) at 60 h, which was lower than the design tensile strength of the concrete pile cap.

3) Huge hydration heat is produced in the initial stage of pouring the concrete pile cap. Therefore, cooling water needs to be injected in the construction process timely, which can effectively cool the interior of the pile cap and control generation of cracks.

4) The finite element analysis of the pile cap can not only optimize the construction scheme and temperature monitoring scheme, but also can provide guidance for field construction to guarantee construction quality and reduce construction risk. In addition, it also provides professional experience in finite element simulation and analysis for construction of large-scale concrete.

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