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**RESEARCH ARTICLE**

# Hydration heat simulation and temperature control analysis of mass pile cap concrete

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**ABSTRACT**

Taking the mass concrete of the main pier bearing platform of a super large bridge in an expressway construction project in Chongqing as the research object, the temperature field within 336 hours after the pouring of the bearing platform is numerically simulated and analyzed by using Midas FEA finite element software, the curves of temperature field with time when the inlet temperature is 10℃, 15℃ and 20℃ are emphatically analyzed. Through the finite element results, the law of hydration heat of cap is familiar, the temperature control scheme is determined and the reasonable pipe cooling design is carried out, so as to guide the construction. The results show that the temperature and crack control are more favorable when the inlet temperature of condensing pipe is 10℃.

***Keywords:*** mass concrete; hydration heat; temperature control; water pipe cooling; numerical analysis

## 1. Engineering background

Selecting a continuous rigid frame bridge located in Chongqing for analysis, the main pier cap of the bridge is a reinforced concrete structure with dimensions of 21.0m (transverse direction) x 21.0m (longitudinal direction) x 7m (layer thickness). The cap concrete is C40, and the pouring volume of the cap reaches 3087.0m$^3$, with 294.4t of steel bars. The pier cap is poured in two stages, with the first stage having a thickness of 4m and the second stage having a thickness of 3m. The volume of concrete in bridge pier caps is relatively large. In order to grasp the highest temperature and temperature difference inside and outside the concrete, and prevent cracks in the concrete structure, it is necessary to simulate the process of hydration heat in large volume concrete caps and conduct temperature testing and control.

## 2. Structural simulation analysis

### 2.1. Model parameter settings

The size of the pier cap is 21.0m x 21.0m x 7.0m. Due to the symmetrical structural dimensions, a 1/4 structure is used for this calculation, as shown in **Figure 1**. Considering the 2.0m foundation around the pier cap, the material parameters are shown in **Table 1**, and the cooling pipe layout is shown in **Figures 2 to 4**. According to the on-site situation, the first and second layers of the bearing platform are planned to use an atmospheric temperature of 15.0℃ and a pouring temperature of 15.0℃ for simulation analysis. This calculation uses solid unit modeling. The first layer of the pier cap considers sub working conditions such as

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10h, 24h, 48h, 72h, 96h, 120h, 144h... 336h, while the second layer of the pier cap considers pouring sub working conditions such as 10h, 24h, 48h, 72h, 96h, 120h, 144h ... 336h. Study the temperature changes and internal and external temperature differences of each layer under three different conditions: 10℃, 15℃, and 20℃ for the inlet temperature of the condenser tube.

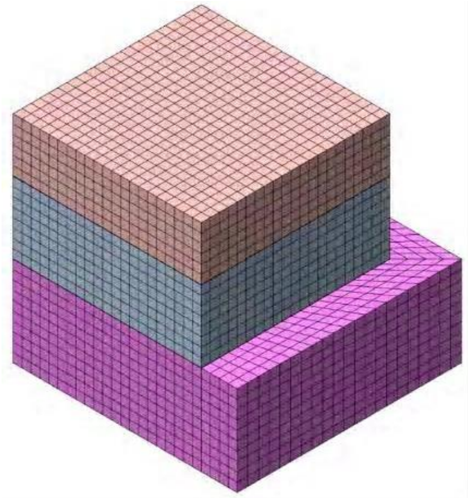


**Figure 1.** 1/4 model of pier cap.

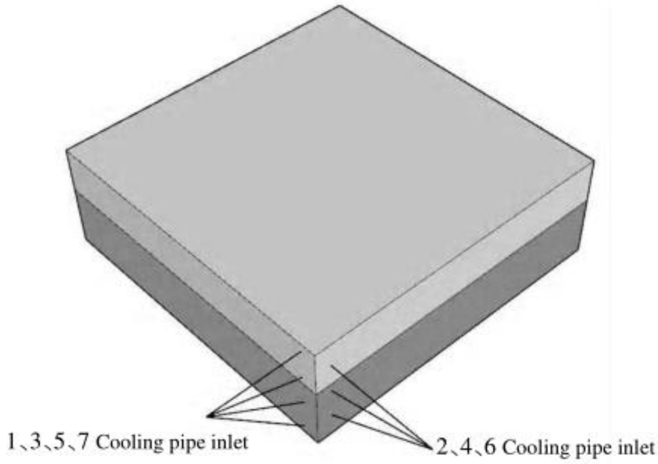



**Figure 2.** Model diagram of the outer surface of the pier cap.

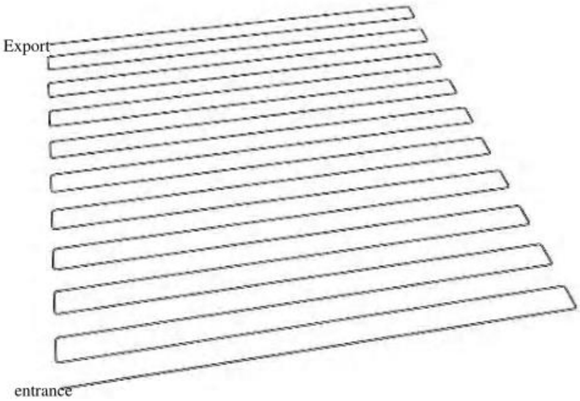



**Figure 3.** Model diagram of cooling pipes on levels 1, 3, 5, and 7.

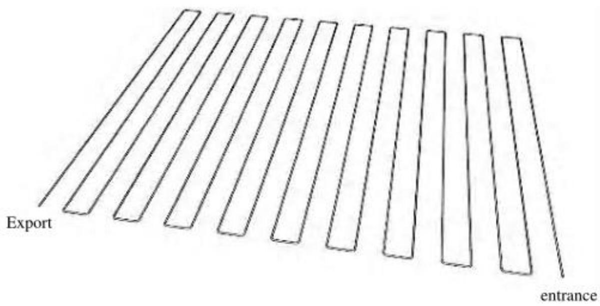



**Figure 4.** Model diagram of cooling pipes on levels 2, 4, and 6.

**Table 1.** Material parameters.

| Material type | Specific heat ( J*g/kN/[T] ) | Thermal conductivity W/m*[T] | Elastic modulus MPa | Poisson's ratio | Linear expansion coefficient | Bulk density kN/m3 |
|---|---|---|---|---|---|---|
| C40 Concrete lower | $10.71\times10^{5}$ | 2.8 | $3.35\times10^{4}$ | 0.2 | $1\times10^{-5}$ | 25 |
| foundation of pier cap | $8.16\times10^{5}$ | 2 | 980.66 | 0.2 | $1\times10^{-5}$ | 17 |

## 2.2. Boundary conditions

Displacement boundary conditions. The bottom layer of this type of pier cap is poured onto the foundation, so the bottom plate of the pier cap is a stationary fixed constraint. Due to the use of the symmetry principle[1-2], only 1/4 of the frame structure was established when establishing the finite element model of the pier cap. Therefore, the two cutting surfaces of the pier cap are symmetrical, which is the second type of boundary.

Temperature boundary conditions. On the basis of sealing in the foundation, the first boundary state is applied: forced temperature[3-4]. During the concrete pouring process, both sides and upper parts of the bearing platform are in contact with the atmosphere. During the pouring process, the concrete will convection with the outside world, forming heat exchange, which belongs to the third type: convection interface[5].

## 2.3. Temperature changes

According to calculation analysis, after the pouring of the first layer of concrete on the bearing platform, with the continuous occurrence of hydration heat, a large amount of heat generated inside the concrete cannot be completely released, and the surface of the concrete continuously exchanges heat with the outside world. Therefore, the temperature of the first layer shows a phenomenon of high temperature in the middle and little difference between the concrete surface and the atmosphere. As shown in **Figure 5**, the temperature of the core of the pier concrete increases sharply within 72 hours after pouring and reaches its maximum value at 72 hours. The first and second layers of core concrete reach 53.07℃ and 55.06℃, respectively. After 72 hours, the temperature of the core slowly decreases with pouring time.

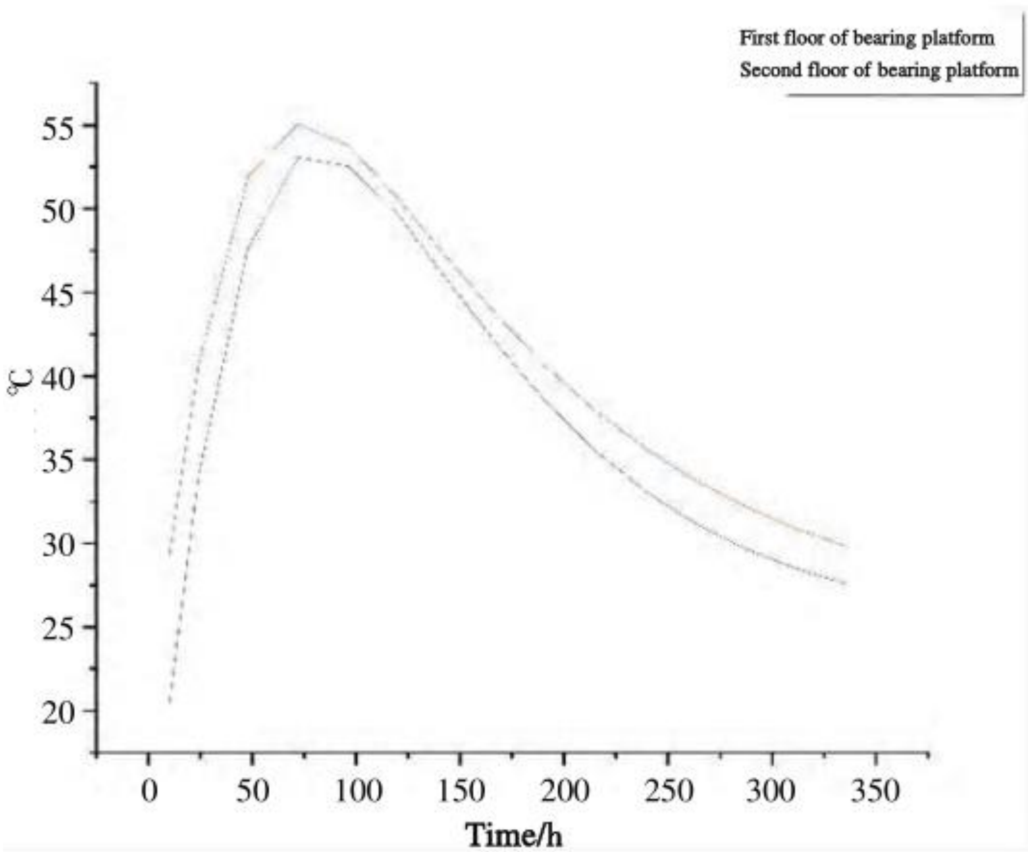



**Figure 5.** Temperature variation of the core of the first and second layers of the pier with time.

## 2.4. Temperature stress analysis

The heat generated by the hydration heat of concrete causes temperature self stress in the concrete. When it exceeds the tensile strength of the concrete, cracks will appear in the structure. Therefore, it is necessary to analyze the stress generated during the pouring process of the bearing platform concrete. When the ambient temperature is 15℃, the stress at the center points of the first and second layers is mostly below 2MPa, and no tensile cracking occurs. Therefore, the stress at the center point of large volume concrete is not sensitive to environmental temperature.

The ambient temperature is 15℃, and the maximum tensile stress on the surface of the first layer of concrete reaches its maximum value of 2.76 MPa 384 hours after pouring, with an overall stress between -2.5~2.76 MPa. The overall tensile stress generated on the surface of the second layer of concrete is relatively small, and the stress change curve is shown in **Figures 6** and **7**.

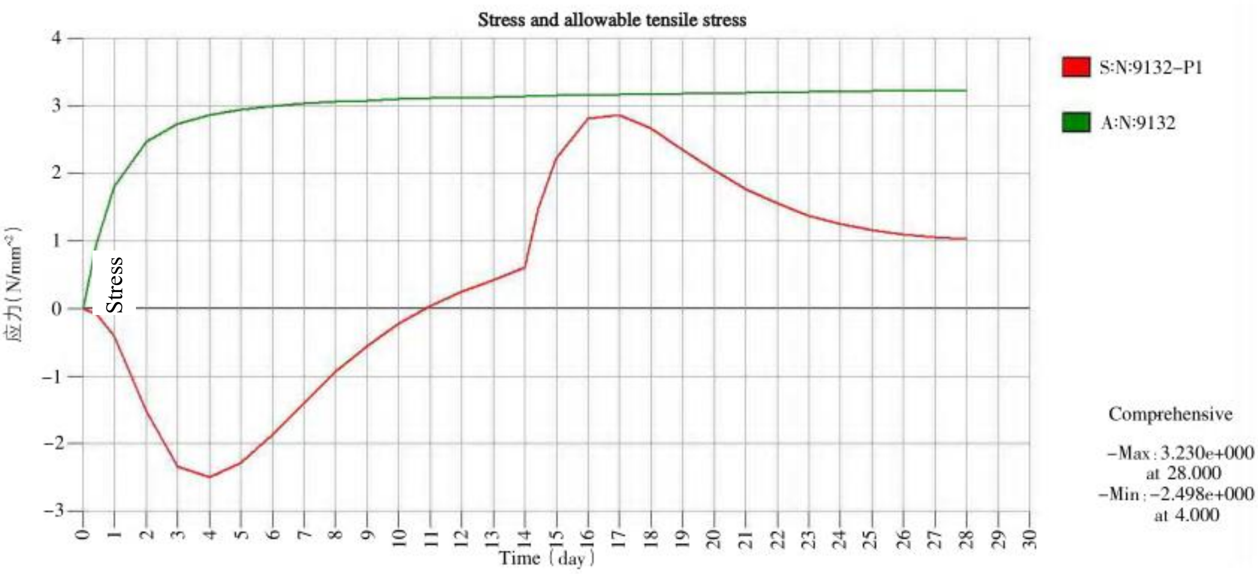



**Figure 6.** Maximum tensile stress point variation curve of the first layer of the pier cap.

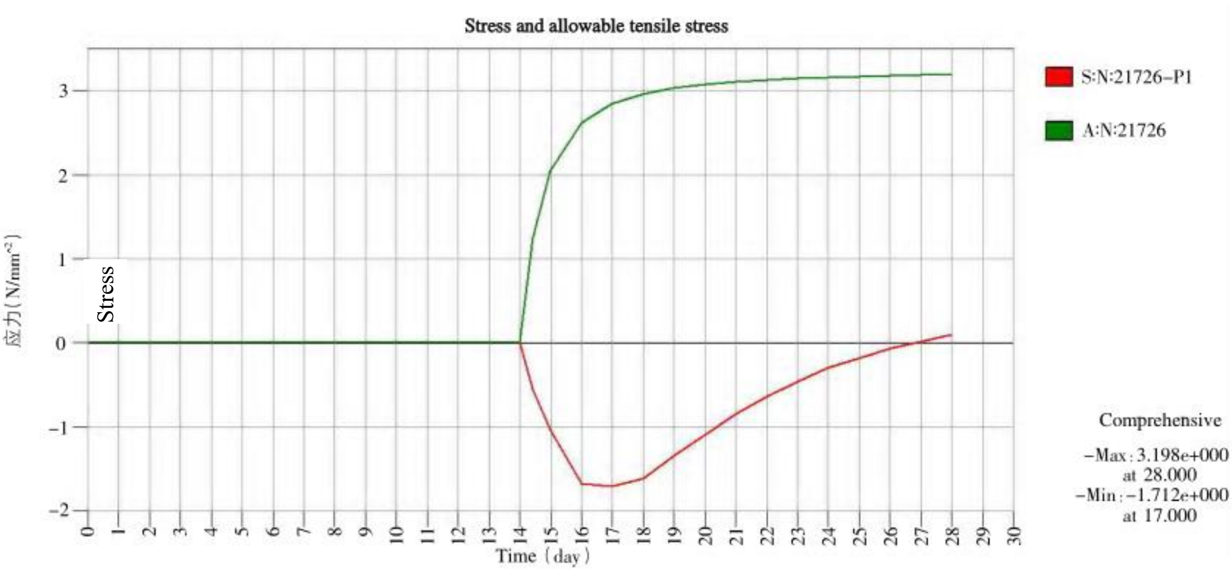



**Figure 7.** Maximum tensile stress point variation curve of the second layer of the pier cap.

# 3. Platform temperature monitoring

## 3.1. Layout of measurement points

Based on the finite element calculation results and in combination with the "Construction Standard for Large Volume Concrete" (GB50496-2018), 21 temperature testing monitoring points are arranged on the bearing platform. As the shape of the pier cap is vertically symmetrical, the temperature measurement points of the pier cap are arranged within the 1/4 pier cap plane. The first layer is poured, with a thickness of 4m and 7 measuring points. Four measuring points are set at each measuring point in the thickness direction, with a total of 28 measuring points for each bearing platform. The second pouring has a thickness of 3m, with 7 measuring points. Three measuring points are set at each measuring point in the thickness direction, and a total of 21 measuring points are set at each bearing platform. The layout plan of measuring points and the layout plan of measuring points in the thickness direction are shown in **Figures 8** and **9**.

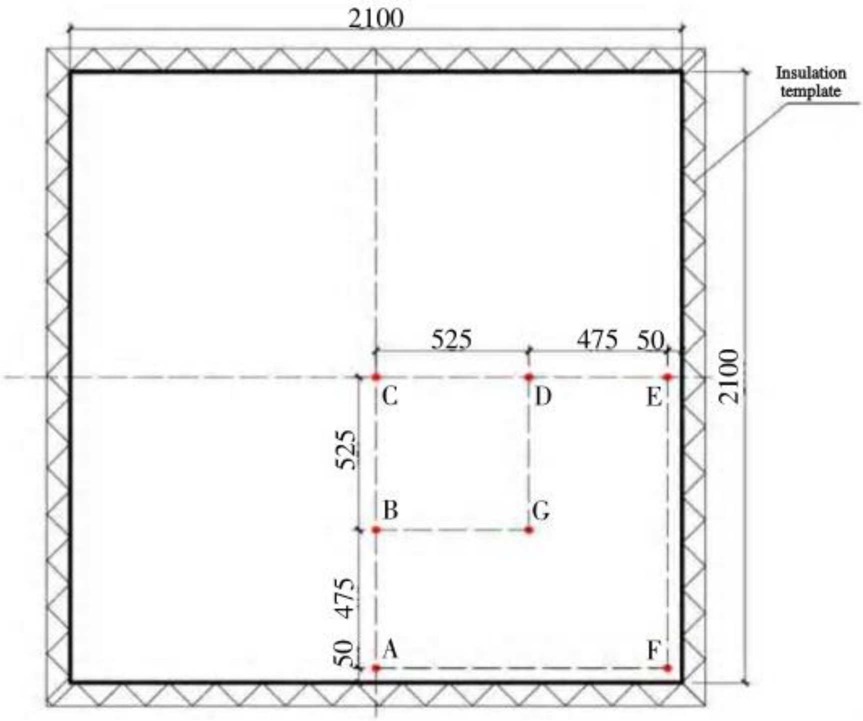



**Figure 8.** Layout Plan of Bearing Platform Temperature Measurement Points (Unit: cm).

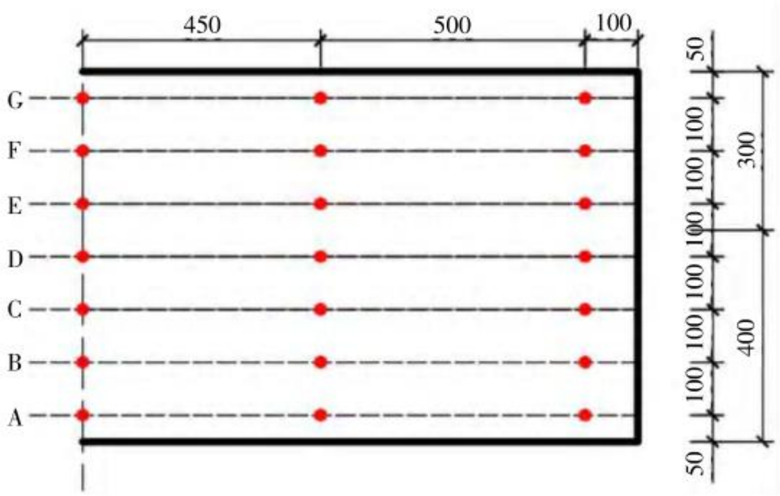



**Figure 9.** Vertical layout of temperature measurement points on the pier cap (Unit: cm).

## 3.2. Testing methods

The intelligent temperature control and automatic detection system for large volume concrete was adopted on site to monitor the temperature of the concrete. The indicators for inspection and control mainly include mold temperature, maximum temperature rise, temperature difference between inner and outer surfaces, interlayer temperature difference, water temperature rise, surface and environmental temperature difference, and cooling rate[6-10]. And based on the monitored temperature data, automatically control the flow and water temperature of the cooling water to control the main indicators such as the highest temperature inside the concrete, temperature difference between the inner and outer surfaces, and cooling rate.

During the curing process, the internal temperature of concrete should be controlled between 60~70℃, and the difference between surface temperature and surrounding temperature, surface temperature and internal temperature should be less than 20℃. The difference between surface temperature and curing water temperature should be less than 15℃. After reaching the temperature peak, the concrete was cooled slowly and the maximum cooling rate was controlled by insulation measures, with a rate controlled at 2.0℃/d.

### 3.3. Monitoring results

The inlet temperature of the cooling water pipe generally affects the peak temperature and heating rate of the concrete. Therefore, analyze the differences in the surface temperature, core temperature, and internal surface temperature difference of the concrete over time when the inlet temperature is 10℃, 15℃, and 20℃.

Extract 1 point from the core of the first layer of bearing platform (node number: 9132), 1 point from the surface (node number: 9152), 2 points from the core of the second layer of bearing platform (node number: 12519), and 2 points from the surface (node number: 12540) to analyze the temperature field of the concrete bearing platform structure. The temperature field of the pier can be divided into three stages: rapid heating stage, rapid cooling stage, and slow cooling stage that tends to stabilize.

(1) Simulation analysis of the first layer of concrete.

After the pouring of the first layer of bearing platform concrete, due to the cement hydration reaction, the temperature of the bearing platform rapidly increases, and the core temperature reaches its peak within 48-72 hours. When the inlet temperature is 10℃, 15℃, and 20℃, the corresponding core temperature peaks are 47.7℃, 50.4℃, and 53.1℃, and the surface temperature peaks are 24.3℃, 25.7℃, and 27.2℃. The maximum internal surface temperature difference increases from 24.9℃ to 28.5℃, as shown in **Figures 10** to **12**.

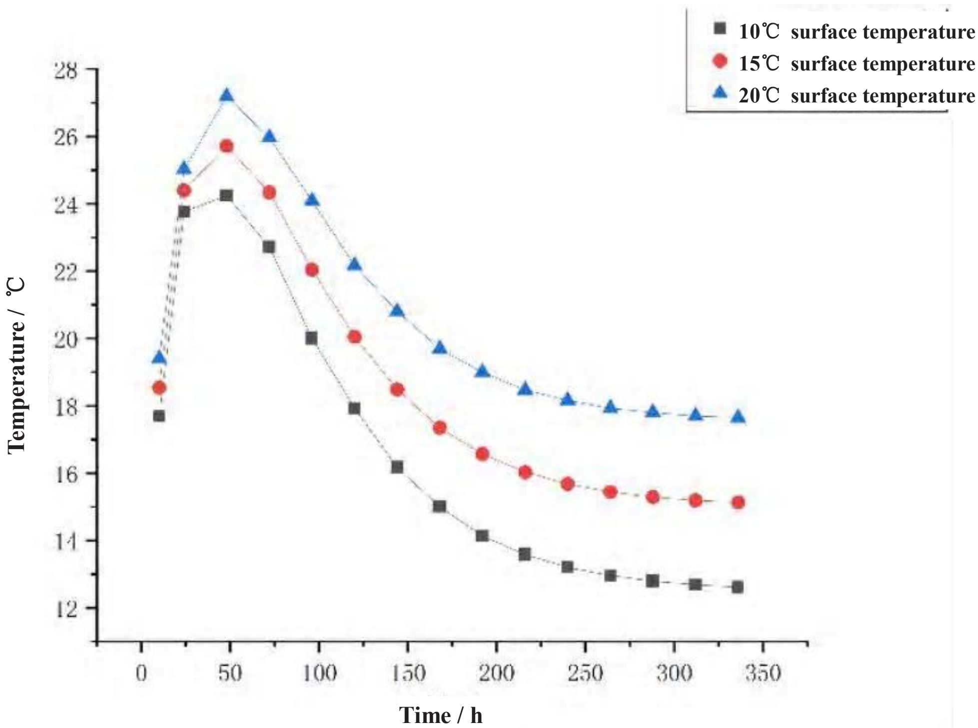



**Figure 10.** Surface temperature variation curve with time at different inlet temperatures on the first floor.

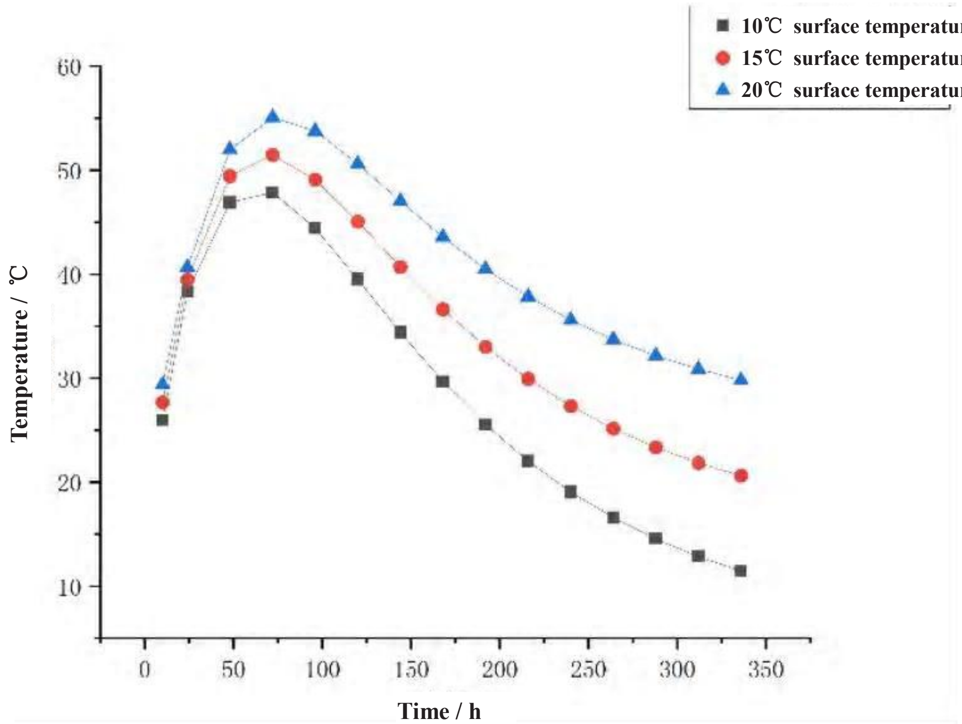



**Figure 11.** Time variation curve of core temperature at different inlet temperatures of the first floor pier.

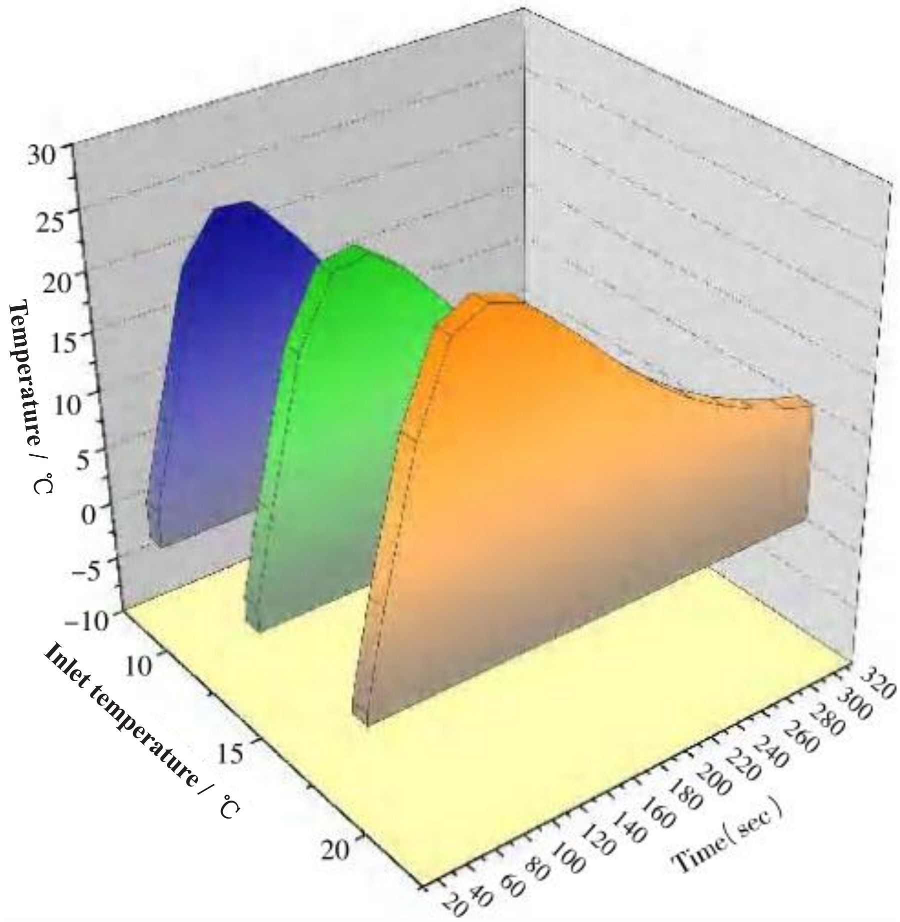



**Figure 12.** Time variation of internal surface temperature difference under different inlet temperatures of the first floor pier.

(2) Simulation analysis of the second layer of concrete.

After pouring the concrete for the second layer bearing platform, the core temperature reaches its peak within 48-72 hours. When the inlet temperature is 10℃, 15℃, and 20℃, the corresponding core temperature peaks are 47.9℃, 51.5℃, and 55.2℃, and the surface temperature peaks are 30.4℃, 30.5℃, and 30.7℃. The maximum internal surface temperature difference increases from 20.2℃ to 26.2℃, as shown in **Figures 13** to **15**.

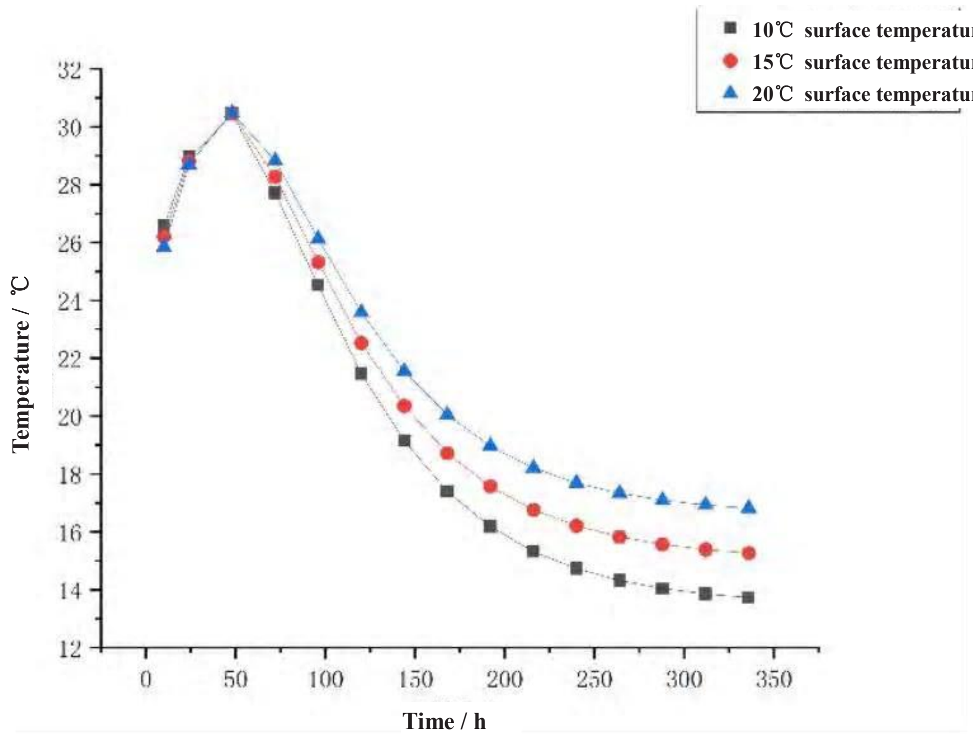



**Figure 13.** Surface temperature variation curve with time at different inlet temperatures of the second floor pier.

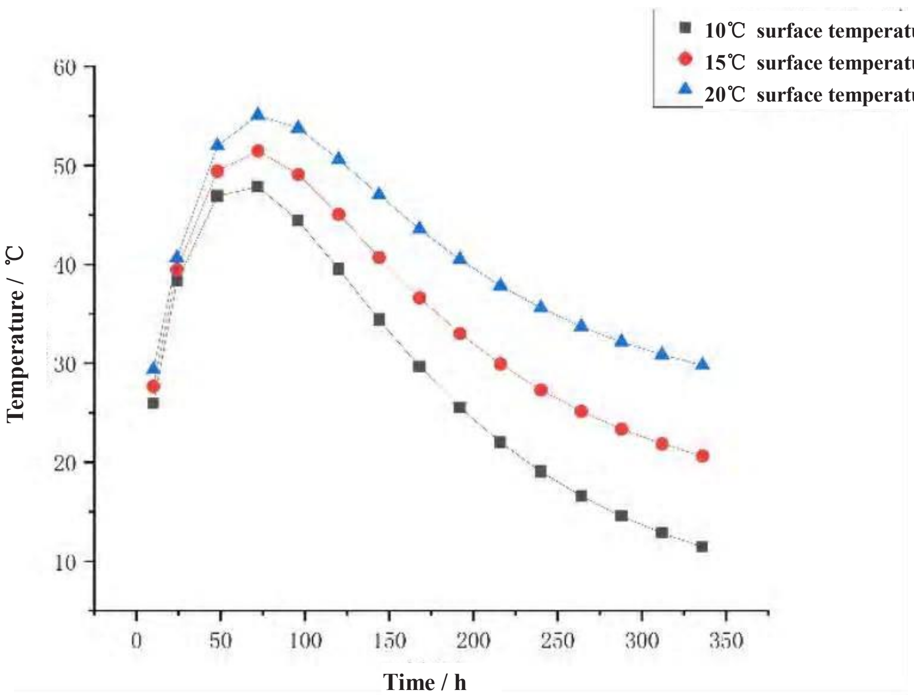



**Figure 14.** Time variation curve of core temperature at different inlet temperatures of the second floor pier.

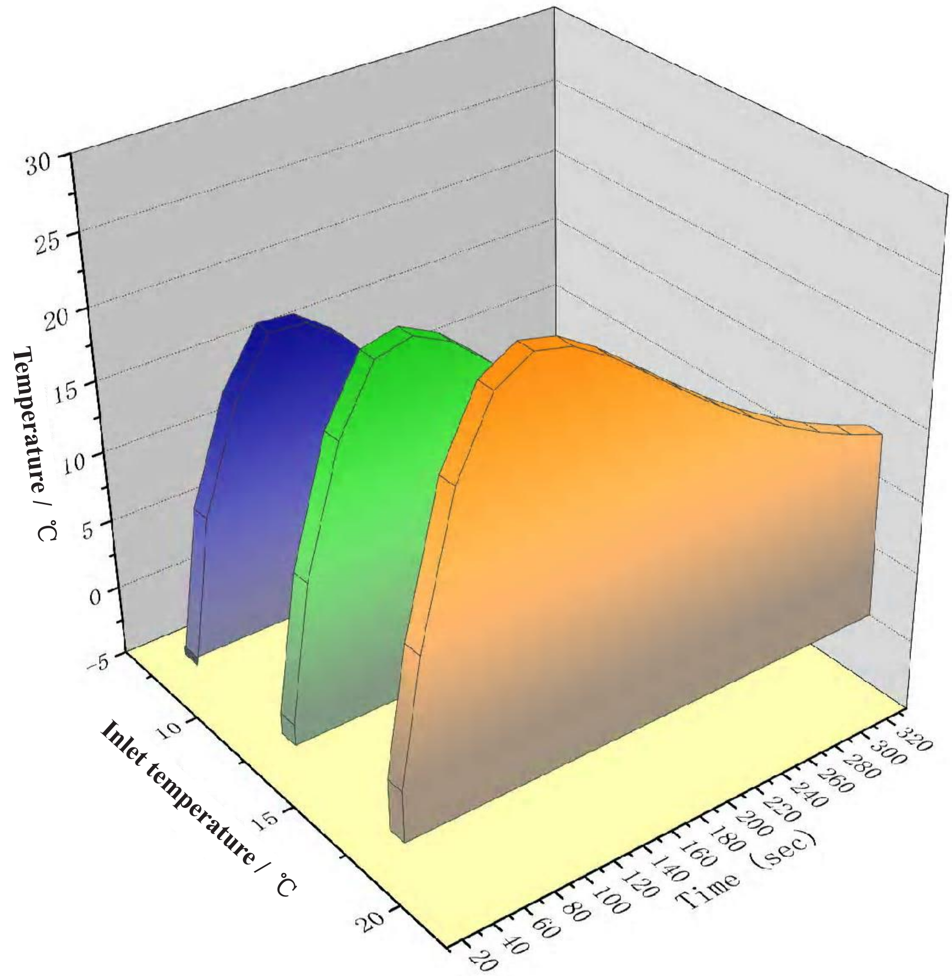


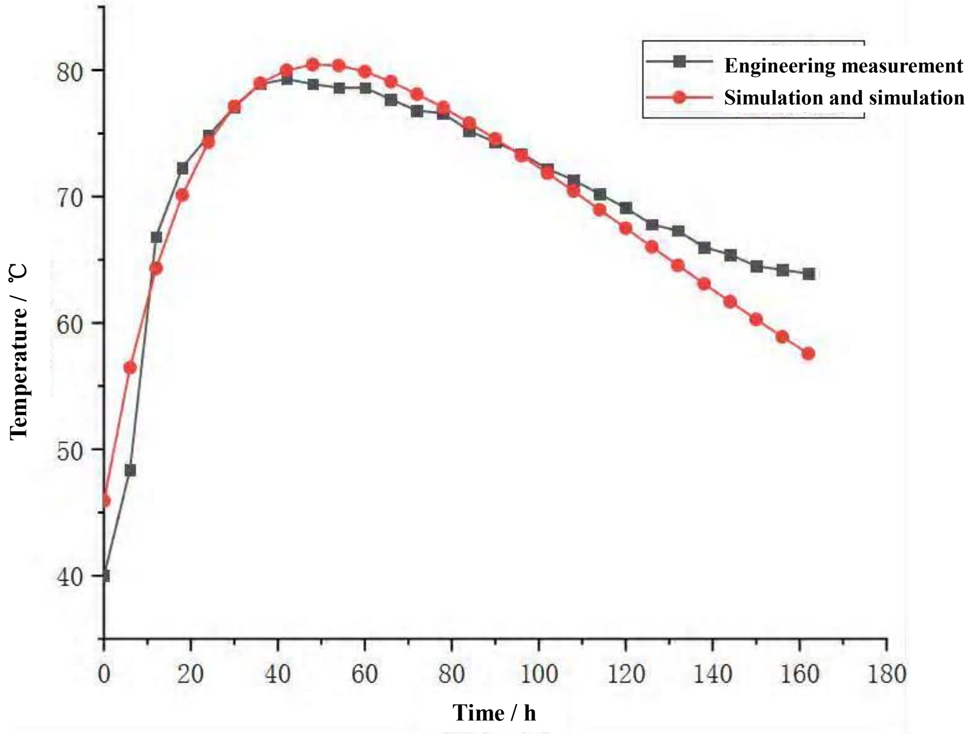

**Figure 15.** Time variation of temperature difference on the inner surface of the second floor pier under different inlet temperatures.

The results show that after the inlet temperature rises, the heating rate and peak temperature of the surface temperature, core temperature, and initial internal surface temperature difference all increase, while the duration of reaching the peak temperature is shorter. Due to the higher inlet temperature and hydration rate, as well as the higher water content, reducing the temperature of the inlet pipeline can be used to reduce the temperature difference between the surface and interior of the concrete[11-13].

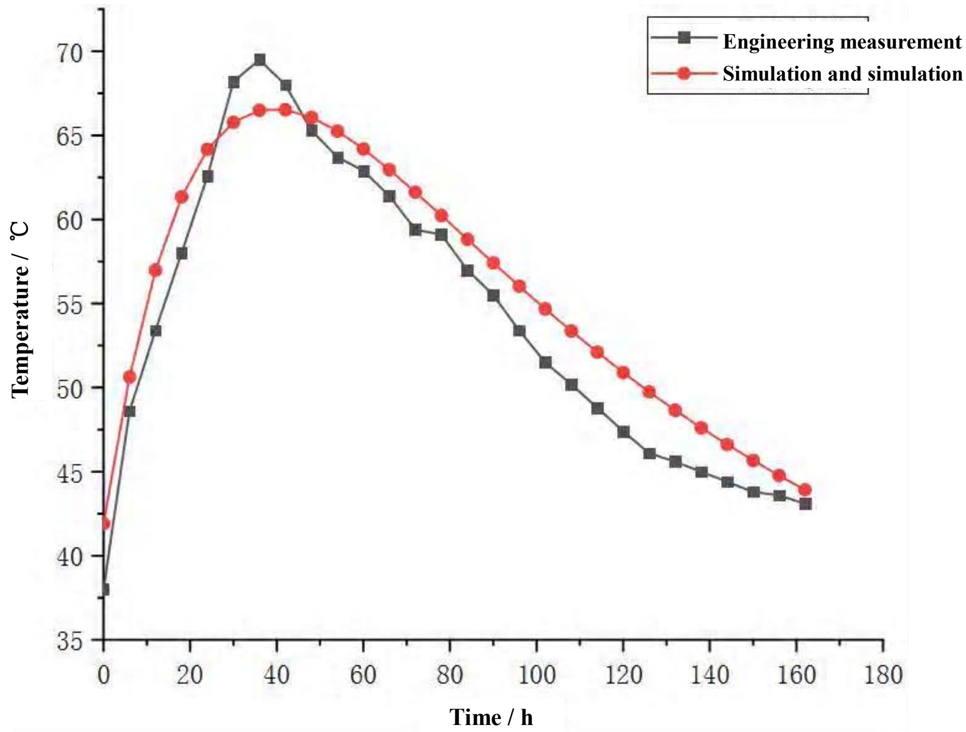
### 3.4. Comparison between numerical simulation and engineering measurement

Due to the large number of temperature measurement points on the pier cap, only two typical temperature measurement layers were selected. Through numerical simulation and comparison with actual measurement results, layer A and layer D were selected as the internal temperature measurement layers to reflect the temperature changes inside the pier cap. The results are shown in **Figure 16**.

By analyzing Figure 16, it can be concluded that the overall trend of the highest temperature inside the A and D layers of the numerical simulation is in good agreement with the engineering measurement. The average temperature difference in layer A is 0.46 ℃, with a relative error of 0.65%. The average maximum temperature difference inside the bearing platform in layer D is 1.82 ℃, with a relative error of 3.38%. After fully considering parameters such as pipe cooling and on-site construction mix ratio, the maximum insulation temperature rise inside the concrete is basically consistent with the measured value in the project, indicating that the finite element model can reach a good state and guide construction.




**(a) The highest temperature inside the concrete of layer A**




**(b) The highest temperature inside the concrete of layer D**

**Figure 16.** Numerical simulation and engineering measurement of temperature changes.

## 4. Conclusion

The temperature monitoring parameters of the large volume bearing platform concrete are within a controllable range and meet the regulatory requirements. On this basis, the temperature at the inlet of the cooling pipe on the pier gradually increases, causing the maximum temperature difference between the surface and interior to also increase, and the heating rate in the early stage is accelerated. The change in temperature distribution of the three bearing platforms can be divided into three stages: rapid heating, rapid cooling, and slow cooling tending to stabilize. By reducing the inlet temperature of the cooling water pipe on the pier, the hydration heat generated during concrete hydration and condensation can be effectively reduced, and the snake shaped arrangement of the cooling water pipe has a significant cooling effect.

## Conflict of interest

Author declare no conflict of interest.

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