Numerical Analysis of Thermal Disturbance and Temperature Field Evolution Induced by Bored Pile Construction in Permafrost Regions

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Abstract. During the construction of bored piles, the heat released from cement hydration inevitably induces thermal disturbance in the surrounding permafrost, thereby altering the temperature field of the pile–soil system and influencing the refreezing process of frozen ground. Taking a bridge pile foundation project in the Chumar River region of the Qinghai–Tibet Plateau as the engineering background, a heat transfer numerical model of the pile–soil system was established using COMSOL Multiphysics. The model was employed to investigate the evolution of the temperature field under different concrete casting temperatures. The results show that the temperature evolution of the pile–soil system can be divided into three stages: heating, heat diffusion, and refreezing. An increase in the concrete casting temperature intensifies the early-stage thermal disturbance during construction and enlarges the thawing zone around the pile, while exerting only a limited influence on the long-term temperature field.

Keywords: Permafrost region; Bored pile; Hydration heat of cement; Pile temperature

1 Introduction

During the construction of bored piles, the surrounding permafrost is inevitably influenced by several thermal factors, including ambient environmental temperature, concrete casting temperature, and cement hydration heat. These factors collectively alter the initial ground temperature field around the pile, among which the heat released during cement hydration is the dominant contributor to the thermal disturbance.

Existing studies on the temperature field of pile foundations in permafrost regions have generally employed a combination of field monitoring, laboratory testing, and numerical simulation. These investigations can broadly be categorized into two main research directions. The first focuses on factors influencing the thermal effects during the refreezing process of bored piles. Hou Xin [1] identified cement hydration heat, cementitious materials, concrete casting temperature, and drilling method as the primary sources of construction-induced thermal disturbance. Shang Yun hu [2] conducted numerical simulations and demonstrated that both the concrete casting temperature and

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the construction timing of the pile significantly influence the temperature distribution of the surrounding frozen soil. Based on in situ observations and theoretical analyses, Chen Kun [3] systematically investigated the thermal evolution of bored piles and suggested that controlling the concrete casting temperature or adopting low-temperature early-strength concrete can help maintain appropriate curing temperatures and reduce the risk of temperature-induced cracking. The second research direction involves the application of external artificial measures to regulate the thermal regime around pile foundations. Through field experiments and monitoring, Jiang Daijun [4] demonstrated that thermosyphons exert a significant cooling effect on the temperature field surrounding pile foundations. In addition, Shang [5] proposed an air-cooling system, in which cold air is injected into pre-embedded ventilation pipes within the pile foundation, effectively shortening the refreezing period of the surrounding frozen soil.

However, the aforementioned studies have not directly investigated the influence of intrinsic factors controlling the early-stage thermal stability of pile foundations on the evolution of the temperature field in the pile–soil system. Therefore, taking a permafrost pile foundation project as the engineering background, this study investigates the thermal effects induced by different concrete casting temperatures and their influence on the temperature field evolution of pile foundations in permafrost. The results provide a useful reference for the design and construction of pile foundations in permafrost regions.

2 Numerical Model Development

2.1 Engineering Background

Using a pile foundation project located in the Chumar River high plain region of the Qinghai–Tibet Plateau as the engineering background, a numerical analysis model was developed using the solid heat transfer module in COMSOL Multiphysics.

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \tag{1}$$

where ρ is the material density ($\mathrm{kg \cdot m^{-3}}$),C is the specific heat capacity ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), k is the thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$), and Q denotes the volumetric heat source ($\mathrm{W \cdot m^{-3}}$).

$$\rho_c C \frac{\partial T}{\partial t} = \lambda \nabla^2 T \tag{2}$$

where ρ denotes the density of concrete, C represents the heat capacity of concrete, and λ is the thermal conductivity of concrete.

The field pile has a diameter of 1.25 m and a total length of 14.5 m, including 0.5 m above the ground surface and 14 m embedded below ground. To approximate the semi-infinite soil domain, the surrounding soil was modeled as a cylindrical region with a diameter of 30 m and a thickness of 30 m. The lithological distribution of the site and the corresponding basic thermal parameters used in the numerical model are summarized in Table 1.

Table 1. Thermal properties of soil and structural materials used in the numerical model

Depth (m)	Soil Type	*C* $(kJ\cdot kg^{-1}\cdot{}^{\circ}C^{-1})$	λ $(\mathrm{kJ\cdot m^{-1}\cdot h^{-1}\cdot{}^{\circ}C^{-1}})$
0.0–0.5	gravelly sand	0.95	7.31
0.5–3.2	Medium sand	1.23	9.23
3.2–3.4	Ice-rich sand layer	1.38	9.11
3.4–13.0	Medium sand	0.98	9.15
13.0–20.0	Silty clay	1.12	7.88
20.0–30.0	Marl	1.51	8.21
	Reinforced concrete	0.92	6.26

2.2 Initial and Boundary Conditions

Because a half-axisymmetric model was adopted, the left boundary of the pile–soil domain was defined as the axis of symmetry and treated as an adiabatic boundary. The right boundary was assumed to be free of both conductive and convective heat exchange with the external environment. Based on the local air-temperature records, the time-dependent thermal boundary condition applied at the upper surface of the model was obtained through curve fitting as follows [6]:

$$T = T_s + At + 12.2\,sin\left(\frac{2\pi}{8760}t + \frac{\pi}{3}\right) \tag{3}$$

In the equation, A represents the long-term warming coefficient. Considering the potential influence of climate warming, the regional air temperature is projected to increase by approximately 2.3 °C over the next 50 years. Accordingly, *A* is taken as 5.25×10^{-6} °C h^{-1}.T_s denotes the mean annual ground surface temperature, which is taken as −0.3 °C, while the time variable t is expressed in hours (h).

Assuming that the temperature gradient at a depth of 30 m is 0.025 °C m^{-1}, the corresponding heat flux density at the bottom boundary can be expressed as follows:

$$q = -\lambda \cdot \frac{\partial T}{\partial n} = -0.06\ \mathrm{W/m^2} \tag{4}$$

The initial temperature condition was defined using the measured ground temperature profile of the natural permafrost prior to concrete casting in June. The resulting initial ground temperature distribution adopted in the model is shown in Fig.1.

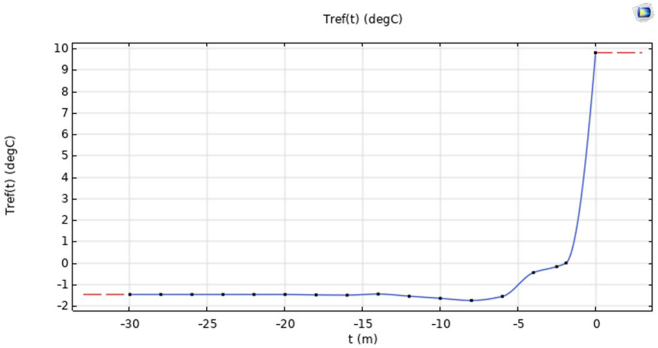


Fig. 1. Initial ground temperature distribution with depth

The heat generated during cement hydration is treated as a volumetric heat source in the numerical model and is introduced in the form of a time-dependent heat generation rate, q(t). This process is thermally equivalent to inserting a heat-emitting pile into the surrounding permafrost. The heat release associated with concrete hydration can therefore be calculated using the following expression:

$$q_v = C\rho \frac{d\theta}{dt} = C\rho\theta_0 m e^{-mt} \tag{5}$$

In the equation, θ_0 represents the ultimate adiabatic temperature rise of concrete, which is taken as 66.74 °C. C denotes the specific heat capacity of concrete. m is the reaction rate coefficient of the hydration process, and its corresponding values are listed in Table 2.

Table 2. m Values at Different Concrete Placement Temperatures

Concrete Casting Temperature	5 °C	10 °C
m/(1/d)	0.295	0.318

2.3 Numerical Model Setup

The mesh configuration of the numerical model is shown in Fig. 2. A total of 12,764 triangular elements were generated, with an average mesh quality of 0.94. The simulation was conducted using a transient analysis, with the output time steps defined as range(0, 6, 8760). The relative tolerance was set to physics-controlled to ensure numerical stability and accuracy.

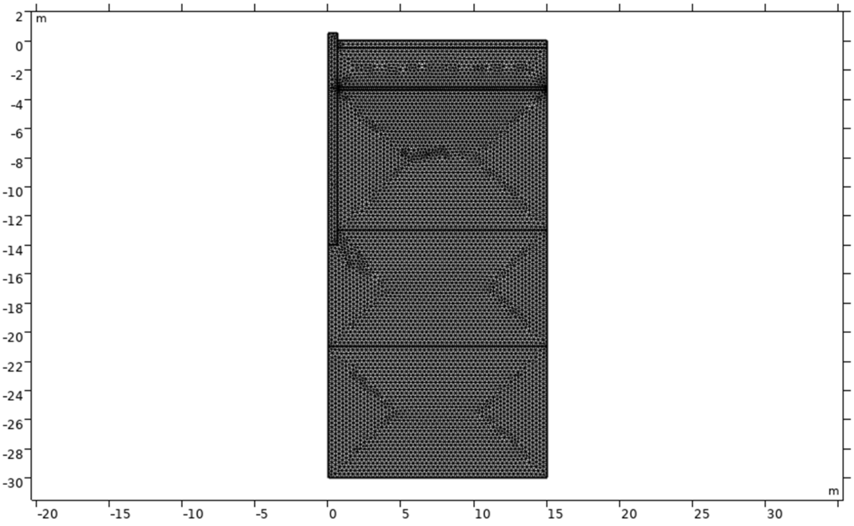
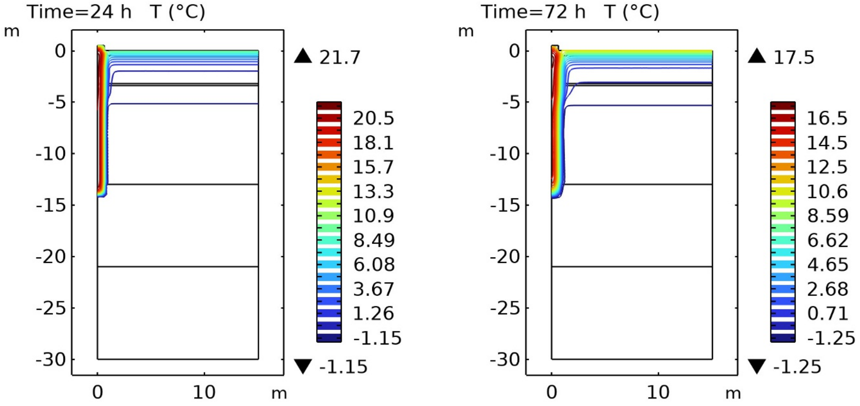


Fig. 2. Mesh of the numerical model

3 Results

Based on the numerical simulations, temperature contour maps of the pile–soil system at different times after pile casting were obtained for various concrete casting temperatures. In the figures, 24 h, 72 h, 168 h, 672 h, and 2400 h correspond to 1 day, 3 days, 7 days, 28 days, and 100 days after pile construction, respectively.

Based on the numerical results obtained for the two considered cases (shown in Figs. 3 and 4, respectively), the variations in pile temperature and permafrost ground temperature were analyzed, leading to the following observations:



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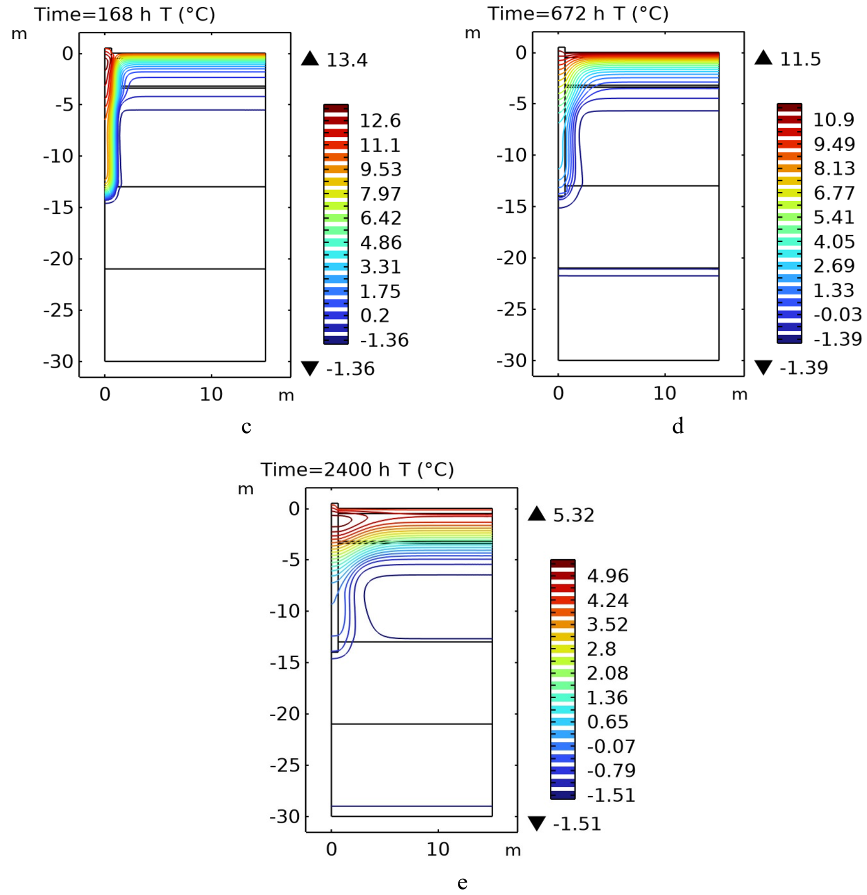
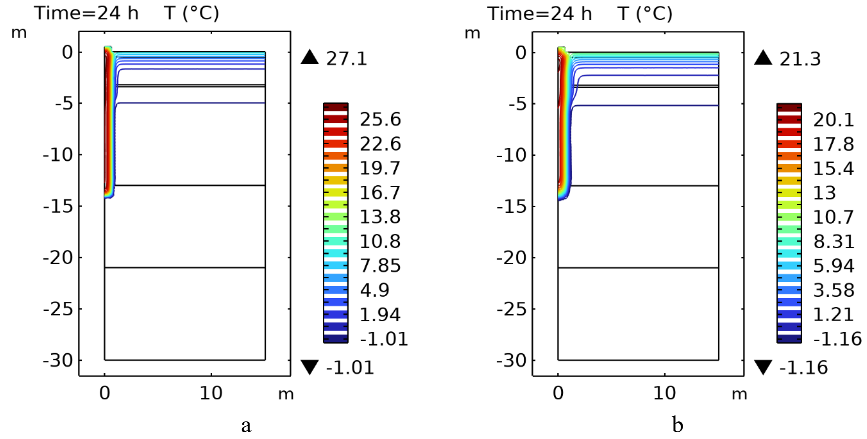


Fig. 3. Temperature contour maps of the pile–soil system at different times under the 5 °C concrete casting temperature condition



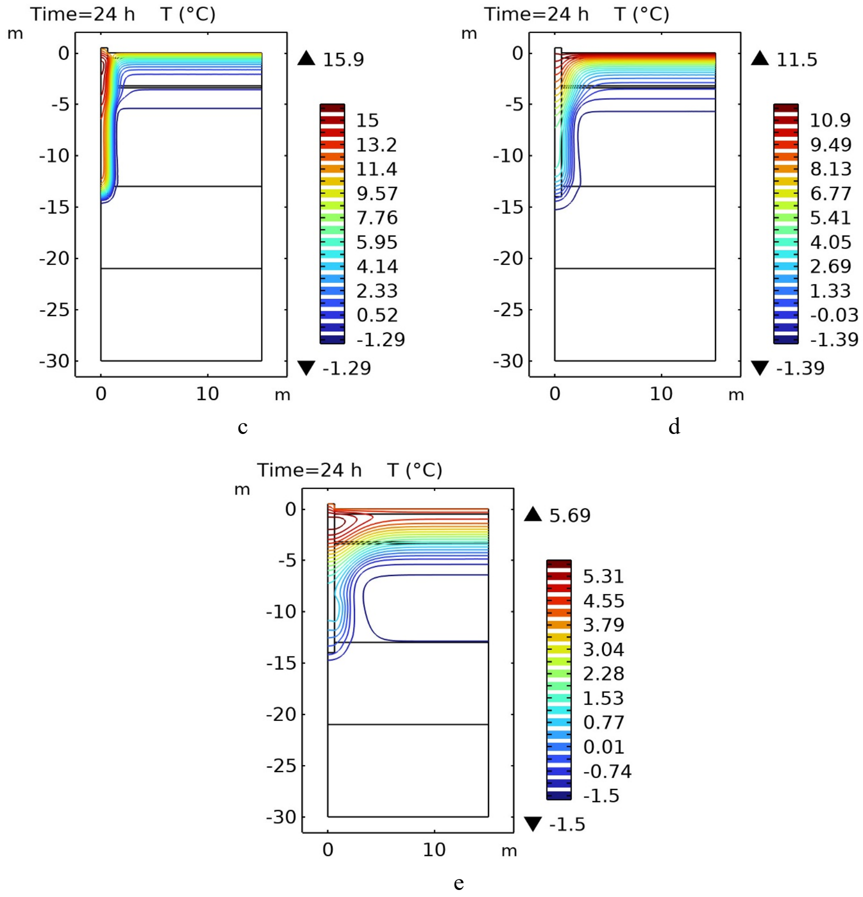


Fig. 4. Temperature contour maps of the pile–soil system at different times under the 10 °C concrete casting temperature condition

(1) The temperature evolution of the pile–soil system can be divided into three distinct stages.

Heating stage (0–24 h). After concrete casting, the cement hydration reaction proceeds intensely, releasing a large amount of hydration heat. As a result, the pile temperature rises rapidly and reaches its peak within a short period. During this stage, the generated heat is mainly concentrated within the pile body and has not yet diffused extensively into the surrounding permafrost. Cooling and diffusion stage (24–672 h). As the hydration reaction gradually weakens, the rate of heat release decreases, and the accumulated heat within the pile begins to transfer rapidly to the surrounding frozen soil, primarily through radial heat conduction. Consequently, the temperature at the pile center decreases, while the temperature of the surrounding soil increases. Meanwhile, the thawed zone around the pile expands progressively, as indicated by the outward migration of the isotherms. Slow refreezing stage (672–2400 h). With the continuous dissipation of heat from the pile body, the temperature difference between the pile and the surrounding soil gradually diminishes, leading to a significant reduction in the cooling rate of the pile–soil system.

(2) Comparison of the temperature contour maps under the two conditions reveals the specific influence of concrete casting temperature on the thermal regime of the pile–soil system.

Peak temperature. A higher casting temperature results in stronger heat accumulation within the pile. Under Condition II, a 5 °C increase in casting temperature leads to an approximately 5.4 °C higher peak temperature at the pile center during the early stage (24 h). Thawing zone development. By comparing the distribution of isotherms under the two conditions, the colored region representing elevated temperatures is noticeably wider in the higher-temperature case. This indicates that a higher casting temperature introduces greater total heat input into the surrounding permafrost, resulting in a larger thawing radius around the pile and consequently a longer refreezing period. Long-term cooling behavior. At 2400 h, the difference in maximum temperature between the two conditions decreases to approximately 0.37 °C. This result suggests that the casting temperature primarily influences the early-stage thermal disturbance and the extent of the thawed zone, whereas the long-term refreezing process is mainly governed by the ambient ground temperature field.

(3) Time-dependent effect of cement hydration heat.

The heat generated during cement hydration exhibits a pronounced time-dependent behavior. In the early stage after concrete casting, the hydration reaction proceeds rapidly, leading to a continuous rise in the pile temperature. Before the peak temperature is reached, the temperature difference between the pile interior and the surrounding soil increases sharply. Owing to the heat dissipation capacity of the surrounding permafrost, the accumulated heat is gradually absorbed by the adjacent frozen soil. After approximately 72 h, as the rate of hydration heat release decreases, the warming effect at the pile surface becomes weaker than the cooling effect induced by heat transfer to the surrounding soil. Consequently, the temperature of the pile wall begins to decline gradually.

4 Conclusion

Taking a bored pile foundation of a bridge project located in the Chumar River high plain region of the Qinghai–Tibet Plateau as the engineering background, a numerical heat transfer model of the pile–soil system in permafrost was established. The model was used to investigate the evolution of the temperature field of the pile–soil system during the construction stage under different concrete casting temperatures. The main conclusions are summarized as follows:

(1)Three-stage temperature evolution. The thermal evolution of the pile–soil system can be divided into three distinct stages: the rapid heating stage (0–24 h), the cooling and heat diffusion stage (24–672 h), and the slow refreezing stage (672–2400 h).

(2)Effect of concrete casting temperature. The concrete casting temperature has a pronounced influence on the early-stage thermal disturbance during construction.

When the casting temperature increases from 5 °C to 10 °C, the peak temperature at the pile center at 24 h rises by approximately 5.4 °C. Meanwhile, the thawing zone around the pile expands, resulting in a longer refreezing period for the surrounding frozen soil. However, as time progresses, its influence on the long-term temperature field gradually diminishes. By 2400 h, the temperature difference between the two conditions decreases to only about 0.37 °C.

(3) Coupled effects of hydration heat and ambient temperature. The temperature evolution of the pile–soil system during the construction stage is jointly controlled by cement hydration heat release and ambient temperature conditions. In the early stage after casting, the hydration reaction proceeds rapidly, releasing heat at a high rate and causing a rapid rise in pile temperature, accompanied by a significant temperature gradient between the pile interior and the surrounding soil. After approximately 72 h, the rate of hydration heat release decreases markedly, and the heat dissipation effect of the surrounding permafrost gradually becomes dominant, leading to a continuous decline in pile temperature. Meanwhile, shallow soil layers are strongly influenced by atmospheric temperature fluctuations, whereas the ground temperature below approximately 4 m depth exhibits relatively small variations, maintaining a comparatively stable thermal regime.

In summary, the concrete casting temperature primarily affects the intensity of early-stage thermal disturbance during construction and the extent of thawing around the pile. If higher early bearing capacity of the pile foundation is required, it is recommended to adopt a lower concrete casting temperature, apply external cooling measures, or use low-heat cement or low-hydration-heat concrete. The findings of this study provide useful guidance for temperature control during pile foundation construction and for the engineering design of pile foundations in permafrost regions.

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