

Heat Transfer Between Concrete Bored Cast-In-Place Piles and Surrounding Frozen Soil in Ice-Rich Area

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Abstract: Based on the concrete test of foundation pile and the heat transfer theory between pile and soil, the heat transfer rule of pile and soil in ice-rich tundra is studied. The results show that the heat flow of foundation pile can be divided into vertical and horizontal heat flows. The vertical heat flow mainly occurs at the top of the pile and reaches the maximum value of 15.36w /m² on 3d. It caused the pile top temperature to drop so fast that it dropped below 0°C in 3d. The value of the horizontal heat flow is 2~3 times that of the vertical heat flow. Its distribution is in descending order: the middle, the top and the bottom of the pile. The maximum temperature difference between pile center and pile wall is 6.8°C because of transverse heat flow. Local high temperature zone is formed inside the pile due to the relatively slow absorption process of thawing permafrost. Then the temperature dropped rapidly, reaching 0°C at 28d. The maximum disturbance radius in the frozen soil reaches 1.5m. Insulation layer can be added to the outside of the foundation pile during construction to obtain more uniform concrete temperature field, so as to improve the concrete strength and reduce the disturbance to the frozen soil. The construction period should be in summer.

Keywords: Ice-Rich Permafrost, Temperature Field, Vertical and Horizontal Heat Flows, Cast-In-Place Concrete Pile

1. Introduction

With the global climate warms, permafrost has gradually become degraded patchy permafrost in The Greater Khingan Mountains region of China [1]. The area is mostly ice-rich permafrost. Permafrost is a multiphase complex system composed of soil particles, ice, unfrozen water and gas. The influence of permafrost on engineering practice is mainly caused by the different combinations of these complex phases [2, 3].

Bored cast-in-place pile is the preferred foundation type of bridge engineering in permafrost area [4, 5], it has the advantages of mature design theory and construction technology and strong applicability. Therefore, 90% of the bridge foundation adopts cast-in-place [6, 7]. Domestic and foreign scholar have done a lot of research on permafrost. Domestic scholar Xiong Wei created the governing equation of temperature field of pile foundation in permafrost region [8]. Shang Yunhu analyzed the influence of pile foundation on ground temperature of permafrost [9]. Wang Xu analyzed the pile foundation under different permafrost conditions and

compared the corresponding freezing time [10, 11]. Foreign scholar Dong-Gen C adjusted different inlet temperature and hydration heat, and analyzed the temperature change rule of permafrost [13]. Lei Shen finds that cracking of mass concrete structures is inevitable [14]. Orlando B. Andersland and B Ladanyi found the potential problem of new concrete freezing during the construction of cast-in-place concrete piles [15].

To sum up, previous researches on pile and soil structure mainly focus on pile foundation quality, permafrost disturbance and freezing problems, and finite element model simulation analysis. The study of heat transfer between pile and soil under harsh geological conditions has not been reported. Therefore, based on the concrete test of foundation pile and the heat transfer theory between pile and soil, the heat transfer rule of pile and soil in ice-rich tundra is studied. The conclusion can be used as a reference for the project construction in this area.

2. Project Profile

Based on jingmo highway bridge concrete bored cast-in-place piles project research. The test site is located in the patchy permafrost area with low hills in Mohe County, The Greater Khingan Mountains, Heilongjiang Province, China. East longitude $121^{\circ}07' \sim 124^{\circ}20'$, North latitude $52^{\circ}10' \sim 53^{\circ}33'$, Average altitude is 550m [16], The average annual glacial period is 7 months [17], The maximum freezing depth in this area is 2.5m~3.0m. The site is located near Pile 11 of The K424+380 Permafrost Bridge. The diameter of pile foundation is 1.4m and the pile length is 11.5m.

2.1. Temperature Field Monitoring Scheme

Eight temperature measuring holes, numbered A~H, were set in the base pile and its periphery respectively. See Figure 1 (a). Fourteen measuring points is arranged along the depth of each temperature measuring hole. The boundary of soil layer should be considered at the measuring points, and the distance between the sensors is 20-130cm. As shown in Figure 1 (b).

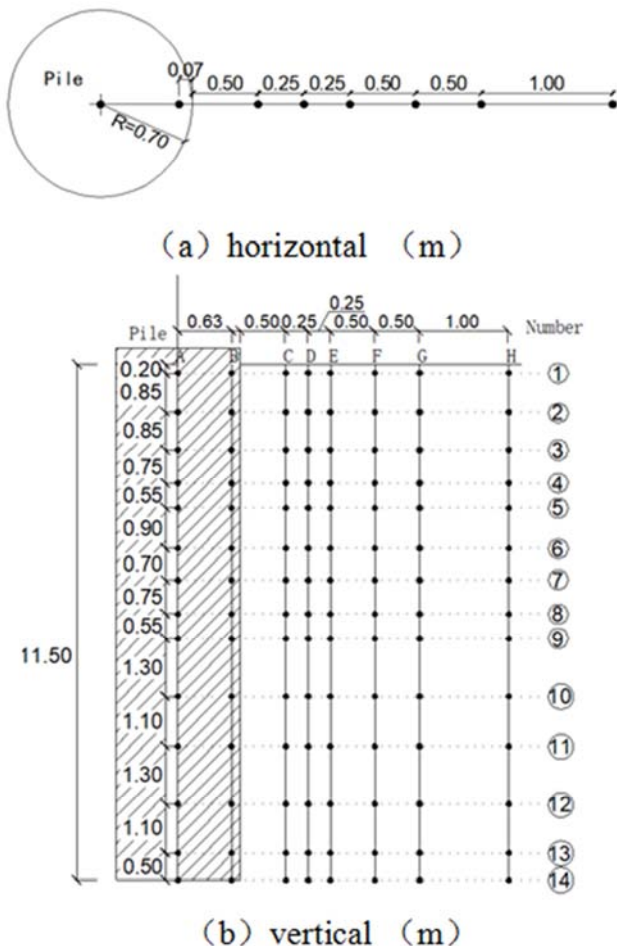


Figure 1. Arrangement of temperature measuring points.

The sensor is a resistance type temperature sensing element DS18B2. The temperature collection range is $-55 \sim +125^{\circ}\text{C}$, and the accuracy is $\pm 0.2^{\circ}\text{C}$. Jmwt-64rt system is used for automatic collection. The system is powered by batteries in

winter and solar energy in summer. The temperature of concrete is tested once before pouring. Temperature data were collected every 4 hours after concrete was poured until 24 hours. After, temperature data will be collected once a day.

2.2. Geological Conditions

When the temperature measuring hole is laid, the permafrost in the temperature measuring hole is taken and stored at low temperature. See the specification for frozen soil sampling method [18]. See Figures 2 and 3.



Figure 2. Collecting soil samples.



Figure 3. Keep soil samples in low temperature.

According to the soil samples, the types of soil are determined, and the names of each soil layer are defined respectively by referring to the provisions in Appendix B of the specification on the naming of ice-bearing characteristics of frozen soil [18]. See Tables 1 and 2.

In Table 2, there are six soil layers in permafrost around the pile. The temperature field at depths of 0.20m, 1.05m, 2.65m, 4.10m, 5.55m, 7.40m, 9.80m and 11.50m was studied by taking the top of the pile, bottom of the pile and the center point of each soil layer.

3. Change rule of Pile-Soil Temperature

For cast-in-place concrete pile, the concrete hydration

reaction should give off 50% heat from 0 to 3 days, and reach 75% on 7 days, and then gradually reduce. In order to better study the hydration heat of pile, its influence on the

temperature of foundation pile and surrounding permafrost. In this paper, the temperature field within 28 days after concrete pouring is analyzed.

Table 1. Try of permafrost.

Name	Characteristics of ice	try of permafrost	try of permafrost
permafrost	Frozen soil with visible ice but with a thickness of less than 25mm	Permafrost with an ice film around the particles	ice-more permafrost
		Irregularly striding bands of ice permafrost	ice-rich permafrost
Thick ice	An earthen or pure sheet of ice over 25mm thick	Including soil ice	Including soil ice
		ice layer	ice layer

Table 2. Soil layer types of the site.

Number	Name	try of permafrost	Thickness (m)	Surface depth (m)
1	cumulosol	Including soil ice	2.1	2.1
2	ice layer	ice layer	1.3	3.4
3	cumulosol	Including soil ice	1.6	5.0
4	silty clay	Including soil ice	1.3	6.3
5	round gravel	ice-rich permafrost	2.4	8.7
6	highly weathered tuff	ice-more permafrost	2.8	11.5

3.1. Base Pile Temperature Field

The 28d temperature field of foundation pile concrete reflects its curing condition and directly affects its quality. In order to study the temperature field of foundation pile, the temperature changes of pile center and pile wall over time were plotted based on the measured data, See Figures 4 and 5.

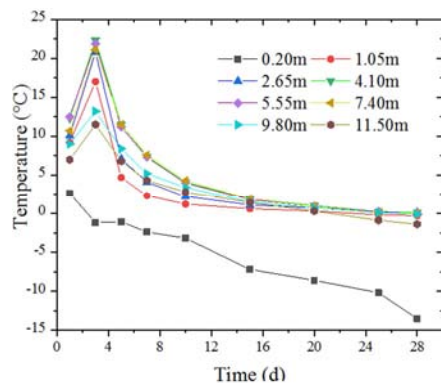


Figure 4. Pile center.

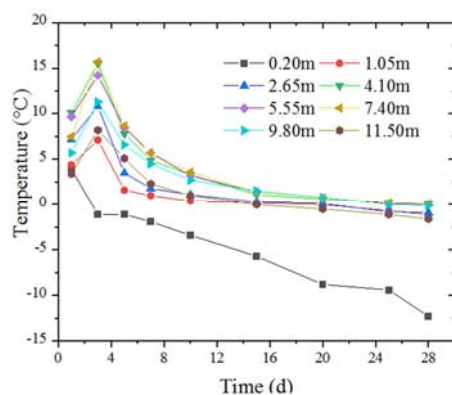


Figure 5. Pile wall.

As can be seen from Figure 4, the temperature of foundation pile at depth of 0.2m is significantly lower than that at other

depths. Because the place was close to the outside environment, most of the heat generated by the hydration of pile foundation flows into the low-temperature atmosphere. In November 2017, the average temperature was -24°C [19], which led to the temperature at the pile top dropping below 0°C at 3d. Then, the temperature dropped rapidly, and it dropped to -13.5°C at 28d.

The temperature field below the pile top appears obvious stratification. The highest temperature was 2.65m~7.4m in the middle of the pile. The temperature of the lower part decreases as the depth deepens. The temperature in the middle of the pile rose rapidly from 0 to 3d, and reached the extreme value of 22.3°C at 3d, then the temperature began to gradually decline, and dropped to about 0°C at 28d. The cooling rate at the bottom of the pile was faster than that at the middle, and it was around 0°C at 20d.

By comparing Figure 4 and Figure 5, it can be found that pile center and pile wall have similar variation trend, but there was a temperature difference. The maximum temperature difference appeared on 3d after pouring, reaching 6.8°C , and then gradually decreased. At 28d, the temperature difference basically disappeared.

3.2. Permafrost Temperature Field Around the Pile

The hydration heat of concrete is inevitably transferred to the permafrost, which contains a large amount of ice. The thermal conductivity of ice is obviously greater than that of water, so the permafrost is greatly disturbed. Therefore, in order to study the disturbance radius of concrete hydration heat to permafrost around the pile, the temperature changes of 0.5m and 1.5m at the pile side are shown in Figures 5 and 6, respectively.

As can be seen from Figures 6 and 7, the maximum temperature of permafrost does not exceed 0°C . This was because the latent heat of ice phase transition will absorb a large amount of heat, but the temperature itself will rise slowly, resulting in a small temperature rise of permafrost. The permafrost of 0.5m on the side of the pile was significantly

affected by hydration heat. The extreme temperature in the permafrost occurs at -0.3°C from 5 to 7 days, after which the temperature begins to decline. The temperature at 28 days ranges from -0.9°C to -1.3°C , and does not return to the initial ground temperature. Permafrost 1.5m away from the pile side was less affected by hydration heat. Except for soil 0.2m deep which was significantly affected by external air temperature, the temperature of other soil layers rises at about 0.3°C and decreases to -1.8°C at 28d, which was close to the original ground temperature, indicating that soil 1.5m away from the pile side was almost not affected by hydration heat. Therefore, the disturbance radius of foundation pile to permafrost was about 1.5m.

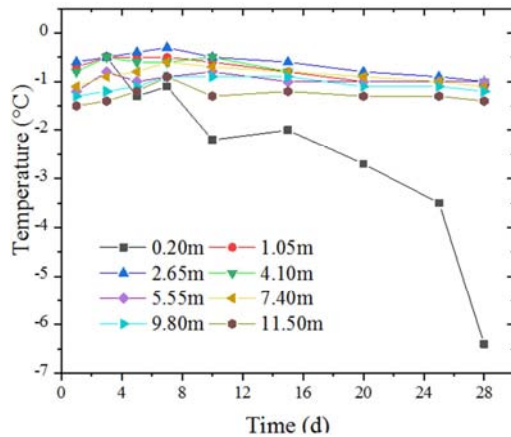


Figure 6. Pile side 0.5m.

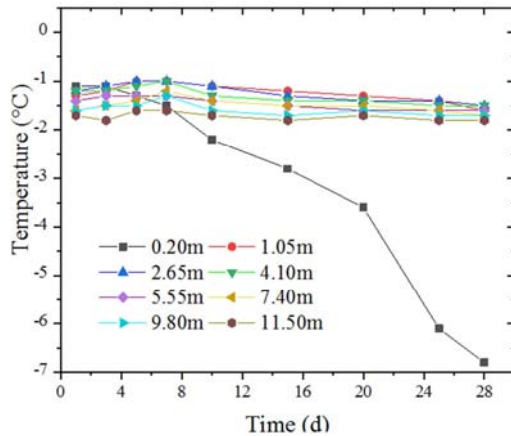


Figure 7. Pile side 1.5m.

4. Research on the Heat Flow of Foundation Piles

In the analysis of temperature field, it can be seen that the temperature distribution of permafrost around the pile is very uneven, and there is obvious stratification, to study the causes of this phenomenon. The heat flow of concrete in foundation piles is analyzed below. According to the basic law of heat conduction, heat flow refers to the heat flow per unit area in unit time, which can be calculated by the following formula [20].

$$q = \lambda \frac{(\theta_2 - \theta_1)}{\delta} \quad (1)$$

Type: q is the heat flux (w/m^2), λ is the thermal conductivity ($\text{w}/\text{m} \cdot \text{k}$), θ_2 is the bottom temperature, θ_1 is the top temperature, and δ is the calculated thickness.

4.1. Pile-Soil Vertical Heat Flow

Vertical heat flow refers to the transfer of hydration heat along the depth of foundation pile. The pile wall is the main heat loss channel, so the vertical heat flow study mainly analyzes the pile wall. According to Equation (1), the thermal conductivity of concrete is $1.28 \text{ w}/\text{m} \cdot \text{k}$, and the temperature gradient is shown in the above temperature field analysis.

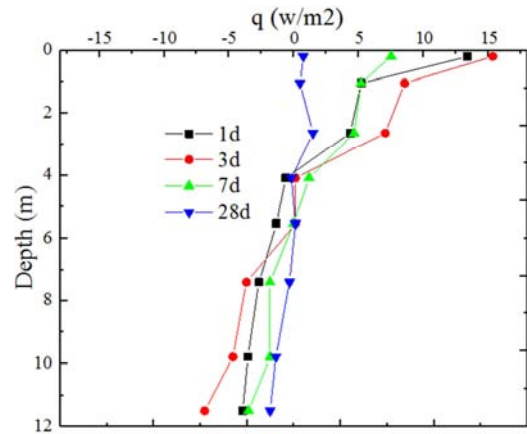


Figure 8. Vertical heat flow distribution.

Figure 8 shows the vertical heat flow distribution at each age after concrete casting. Positive means heat is going up, negative means opposite. On 1d, obvious positive heat flow appears at the top of pile foundation, but not obvious negative heat flow at the bottom. At 3d, the positive and negative heat flows reached the maximum, and then gradually decreased. At 28d, the positive and negative heat flows converged to $\pm 2 \text{ w}/\text{m}^2$.

On the whole, opposite exothermic phenomena occur at pile top and bottom, because heat can be transferred spontaneously from high temperature to low temperature. The pile top at 0.2m is affected by external low temperature, and the extreme value of forward heat flow is $15.36 \text{ w}/\text{m}^2$ in 3d. In the pile top temperature field, the temperature has already dropped below 0°C , which affects the concrete quality of the pile top. Therefore, construction in rich permafrost areas is best in summer. The contact area between the pile bottom and permafrost is relatively large, and the heat of pile foundation can flow into the permafrost rapidly. In 3d, the negative heat flow reaches an extreme value of $-6.84 \text{ w}/\text{m}^2$, resulting in a rapid drop in the temperature of the pile bottom.

With the deepening of depth, the heat flow of foundation pile 0.2-4.1m gradually decreases. The vertical heat flow at a depth of 4.1m~7.4m is basically maintained at about $0 \text{ w}/\text{m}^2$, indicating that the heat flow here neither transfers upward nor transfers downward. As can be seen in section 3-1 above, the temperature here is the highest. This phenomenon is analyzed

below.

4.2. Horizontal Pile-Soil Heat Flow

Horizontal heat flow refers to the transfer between concrete hydration heat and permafrost around the pile. The thermal conductivity of frozen soil needs to be measured when calculating heat flow q according to Equation (1). The thermal conductivity of permafrost is slightly increased with the decrease of negative temperature, but the increase is very small. In general thermal calculation, the thermal conductivity can only be taken in freeze-thaw state and ignore the influence of temperature [20]. Therefore, the thermal conductivity of permafrost under freezing-thawing condition has been measured in laboratory. The test instruments and data are shown in Figure 9 and Table 3. The perturbed radius of permafrost around the pile is about 1.5m. When calculating

the lateral heat flow Q , the soil within the width range of 1.5m on the side of the pile is calculated.



Figure 9. ISOMET2104 heat transfer analyzer.

Table 3. Thermal conductivity of soil.

Number	Name	Depth (m)	Thermal conductivity (w/m · k)	
			Freeze	Thaw
1	cumulosol	0.2	1.01	0.60
2	ice layer	1.05	2.21	0.58
3	cumulosol	2.65	1.01	0.60
4	silty clay	4.1	2.09	1.72
5	round gravel	5.55	1.78	1.77
6	highly weathered tuff	7.4	1.03	0.79
		9.8		
		11.5		

In Figure 10, the positive value represents the concrete hydration heat flow to permafrost, and vice versa. It can be seen from the figure below that only 0.2m depth of soil layer presents negative heat flow, while the remaining depths are all positive heat flow. It shows that the lateral heat flow direction of the pile is mainly from the foundation pile to the permafrost in 28d.

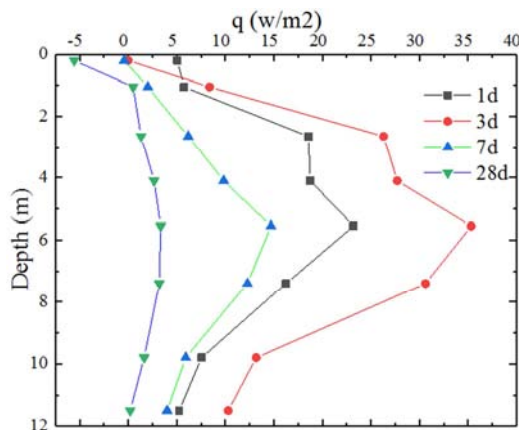


Figure 10. Horizontal heat flow distribution.

The value of the horizontal heat flow is 2~3 times that of the vertical heat flow. Its distribution is in descending order: the middle, the top and the bottom of the pile. This is due to the different thermal conductivity between the soil layers. The thermal conductivity is the largest at 2.65m ice layer, and the transverse heat flow is indeed small. The reason is that part of the

heat of the pile foundation at 2.65m depth is lost from the pile top, leading to the relative decrease of the transverse heat flow.

The rate of transverse heat flow between pile and soil increases due to high ice content and high thermal conductivity in the middle of the pile. In 3d, the heat flow reaches a maximum of 35.32w/m². Make pile center and pile wall form big temperature difference. Local high temperature zone is formed inside the pile due to the relatively slow absorption process of thawing permafrost. Then the temperature dropped rapidly, reaching 0°C at 28d. That is, the foundation pile and surrounding permafrost began to refreeze.

The rapid lateral heat flow not only affects the temperature field of the pile, but also increases the thermal disturbance to the permafrost around the pile. Insulation layer can be added to the outside of the foundation pile during construction to obtain more uniform concrete temperature field, so as to improve the concrete strength and reduce the disturbance to the permafrost.

5. Conclusion

- 1) Vertical heat flow mainly appears on the top of foundation pile, and reaches the extreme value of 15.36w/m² in 3d, leading to a rapid decline in the top temperature, which drops below 0°C in 3d. It is difficult to guarantee the concrete quality of pile top.
- 2) The value of the horizontal heat flow is 2~3 times that of the vertical heat flow, it is the main way of heat loss of pile concrete.

3) The rate of horizontal heat flow between pile and soil increases due to high ice content and high thermal conductivity. Make pile center and pile wall form big temperature difference. Local high temperature zone is formed inside the pile due to the relatively slow absorption process of thawing permafrost. Then the temperature dropped rapidly, reaching 0°C at 28d. It also increases the perturbed range of permafrost around the pile.

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