

# Long-term Influence of Cement Hydration Heat on Ground Temperature Around Energy Piles

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**Abstract.** The long-term (one year) influence of hydration heat released by cement during solidification on the ground temperature around the energy piles is discussed in this paper. The one-dimensional multi-layer medium model and the Green's function method are used to obtain the analytical solution of the ground temperature field. The influences of several factors on the magnitude of the temperature rise are discussed. The results show that the pile diameter has the most significant effect on the ground temperature around a single pile, and the temperature rise in the pile group can reach up to 3.4°C in some cases.

## 1. Introduction

The energy pile combines a heat pump water loop system with a building pile foundation and is used as an underground heat exchanger. Compared with the conventional borehole geothermal heat pump system, it has the advantages of low cost, space saving and large heat exchange capacity [1]. Compared with the air source heat pump, it saves 20%~40% and 30%-50% energy consumption respectively when heating and cooling[2] and reduces up to 80% overall carbon emission [3]. Due to its huge economic and environmental advantages, it is considered to be a very promising technology. Various heat transfer models have been established to predict the heat exchange capacity of the energy pile in order to understand its operating characteristics. These models, like the models of borehole geothermal heat exchanger, take the original ground temperature as the initial ground temperature. In fact, the amount of cement used in energy piles is much larger than that of borehole heat exchangers since the diameter of the former is much larger, which may cause the initial ground temperature to rise significantly due to the hydration heat released by cement for the cast-in-place piles. This may decrease the heat exchange capability of the energy pile and cause the heat pump to deviate from its design condition, it is therefore necessary to analyze this issue.

There are only few researches on similar issue. Xia Caichu et al.[4] studied the influence of concrete casting of the underground structure on the ground temperature in the Shanghai Natural History Museum through numerical simulation. They found that the average ground temperature rises about 2.2°C at 2.85m from the underground continuous wall about 2 years after casting. They also proved that the heat exchange capacity of the buried pipes decreases by more than 5% for every 1°C increasement in ground temperature by field test. You Shuang[5] measured the ground temperature increasement caused by hydration heat within 8 days after the casting of CFG energy piles with diameter of 420mm. The pile body is still about 1°C higher than the original temperature on the 8th day. However, this study did not predict the long-term change of ground temperature.



In order to predict the long-term temperature change around energy piles caused by cement hydration heat, we firstly expound the release law of cement hydration heat and then obtain the analytical solution of the temperature field by using the one-dimensional multi-layer medium model and the Green's function method. The influences of several factors on the ground temperature rise and the possible magnitude of temperature rise are also discussed.

## 2. Heat transfer model

### 2.1. Release law of cement hydration heat

The characteristic of the cement hydration heat release curve is related to cement age and variety. Here we cite the expression in the form of composite index given by Academician Zhu Bofang[6] and take the derivative of it with respect to  $t$ . Then the volume heating rate in concrete can be obtained:

$$q_v(t) = \rho_c Q_0 g h t^{h-1} \exp(-gt^h) \quad (1)$$

Where  $q_v$  is the concrete volume heating rate ( $\text{kW}/\text{m}^3$ );  $t$  is the age of the cement (day);  $\rho_c$  is the amount of cement used per unit volume concrete ( $\text{kg}/\text{m}^3$ );  $Q_0$  is the total hydration heat when  $t \rightarrow \infty$  ( $\text{kJ}/\text{kg}$ );  $g$  and  $h$  are coefficients related to the cement variety.

### 2.2. Model description and calculation

We first take a single pile as the research object which is shown in figure 1.  $R_1$  is the energy pile radius,  $R_2$  is the calculation domain radius and should be greater than the heat influence radius of the energy pile. In order to simplify the problem, the following assumptions need to be made:

- The pile is abstracted into an infinitely long solid cylindrical heat source in an infinite medium since the length of the pile is about tens of times the diameter. Therefore, the problem is also simplified to a one-dimensional heat transfer problem along the radial direction, as shown in figure 2;
- The contact thermal resistance between the pile and the soil is ignored. The thermophysical properties are constant and the original temperatures of the pile and soil are uniform respectively.
- The effect of groundwater seepage is not considered.

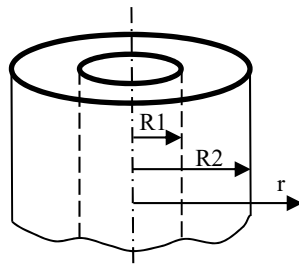


Figure 1. Heat transfer model of an energy pile.

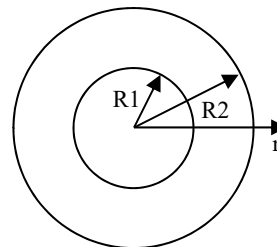


Figure 2. Simplified heat transfer model of an energy pile.

Under the above assumptions, the mathematical description of the problem is as follows:

$$\frac{\partial^2 \theta_i}{\partial r^2} + \frac{1}{r} \frac{\partial \theta_i}{\partial r} + \frac{1}{k_i} q_{vi}(t) = \frac{1}{\alpha_i} \frac{\partial \theta_i}{\partial t} \quad (2)$$

Where  $\theta_i$  is excess temperature relative to ground temperature at infinity,  $i=1$  when  $0 \leq r \leq R_1$  and  $i=2$  when  $R_1 < r \leq R_2$ ;  $q_{v1}(t) = q_v(t)$ ,  $q_{v2}(t) = 0$ .

$$\text{Boundary conditions:} \quad \begin{cases} r = 0, t > 0 & \partial \theta_1 / \partial r = 0 \\ r = R_1, t > 0 & k_1 \partial \theta_1 / \partial r = k_2 \partial \theta_2 / \partial r, \quad \theta_1 = \theta_2 \\ r = R_2, t > 0 & \partial \theta_2 / \partial r = 0 \end{cases} \quad (3)$$

$$\text{Initial conditions: } \begin{cases} 0 \leq r \leq R_1, t = 0 & \theta = \theta_0 \\ R_1 < r \leq R_2, t = 0 & \theta = 0 \end{cases} \quad (4)$$

Where  $k_1$ ,  $k_2$  and  $\alpha_1$ ,  $\alpha_2$  are the thermal conductivity and diffusivity of concrete and soil respectively;  $\theta_0$  is excess temperature of concrete relative to ground temperature when it is casted.

This is a one-dimensional heat conduction problem in composite medium with an unsteady time-dependent heat source, which can be solved by the Green's function method. The homogeneous problem corresponding to the non-homogeneous problem can be solved by the separation variable method to obtain the Green's function[7], which takes the form as

$$G_{ij}(r, t | r', \tau) = \sum_{n=1}^{\infty} e^{-\beta_n^2(t-\tau)} \frac{1}{N_n} \frac{k_i}{\alpha_i} \psi_{in}(r) \psi_{jn}(r') \quad (i, j = 1, 2) \quad (5)$$

Where the norm  $N_n$  is defined as

$$N_n = \frac{k_1}{\alpha_1} \int_0^{R_1} r' \psi_{1n}^2(r') dr' + \frac{k_2}{\alpha_2} \int_{R_1}^{R_2} r' \psi_{2n}^2(r') dr' \quad (6)$$

Characteristic functions  $\psi_{1n}(r)$  and  $\psi_{2n}(r)$  in equation (5) and equation (6) are

$$\begin{aligned} \psi_{1n}(r) &= J_0(\beta_n r / \sqrt{\alpha_1}) \quad , 0 \leq r \leq R_1 \\ \psi_{2n}(r) &= A_{2n} J_0(\beta_n r / \sqrt{\alpha_2}) + B_{2n} Y_0(\beta_n r / \sqrt{\alpha_2}) \quad , R_1 < r \leq R_2 \end{aligned} \quad (7)$$

$J_0$  and  $Y_0$  in equation (7) are zero-order first-class and second-class Bessel functions, respectively.  $A_{2n}$  and  $B_{2n}$  are constant coefficients which can be calculated by the following formulas

$$\begin{aligned} A_{2n} &= [J_0(\gamma) Y_1(\eta) - K J_1(\gamma) Y_0(\eta)] / \Delta \\ B_{2n} &= [K J_1(\gamma) J_0(\eta) - J_0(\gamma) J_1(\eta)] / \Delta \\ \Delta &= J_0(\eta) Y_1(\eta) - J_1(\eta) Y_0(\eta) \end{aligned} \quad (8)$$

Where defining  $\gamma = R_1 \beta_n / \sqrt{\alpha_1}$ ,  $\eta = R_1 \beta_n / \sqrt{\alpha_2}$ ,  $K = k_1 k_2^{-1} \sqrt{\alpha_2 / \alpha_1}$ .  $\beta_n$  is a set of numerous eigenvalues corresponding to the eigenfunction, which can be obtained by equation (9). Trial calculation proves that precise result can be obtained when the first 30 positive  $\beta_n$  are taken into calculation.

$$\begin{vmatrix} J_0(\gamma) & -J_0(\eta) & -Y_0(\eta) \\ K J_1(\gamma) & -J_1(\eta) & -Y_1(\eta) \\ 0 & -J_1(\eta R_2 / R_1) & -Y_1(\eta R_2 / R_1) \end{vmatrix} = 0 \quad (9)$$

Finally, the solution of the problem can be expressed in the form of Green's function:

$$\begin{aligned} \theta_i(r, t) &= \int_{r'=0}^{R_1} r' G_{il}(r, t | r', \tau) \big|_{\tau=0} \theta_0 dr' + \frac{\alpha_1}{k_1} \int_{\tau=0}^t q_v(\tau) d\tau \int_{r'=0}^{R_1} r' G_{il}(r, t | r', \tau) dr' \\ 0 &\leq r \leq R_1, i = 1; R_1 < r \leq R_2, i = 2 \end{aligned} \quad (10)$$

Equation (10) can be calculated numerically. Take the parameter values in table 1 into calculation and define it as the baseline condition, the corresponding results are shown in figure 3.

Table 1. Parameter values used in calculation (baseline condition)

Parameters	Values
$R_1$	0.3m
$R_2$	20m
$\theta_0$	0°C
$\rho_c$	360kg/m <sup>3</sup>
$g$ $h$	0.36 0.74
$Q_0$	350kJ/kg
$\alpha_1$	$7.78 \times 10^{-7} \text{m}^2/\text{s}$
$\alpha_2$	$2.75 \times 10^{-7} \text{m}^2/\text{s}$
$k_1$	1.63W/m·K
$k_2$	1.30W/m·K

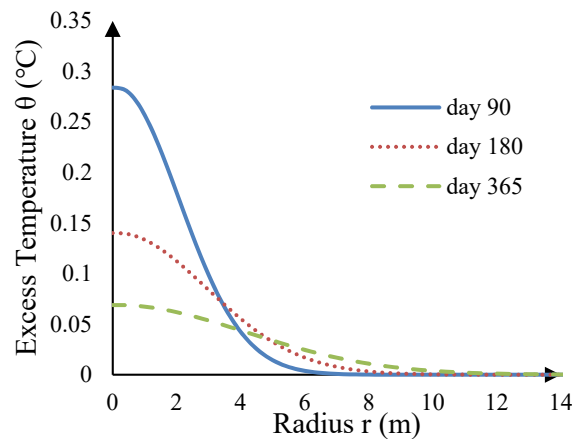


Figure 3. Calculation results of equation (10) using the values in table 1 (baseline condition). The horizontal axis represents the distance from the pile core.

It can be seen in figure 3 that the temperature rise caused by hydration heat of a single pile is almost zero after one year in baseline condition and will not affect the subsequent operation of the heat pump. However, the magnitude of the temperature rise is related to factors like the release characteristics of hydration heat, soil thermophysical properties, pile diameter and concrete molding temperature, etc. In addition, the pile group effect will also affect the ground temperature change. We will discuss the effects of the above factors on the magnitude of temperature rise one year after casting in the following.

### 3. Result analysis

#### 3.1. Effect of hydration heat release characteristics

The parameters  $g$ ,  $h$  and  $Q_0$ ,  $\rho_c$  vary with cement variety and concrete composition. The values of  $g$  and  $h$  determine the release rate of hydration heat. For most cement, 90% of the total hydration heat will be released within 5 to 15 days[6], so the changes of  $g$  and  $h$  has little effect on the long-term change of ground temperature. The values of  $Q_0$  and  $\rho_c$  determine the total amount of hydration heat, it is clear that more heat will cause the ground temperature to rise more.  $Q_0=350\text{kJ/kg}$  and  $\rho_c=500\text{kg/m}^3$  are possible when high-strength concrete is used, in this case the total amount of hydration heat increases by 38% compared with the baseline condition. The curve of “Heat amount” in figure 4 shows that the ground temperature rise also increases by 38% uniformly.

#### 3.2. Effect of soil thermophysical properties

For all types of soils,  $\alpha_2$  varies in the range of  $1\sim 3 \times 10^{-7} \text{m}^2/\text{s}$ , and  $k_2$  varies in  $0.2\sim 1.7 \text{W/m}^2\cdot\text{K}$ , both of them increase with increasing moisture content[8]. Obviously, the temperature rise near the pile will be promoted when  $\alpha_2$  and  $k_2$  decrease. Take  $\alpha_2=1.25 \times 10^{-7} \text{m}^2/\text{s}$  and  $k_2=0.35\text{W/m}^2\cdot\text{K}$  (clay, moisture content 5%, which are very low values) into calculation and the other parameters be same with the baseline condition. The result in figure 4 shows that the decrease of  $\alpha_2$  and  $k_2$  makes the temperature rise by up to 4 times in the range of  $r<6\text{m}$  and decrease in the range of  $r>6\text{m}$ , while the heat influence radius also decreases. This means that the extremely low thermal conductivity and diffusivity of soil can cause a significant increase in the temperature near the energy pile.

#### 3.3. Effect of pile diameter

The pile diameters of different buildings vary greatly. The pile foundation with diameter greater than 800mm is classified as large diameter pile, and the diameter of piles used in actual engineering may even be greater than 1400mm[9]. Large diameter piles will release more hydration heat and make the ground temperature to rise more. Take  $R_1=0.7\text{m}$  into calculation and the other parameters be same

with the baseline condition. The result in figure 4 shows that the increase of  $R_1$  increases the ground temperature significantly, which indicates that the pile diameter is an important influence factor of the ground temperature. However, the heat influence radius is basically the same as the baseline condition.

### 3.4. Effect of concrete molding temperature

When the pile foundation is casted in summer, the concrete molding temperature will increase due to the influence of solar radiation and air temperature. Therefore, this part of extra heat will release to the soil together with the hydration heat and cause a further increase in ground temperature. Take  $\theta_0=20^\circ\text{C}$  into calculation and the other parameters be same with the baseline condition. The result in figure 4 shows that this change only makes the ground temperature rise about 30~33% greater than the baseline condition after one year. In fact, the extra heat released by concrete with excess temperature of  $20^\circ\text{C}$  is equivalent to 37% of the total hydration heat in baseline condition.

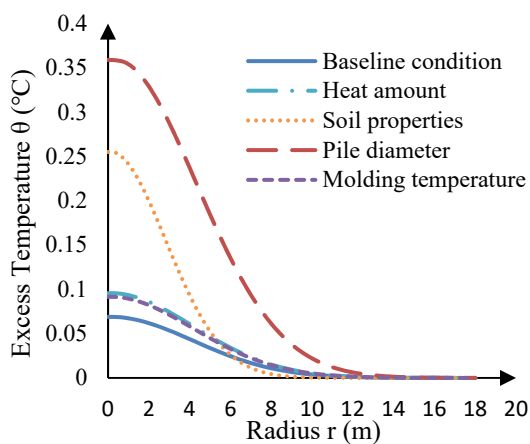


Figure 4. Calculation results of the influence of various factors on the ground temperature after one year of casting.

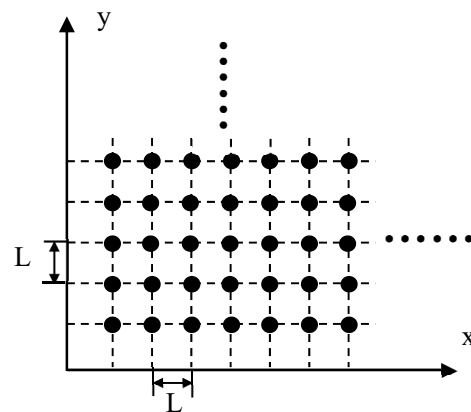


Figure 5. Layout of pile group. Each black circle represents an energy pile.

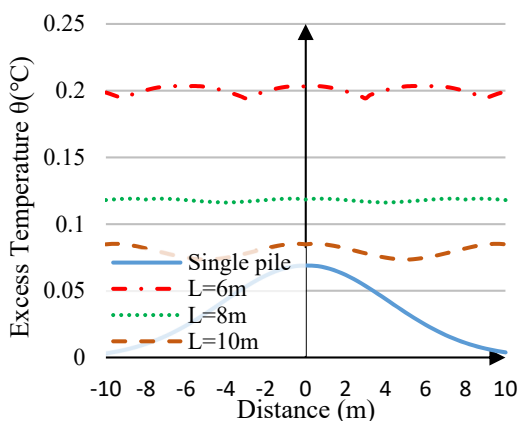


Figure 6. Temperature rise of pile group and single pile (baseline condition).  $x=0$  coincides with the pile core.

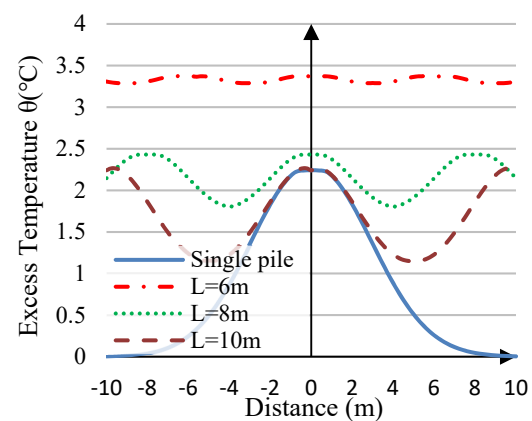


Figure 7. Pile group temperature rise when  $R_1=0.7\text{m}$ ,  $\theta_0=20^\circ\text{C}$ ,  $\rho_c=500\text{kg/m}^3$ ,  $\alpha_2=1.25\times 10^{-7}\text{m}^2/\text{s}$ ,  $k_2=0.35\text{W/m}^2\cdot\text{K}$ .

### 3.5. Pile group effect

The pile foundation of the actual building is composed of a large number of single piles arranged in a certain regularity. The temperature field around a pile will be changed due to the presence of the other piles near it, which is known as the pile group effect. According to the superposition principle, the temperature field of pile group can be obtained by linearly superimposing the temperature field of

each single pile[10]. Assuming that the pile foundations are arranged in a grid pattern of  $L$  (m)  $\times$   $L$  (m) spacing as shown in figure 5, the superposed temperature field of the section crossing the pile core along the  $x$  direction under the baseline condition is shown in figure 6. It can be seen that when the pile spacing is small enough, the pile group effect will increase the ground temperature significantly, and the smaller the pile spacing is, the more the temperature rises.

### 3.6. Possible magnitude of temperature rise

When the above factors contributing to the increase in ground temperature work simultaneously, it is possible to cause a significant increase in the ground temperature after one year of casting. Consider the case of  $R_1=0.7\text{m}$ ,  $\theta_0=20^\circ\text{C}$ ,  $\rho_c=500\text{kg/m}^3$ ,  $\alpha_2=1.25\times 10^{-7}\text{ m}^2/\text{s}$ ,  $k_2=0.35\text{W/m}^2\cdot\text{K}$  and the other parameters are same with the baseline condition, the calculation result is shown in figure 7. It can be seen that the temperature rises about  $3.4^\circ\text{C}$  when the pile spacing is 6m, which is a very considerable value.

## 4. Conclusions

- The pile diameter is the most important factor affecting the long-term ground temperature around a single pile. When the pile diameter increases from 600mm to 1400mm and the other conditions remain unchanged, the temperature rise of the single pile core increases from  $0.069^\circ\text{C}$  to  $0.36^\circ\text{C}$  after one year of casting. However, the heat influence radius remains unchanged.
- The pile group effect may promote the ground temperature rise, the extent of which is related to the pile spacing and the heat influence radius of a single pile closely. The pile group effect will be significant when the pile spacing is less than the heat influence radius.
- When thick piles and small pile spacing are used, the ground temperature in the pile group may be significantly higher than the original ground temperature in a long time. If the ground source heat pump comes into the cooling operation during this period, its performance and operational stability may be affected by the increasement of ground temperature. This problem needs to be further researched.

## References

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