Study on Heat Transfer Model and Applicability of Energy Piles in Nanning Basin under Subtropical Climate

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Abstract. In order to meet the requirements of peak carbon dioxide emissions, energy pile systems have been widely used in more and more regions because of their low-carbon, energy-saving, and emission-reducing characteristics. To explore the applicability of the energy pile project in Nanning, which has typical subtropical climate characteristics with warm winters and hot summers, some research work has been carried out in this paper. Firstly, through indoor thermophysical property tests, the geotechnical thermophysical parameters of typical composite strata in this area are obtained. Then a transient heat transfer model of the energy pile is established, which can fully reflect the heat transfer characteristics of the pile and the soil. On this basis, the superposition principle and stepped heat flow theory are used to analyze the temperature recovery characteristics of typical strata in Nanning area under different intermittent operation conditions. The results show that: the rock-soil mass of the typical stratum in Nanning area has good heat transfer characteristics, which is conducive to the promotion of energy pile engineering. The heat transfer model proposed in this paper has higher accuracy than the classical linear heat source model, which can reflect the material characteristics of energy pile system and avoid overestimating or underestimating the temperature field of energy pile system. The operation of energy pile system in a subtropical climate will produce an unbalanced heat load, and corresponding measures need to be taken to achieve the balance of heat load. The research results can provide a reference for energy pile engineering design in different climate regions.

1. Introduction

Energy pile is a new form of underground heat exchanger in ground-source heat pump system (GSHP). The energy pile saves the construction period and the cost of drilling by embedding the heat exchange PE pipe in the pile foundation. At the same time, the pile with good heat transfer performance is used as the main heat transfer medium for heat exchange with soil, which has a good engineering application prospect[1-2]. Energy pile shows superior engineering economy and energy saving, has been applied in Shanghai, Kunshan, Ningbo, etc. However, there are few reports about the application of energy piles in areas with special climate characteristics and typical soil types, especially in subtropical regions. Therefore, the applicability of energy pile in other regions with different climate and geotechnical types needs to be studied.

In addition, the relevant heat transfer design theory and method of energy pile are still not fully perfect at this stage. And problems such as "heat accumulation" and "thermal interference" often appear in engineering, which reduces the operational efficiency of energy pile or even fails[3].
Therefore, accurate analysis of the heat transfer process of the energy pile is the key to the long-term operation of the energy pile system. At present, the heat transfer calculation model of energy pile is mainly based on the classical line-source model theory\(^4\) and cylindrical-source model theory\(^5\). Afterward, according to the distribution of heat source in the pile, scholars put forward heat transfer models such as finite line source model\(^6\), solid cylindrical surface source model\(^7\-\(^8\)), spiral source model\(^9\-\(^10\)), etc. These models improve the heat transfer theory of energy pile to a certain extent. However, few studies on the models consider the differences in thermophysical properties between pile and soil. Yan\(^11\) derived the heat transfer model of energy pile for the spiral-tube. And the calculation results show that taking pile-soil as the same medium will produce some errors in the heat transfer analysis of energy pile. Bourne\(^12\) tested the thermal response of concrete energy piles in London, which found that the pile's temperature varies unevenly in the radial direction. There is a significant temperature difference between the pile and soil. It is proved that the thermophysical properties of pile and soil have a considerable influence on the heat transfer process of energy pile in the radial direction. At the same time, in order to improve the heat transfer performance of traditional energy piles with concrete as the main material, scholars have greatly enhanced the thermal conductivity and heat storage performance of energy pile materials by adding modified fiber, graphite, iron ore, and new energy storage materials (such as phase change materials, etc.) into pile concrete. These make the difference in thermophysical properties between pile and soil very obvious. However, most of the existing heat transfer models can not consider the difference between pile and soil materials.

In view of the deficiencies in previous studies, the geotechnical thermophysical characteristics parameters of the typically combined stratum in this area are obtained by laboratory tests in this paper at first. Then, establishing the unsteady heat transfer model of energy pile by using the theoretical derivation method, which can fully reflect the heat transfer characteristics of pile and soil. On this basis, under the intermittent operation condition of energy pile, the temperature recovery characteristics of a typical stratum in Nanning area with subtropical climate are analyzed by using the superposition principle and step heat flow theory. And the applicability and economy of energy pile in Nanning area are evaluated by it.

2. Typical strata and their thermophysical parameters in Nanning area

2.1. Typical stratigraphic model in Nanning area

According to the previous geological exploration reports, the river terrace topography is widely distributed in Nanning basin, and the vertical distribution of strata has an obvious dual structure. The specific stratum structure mainly includes miscellaneous fill, silty clay, silt, coarse sand, gravel, and bedrock (general composition: plaster rock, red sandstone, conglomerate, etc.). Due to different geological origins and geological structures, the strata in various areas of Nanning are different, and some of them lack stratum. Combined with the stratigraphic distribution and the general situation of rock and soil layers in Nanning area, the main soil layers in Nanning basin can be summarized as two typical strata: "miscellaneous soil layer + round gravel layer + mudstone layer" and "miscellaneous soil layer + mudstone layer", as shown in Figure 1. In these two typical formations, it is obvious that the thickness of the mudstone layer is relatively large, and it is the main part of the formation. At the same time, the heat transfer characteristics of energy pile have a great relationship with the thermophysical characteristics of soil, so this paper will test and analyze the thermophysical characteristics of mudstone in Nanning basin.

2.2. Values of geotechnical thermophysical parameters

The mudstone sample in this test is selected from the excavation of Nanning Metro. The KD2 Pro thermal characteristic analyzer and SH-1 double-needle probe were used to test the thermal physical parameters of mudstone. Because of the high hardness of mudstone, it is necessary to drill small holes in the soil sample before the test to facilitate the insertion of a double-needle probe. And then inject
and 1.18 kJ/(kg·K) in turn.

W/(m·K), \(8.1 \times 10^{-7}\) m²/s ,

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3. Heat transfer model of energy pile considering the difference of thermal properties between pile and soil

3.1. Calculation model

Figure 4 is a schematic diagram of the heat transfer calculation model of energy pile. The calculation model combines the characteristics of the discontinuous distribution of heat source in the circumferential direction of U-shaped buried pipe energy pile and rapid heat transfer in the pile body. The equivalent diameter method is used to simplify the U-shaped PE pipe into a linear heat source acting...
on the pile core. The pile and soil are regarded as homogeneous media with different thermophysical properties. The influence of material difference on heat transfer of energy pile is fully considered. Therefore, it is reasonable to describe the heat transfer process of energy pile for the simplified model proposed in this paper.

3.1.1. Basic assumption. The calculation model adopts the following assumptions:

1) The heat exchange pipe is regarded as an infinite line-source, and the heat exchange per unit length is constant;
2) Considering the difference of thermophysical properties between the pile and the rock-soil, the two materials are homogeneous materials with constant physical properties;
3) The pile lining is in close contact with the soil without reference thermal resistance;
4) Without considering the vertical heat transfer, it is regarded as a plane heat conduction problem.

3.1.2. Governing equations.

\[
\frac{\partial^2 \theta_1}{\partial r^2} + \frac{1}{r} \frac{\partial \theta_1}{\partial r} = \frac{1}{a_1} \frac{\partial \theta_1}{\partial t}, \quad (0 \leq r \leq r_0) \tag{1}
\]

\[
\frac{\partial^2 \theta_2}{\partial r^2} + \frac{1}{r} \frac{\partial \theta_2}{\partial r} = \frac{1}{a_2} \frac{\partial \theta_2}{\partial t}, \quad (r_0 \leq r \leq +\infty) \tag{2}
\]

Where is:
- \(\theta_1\) --Excess temperature of pile, °C;
- \(\theta_2\) --Excess temperature of soil, °C;
- \(a_1\) --Thermal diffusivity of the pile, \(m^2/s\);
- \(a_2\) --Thermal diffusivity of soil, \(m^2/s\);
- \(r_0\) --Pile radius, m.

3.1.3. Initial conditions and boundary conditions.

\[
\theta_1(r, t) = \theta_2(r, t) = 0, \quad (t = 0) \tag{3}
\]

Because the excess temperature of rock-soil at infinity is 0, The temperature and radial heat flux at the interface between pile lining and soil are continuous, it can be obtained:

\[
\frac{\partial \theta_1}{\partial r} = 0, \quad (r \to \infty) \tag{4}
\]

\[
\theta_1 = \theta_2, \quad (r = r_0) \tag{5}
\]

\[
k_1 \frac{\partial \theta_1}{\partial r} = k_2 \frac{\partial \theta_2}{\partial r}, \quad (r = r_0) \tag{6}
\]

3.1.4. Equation solving. Through dimensional analysis, dimensionless variables are introduced:

Let \(x = \frac{r^2}{4at}\) \tag{8}

From the conservation of heat flux, it can get the following results:

\[
\lim_{r \to 0} (2\pi r k_1 \frac{\partial \theta_1}{\partial r}) = -q_l \tag{7}
\]

Where is:
- \(q_l\) --heat exchange of unit length, W/m;
- \(k_1\) --Thermal conductivity of pile, W/(m·°C);
- \(k_2\) --Thermal conductivity of soil, W/(m·°C).

By substituting (8) into (1) and (2), the partial differential equation can be obtained by Boltzmann manipulation:
\[ \frac{\partial^2 \theta}{\partial x_1^2} + \left(1 + \frac{1}{x_1} \right) \frac{\partial \theta}{\partial x_1} = 0, (0 \leq x_1 \leq \eta_1) \] (9)
\[ \frac{\partial^2 \theta}{\partial x_2^2} + \left(1 + \frac{1}{x_2} \right) \frac{\partial \theta}{\partial x_2} = 0, (\eta_2 \leq x_2 < \infty) \] (10)

The concrete solutions of equations (9) and (10) can be expressed as follows:
\[ \theta_1 = -A_1E_i(-x_1) + B_1 \] (11)
\[ \theta_2 = -A_2E_i(-x_2) + B_2 \] (12)

Where: \[ -E_i(x) = \int_x^\infty \frac{e^{-y}}{y} dy \] --exponential integral function.

3.1.5. Model simplification. When the thermophysical properties of pile-soil materials are similar, the difference in pile-soil materials' thermophysical properties can be ignored. Then \[ k_1 = k_2 = k, a_1 = a_2 = a, \eta_1 = \eta_2 \] can be uniformly expressed as Eq.(15). Therefore, the model proposed in this paper can degenerate into the classical infinite line-source model, which is consistent with the expression of the classical infinite line-source model[4]. Meanwhile, the model proposed in this paper has fewer calculation parameters, simple form, and is convenient for engineering applications.

\[ \theta = -\frac{q_l}{4\pi k} E_i\left(\frac{r^2}{4at}\right), (0 \leq r < \infty) \] (15)

3.2. Expression of the excess temperature of energy pile in intermittent operation
In the intermittent phase, the heat flux load is considered. A rectangular step heat flux is formed between the operation and intermittent periods, as shown in figure 5- (a). According to the superposition principle\cite{4,13}, the no-thermal load condition in the intermittent phase can be regarded as the same size of positive and negative thermal load, as shown in figure 5-(b). At the same time, because the previous step heat flow impacts the subsequent life cycle of the energy pile system, the piecewise linear step load superposition method is adopted for calculation, as shown in figure 5-(c). Therefore, the expression of the excess temperature of energy pile in intermittent operation is as follows:

\[ \theta = -\frac{q_l}{4\pi k} E_i\left(\frac{r^2}{4at}\right), (0 \leq r < \infty) \] (15)

Figure 5. Schematic diagram of thermal load superposition
where is:

\[ \eta_i^* = \frac{r_0^2}{4a_i(t_n - t_{j-1})}; \eta_2^* = \frac{r_0^2}{4a_2(t_n - t_{j-1})} \]  \hspace{1cm} (17)

The temperature recovery rate (\( \zeta \)) is defined as: The ratio of the excess temperature change after the end of an intermittent period to the excess temperature before the start of the intermittent period.

\[ \zeta = \frac{\theta_2^{(n-1)} - \theta_2^{(n)}}{\theta_2^{(n)} - \theta_2^{(n-1)}} = 1 - \frac{\theta_2^{(n-1)}}{\theta_2^{(n)}} \]  \hspace{1cm} (18)

In the formula: the smaller \( \theta_2^{(n)} \) is, the closer \( \zeta \) is to 1, indicating that the better the temperature recovery effect is.

4. Model validation and parameter analysis

4.1. Model validation

In order to verify the accuracy of the energy pile heat transfer model proposed in this paper, it is compared with the calculation results of the linear-source model\[4\] and the finite element model\[14\]. And the calculation parameters of the model verification were the same as those in the literature\[14\].

![Figure 6](image1.png)

**Figure 6.** Comparison of the excess temperature of pile wall in different analytical models

Figure 6 shows the variation of excess temperature of energy pile lining with time in different analytical models. It can be seen from Figure 6 that the excess temperature at the pile lining calculated by the model in this paper is in good agreement with the finite element model and the infinite line heat source model, which verifies the accuracy of the model in this paper. However, in the initial stage of energy pile operation, the excess temperature of pile lining calculated by the finite element model and the model in this paper is slightly larger than that calculated by the line heat source model, which can more accurately reflect the thermal conductivity of energy pile is higher than soil, i.e., heat can be transferred to the pile lining faster through the pile. Therefore, the model in this paper can avoid overestimating the pile’s temperature in the initial stage of heat transfer. Figure 7 shows the radial distribution of excess temperature in different analytical models. As shown in Figure 7, the model in this paper considers the differences in thermophysical properties of pile and soil material, so the heat transfer rules in pile-soil medium are different in the radial heat transfer direction with the radius of pile as the boundary. Similarly, the linear-source model fails to reflect it. At the same time, the thermophysical properties of pile and soil are considered to be the same in the linear-source model. Due to the relatively large heat capacity and strong heat storage capacity of the soil, the heat...
transferred to remote soil is reduced, and the excess temperature of the soil is low. In this model and finite element model, the excess temperature of soil along the radial distribution is relatively higher, which reflects the influence of energy pile material on the temperature field of energy pile system better. In conclusion, this model can reflect the heat transfer characteristics of the energy pile system more accurately than the classical linear-source model.

4.2. Parameter analysis

4.2.1. Effect of intermittent operation mode on temperature recovery. Nanning basin is located in the south of the Tropic of cancer, with low altitude. Affected by the warm and humid climate in the south, it has abundant precipitation. And the annual average temperature is about 21.6 °C. It has the typical climate characteristics of "hot summer and warm winter" and belongs to the standard subtropical monsoon climate area. At the same time, combined with the monthly average temperature in Nanning area, the operation time of energy pile refrigeration in Nanning area is from the middle of April to the middle of September. The running time of energy pile system is about 5~7 months, and the corresponding intermittent time is 7~5 months. In winter, the climate is relatively warm, and there is no heating demand. Because the energy pile project in Nanning has the characteristics of long operation time in summer, the influence of different "operation intermittent" cycles on the temperature recovery of energy pile is studied. Take the "operation-intermittent" as follows: 6 Months - 6 Months (working condition 1: standard start-up refrigeration operation time), 5 Months - 7 Months (working condition 2: reduced start-up refrigeration operation time), and 7 Months - 5 Months (working condition 3: increased start-up refrigeration operation time). According to the measured data of the GSHP project in Nanning[15-16], the heat transfer per unit depth of the heat exchange tube is about 30 ~ 55 W / m. Considering the high heat exchange efficiency of the energy pile, the heat exchange per unit length of the energy pile during operation is 50 W/m. Other calculation parameters are as follows. Pile: $k_1 = 2.94 (W/m \cdot ^\circ C)$, $a_1 = 1.2 \times 10^{-6} (m^2/s)$; Mudstone: $k_2 = 1.97 (W/m \cdot ^\circ C)$, $a_2 = 8.1 \times 10^{-7} (m^2/s)$.

Figure 8. Effect of intermittent time on temperature recovery

Figure 8 shows the influence of different "operation intermittent" conditions on the temperature recovery of the energy pile system. As can be seen from Figure 8, the temperature recovery rate at the pile lining of energy pile with intervals of 5, 6, and 7 months is 0.823, 0.855, and 0.883, respectively. Moreover, with the increase of intermittent time, the recovery rate of temperature increases approximately linearly, but the effect is not obvious. Therefore, it is not economical to restore the temperature of the energy pile system by increasing the interval time. At the same time, due to the existence of temperature gradient, even in the intermission period, the heat of pile is always transferred to the distant soil. When the intermission period is short, the excess temperature of the remote soil will increase at the end of the intermission period. For example, the excess temperature of the soil 5 meters away from the pile core at the end of the intermission period is about 0.2 °C higher than that at the beginning of the intermission period in condition 2 and condition 3.
4.2.2. Effect of thermal load on temperature recovery. In order to balance the cooling and heating load as much as possible and improve the temperature recovery rate of the energy pile system. In actual engineering, it is generally considered to reduce the "temperature accumulation" effect by producing domestic hot water during the operation and intermittent periods. However, due to the influence of the season, the distribution of the cooling load generated by the production of domestic hot water in one cycle of the energy pile will be different. Generally, because the tap water temperature in the intermittent period is relatively low, the cooling load for producing the same amount of domestic hot water in the intermittent period is higher. In order to consider this factor, a period of "standard start-up cooling operation time" (i.e., operation period and intermittent period are both 6 months) is used to study the effect of different cooling and heating load ratios on the temperature recovery rate of the energy pile system. And the specific cooling - heating load ratio is calculated according to formula (19). The calculation conditions are shown in Table 1.

\[
\frac{q_{\text{cooling-operation}} t_1 + q_{\text{cooling-intermittent}} t_2}{q_{\text{heating}} t_1} = \xi \quad (19)
\]

Where \( \xi \) -- Cooling - heating load ratio; \( q_{\text{heating}} \) -- Heating load during operation period, W/m; \( q_{\text{cooling-operation}} \) -- Cooling load during operation period, W/m; \( q_{\text{cooling-intermittent}} \) -- Cooling load in the intermittent period, W/m; \( t_1 \) -- Operation period, month; \( t_2 \) -- Intermittent period, month.

| Type of working condition | (6 months) heating load during operation period (W/m) | (6 months) Cooling load during operation period (W/m) | (6 months) Cooling load in intermittent period (W/m) | Heating load ratio |
|---------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|----------------------|
| Condition 4              | 50.0                                              | 0                                                | 0                                                | 0                    |
| Condition 5              | 50.0                                              | 25.0                                             | 25.0                                             | 1.00                 |
| Condition 6              | 50.0                                              | 20.0                                             | 30.0                                             | 1.00                 |
| Condition 7              | 50.0                                              | 12.5                                             | 12.5                                             | 0.25                 |

Figure 9 shows the influence of different thermal load conditions on temperature recovery. When the cooling-heating load ratio increases from 0 to 0.25 and 1, the temperature recovery rate at the pile lining increases from 0.86 to 1.18 and 1.85, respectively. Obviously, with the increase of cooling-heating load ratio, the higher the temperature recovery rate of the energy pile system, the better the ground temperature recovery effect. And it is a benefit to improve the refrigeration efficiency of the next operation cycle. Considering that it is not easy to achieve complete cooling and heating load balance in practical engineering, When the intermittent ratio is about 1, and the cooling-heating load ratio is about 0.25 by trial calculation, a better temperature recovery effect can be achieved. Because the heat transfer efficiency of the energy pile is relatively good, and the energy pile system in the subtropical climate region also has relatively sufficient intermittent time. At the same time, compared with condition 5 and 6, the temperature recovery rate depends on the cooling-heating load ratio, but the form of heating load will affect the excess temperature. Obviously, condition 5 (i.e., higher cooling-heating load ratio in refrigeration operation period) will make the excess temperature of pile lining rise lower, which is conducive to the operation of energy pile projects in the subtropical region. However, the thermal load form of mode 6 is more suitable for the demand of subtropical climate regions. Despite all this, the difference of excess temperature between the two conditions is within 1 °C.

4.2.3. Influence of soil type on temperature recovery. This section studies the characteristics of intermittent operation of energy pile in the sand, clay, and typical mudstone in Nanning area to analyze the influence of soil type on the temperature recovery of energy pile system. And the applicability of energy piles in Nanning area is evaluated by temperature recovery. At the same time, to analyze the economy of energy pile in Nanning area, the characteristics of temperature recovery of
energy pile system under long-term operation conditions are studied. Take 15 "running intermittent" working cycles, and select the standard start-up refrigeration running time for each working cycle. Calculation parameters are the same as those in Section 4.2.1. Sandy soil: \( k_2 = 2.80 \text{ (W/m} \cdot \text{C)} \), \( a_2 = 11.2 \times 10^{-7} \text{ (m}^2/\text{s)} \); Clay: \( k_2 = 1.35 \text{ (W/m} \cdot \text{C)} \), \( a_2 = 5.1 \times 10^{-7} \text{ (m}^2/\text{s)} \).

Figure 10 shows the recovery of pile lining temperature in different soil types. As can be seen from Figure 10, the excess temperatures of pile lining in the sand, mudstone, and clay increase in turn. And the pile lining temperature increases with the rise in the operation cycle, but the increase is less than 2°C. A certain degree of "cooling-heating load balance" deals with, the temperature of the energy pile lining in different types of soil after each intermission period recovers well, which is about 1.5°C lower than the initial ground temperature. At the same time, compare the temperature variation characteristics of the energy piles in mudstone stratum with or without the "heating - cooling load balance" deal with, it can be found that the excess temperature of the energy pile lining without "cooling-heating load balancing" deal with is 2.5 ~ 4°C higher than that of the energy pile lining with "cooling-heating load balancing" deal with, no matter before or after the intermission. And in the 15 years of the intermittent refrigeration operation cycle, it always has the same rule. But, even without the measures of "cooling-heating load balance", the working efficiency of energy piles in mudstone stratum is very close to that of energy piles in clay stratum, which have undergone thermal load balancing treatment. So it can be seen that the typical stratum in Nanning area is suitable for energy pile engineering.

![Figure 9](image9.png)  
**Figure 9.** Influence of thermal load on the recovery of temperature

![Figure 10](image10.png)  
**Figure 10.** Influence of soil type on the recovery of temperature

5. Conclusions

In this paper, the relevant thermophysical parameters of typical mudstones in Nanning area are obtained through experiments. At the same time, a heat transfer model which can accurately describe the heat transfer characteristics of energy pile is derived. According to the above results, the intermittent operation characteristics of energy piles in Nanning region under the subtropical climate are studied, and the specific conclusions are as follows:

(1) The mudstone in Nanning area with good thermal conductivity, which is suitable for energy pile engineering. The thermal conductivity, thermal diffusivity, and specific heat capacity of mudstone in Nanning area can be taken as 1.97 \text{ W/(m} \cdot \text{C)} , 8.1 \times 10^{-7} \text{ m}^2/\text{s} and 1.18 \text{kJ/(kg} \cdot \text{C)} respectively.

(2) The temperature recovery rate depends on the cooling-heating load ratio and has nothing to do with thermal load. But the form of thermal load will affect the change of excess temperature. The energy pile project in the subtropical region where refrigeration is the main working condition, the larger the
cooling-heating load ratio, the lower the excess temperature rise of the energy pile system in the operation period. It is conducive to improving the operational efficiency of the energy pile.

(3) The temperature recovery rate of energy pile system increases with the increase of intermittent time, but the effect is not obvious. It is necessary to adopt the measure of "cooling-heating load balance" to improve the temperature recovery rate of energy pile system. Under the climate and stratum conditions in Nanning area, when the interval ratio of operation is about 1, the cooling-heat load ratio is about 0.25, then a better temperature recovery effect can be achieved.

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