Estimation of soil and grout thermal properties for energy piles: A new parameter estimation method

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Abstract. It is critical to determine the thermal parameters of the soil and pile for designing energy piles. Based on the infinite different-thermal properties cylindrical heat source model, this paper proposes a method that can use short-term thermal response test (TRT) data to estimate the soil thermal conductivity, thermal diffusivity and thermal resistance in the pile. A three-dimensional numerical model was established and verified by a large sandbox test. The numerical model was used to generate virtual TRT data, and the pattern search algorithm was adopted to estimate the parameters. Then the accuracy of the parameter identification results was discussed. It is found that, compared with the previous methods, the proposed method can greatly shorten the time required for TRT. At the same time, this method can estimate the thermal parameters more accurately, especially the soil thermal conductivity that has the greatest impact on heat transfer performance, with an estimated error of 1.23%.

1. Introduction
The great challenge brought by energy use has become an important issue of concern to all countries in the world. In most regions, building operation consumption accounts for a large proportion of the total energy consumption, which can even reach 30% [1]. Therefore, ground source heat pump systems(GSHPs), as a technology that utilizes shallow geothermal energy for building cooling and heating, have attracted more attention. According to the report of the World Geothermal Congress 2020, from 2015 to 2019, the capacity of the installed GSHPs has increased by 1.54 times [2].

The typical GSHPs are composed of three parts: a space heating or cooling part in the building, heat pump and ground heat exchanger (GHE). GHE is the most critical part and has the greatest impact on performance and investment cost. The traditional GHE is a borehole heat exchanger (BHE), in which the heat exchange pipes are buried in a borehole with backfilled materials. Since the 1980s, in Austria, Switzerland and other European countries, energy piles that combine the bearing capacity of pile foundations with the utilization of shallow geothermal energy have rapidly developed [3].

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Energy piles can save drilling costs and underground space, and concrete has better thermal conductivity than the traditional backfilled material. Therefore, energy piles have higher heat exchange efficiency and better technical economy index.

When designing GHEs, the soil thermal conductivity, thermal diffusivity, and borehole thermal resistance are important parameters, which affect the operation performance and economy of the energy pile system. The inaccuracy of parameters will lead to deviation of design results. Studies have shown that when the soil thermal conductivity deviates by 10%, the deviation of the design length of GHE is 4.5%–5.8% [4]. The most commonly used method to obtain these thermal parameters is in-situ thermal response test (TRT). By exerting a heating load on a GHE, the fluid is heated and circulates in the pipe. The temperature data of the inlet and outlet will be measured, processed and analyzed to determine the thermal properties. The slope method [5] based on the infinite line source (ILS) model is widely used in data processing, which is simple and clear. However, the slope method can only use the data after heat transfer reaches the quasi-steady state. Because the diameter of energy piles is generally larger than that of boreholes, the TRT requires a long quasi-steady state time, which is difficult to achieve in the test. Moreover, only the soil thermal conductivity can be directly obtained, and other parameters such as borehole thermal resistance and soil thermal diffusivity cannot be directly obtained. Another parameter identification method is parameter estimation method, which uses analytical or numerical models to perform inverse calculation and fitting analysis, so that the calculated values of temperature are as close to the measured values as possible. This kind of method can obtain multiple thermal parameters at the same time. The analytical models adopted are ILS model [6,7], infinite hollow cylindrical source (IHCS) model [8,9,10] and infinite solid cylindrical source (ISCS) model [11].

However, when calculating the temperature on the borehole wall, these models ignore the influence of materials in the borehole on short-term heat transfer. Hence, as for the TRT on energy piles, the parameter estimation error is relatively large. On the other hand, numerical models can be established in FLUENT software and COMSOL Multiphysics for parameter estimation [12,13,14]. However, due to the high computational cost and low computational efficiency, there are fewer applications, and they are often used to carry out virtual TRT that cannot be completed under actual conditions [15,16].

The purpose of this paper is to find a suitable method for using the early data measured in the TRT on energy piles to estimate the thermal parameters. Compared with the previous analytical models, the model used in this paper takes into account the inconsistency of thermal properties inside and outside the pile. In that case, the transient heat transfer process inside the pile can be more accurately described. A numerical model was established to generate virtual TRT data, which was verified with the data from a sand box test. Moreover, the soil thermal conductivity, thermal diffusivity and thermal resistance in the pile were estimated at the same time and the identification accuracy were analyzed.

2. Methodology of parameter estimation

2.1. Analytical model

Yan et al. [17] proposed the infinite different-thermal properties cylindrical heat source model, referred to as the IDCS model in 2020. This model considers the influence of different thermal properties inside and outside the pile on the transient heat transfer, while assuming that the infinite heat source is
distributed on the pile surface. The temperature outside the pile can be calculated as:

\[
T_2(r,t) = T_0 + \frac{q_1}{2\pi r_0} \int_0^\infty \frac{1-e^{-r^2}}{r^2} \left( H(\lambda) \right) \left( \frac{\lambda}{a_1} \right) \left( R(\lambda) \right) \left( \frac{\lambda}{a_2} \right) \left( J_0(r_0) \left( \frac{\lambda}{a_1} \right) \right) d\lambda
\]

\[
H(\lambda) = \frac{k_1}{a_1} J_1(r_0) \left( \frac{\lambda}{a_1} \right) J_0(r_0) \left( \frac{\lambda}{a_1} \right) - \frac{k_2}{a_2} J_0(r_0) \left( \frac{\lambda}{a_1} \right) J_2(r_0) \left( \frac{\lambda}{a_2} \right)
\]

\[
R(\lambda) = \frac{k_1}{a_1} J_1(r_0) \left( \frac{\lambda}{a_1} \right) Y_0(r_0) \left( \frac{\lambda}{a_1} \right) - \frac{k_2}{a_2} J_0(r_0) \left( \frac{\lambda}{a_1} \right) Y_2(r_0) \left( \frac{\lambda}{a_2} \right)
\]

(1)

Where \( T_2 \) are the temperature outside the pile, \( K \); \( T_0 \) is the initial temperature, \( K \); \( q_1 \) is the heat rate per length of pile, \( W \cdot m^{-1} \); \( r_0 \) is the radius of the pile, \( m \); \( k_1, k_2 \) are the thermal conductivity of the pile and soil respectively, \( W \cdot m^{-1} \cdot K^{-1} \); \( a_1, a_2 \) are the thermal diffusivity of the pile and soil respectively, \( m^2 \cdot s^{-1} \); \( J_n \) are Bessel functions of the first kind of order \( n \), \( Y_n \) are Bessel functions of the second kind of order \( n \).

Compared with the previously proposed model, the IDCS model can more accurately describe the temperature at the initial stage of heat transfer. Because the geometric dimension of the pile is smaller than the dimension of the soil outside the pile, the heat transfer inside the pile is considered to reach a steady state in a relatively short time. Then the relationship between the temperature of fluid and solid can be described as:

\[
q_f = \frac{T_f(t) - T_b(t)}{R_b}
\]

(2)

Where \( T_f \) is the average temperature of fluid, \( K \); \( T_b \) is the temperature at the pile surface, \( K \); \( R_b \) is the thermal resistance in the pile, \( m \cdot K \cdot W^{-1} \).

2.2. Optimization algorithm

Given the TRT data, the parameter estimation process of \( k_2, a_2 \) and \( R_b \) shown in the figure 1. In this paper, the root mean square error (RMSE) is used to measure the difference between the calculated temperature by IDCS model and the experimental temperature:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{N} (T_{cali} - T_{expi})^2}{N}}
\]

(3)

Where \( N \) is the total number of selected data measurements.

With RMSE as the objective function, the pattern search algorithm is used to continuously adjust the input parameters for optimization. This algorithm looks for a better point near the current point through a fixed pattern so that its objective function value is lower than the current point. A pattern is a set of vectors, and the algorithm applies this set of vectors to the current point to obtain a set of grid points. Certain stopping criteria can be set in the algorithm, such as mesh size tolerance, the maximum iteration number, or the maximum calculation time.

3. Numerical model and validation

3.1. Numerical model

By coupling two physical fields of solid heat transfer and non-isothermal pipe flow in COMSOL
Multiphysics software, the process of heated fluid circulating in the pipe and exchanging heat with the soil were simulated. It is necessary to add the wall heat transfer part in the non-isothermal pipe flow physical field to consider the heat conduction through the pipe wall. Beier et al. [18] conducted a large indoor sandbox test to perform a TRT on a BHE in 2011. The size of the test and related thermal parameters are shown in Table 1. A three-dimensional finite element model of this test was established (figure 2). The top and bottom are insulated, and the surrounding boundary are constant temperature. Since the heating power is constant during TRT, the inlet and outlet temperature should meet the following relationship in the numerical model:

$$T_{in} = T_{out} + \frac{Q}{V_f \rho_f C_{pf}}$$

(4)

Where $T_{in}$ and $T_{out}$ are the temperature of the inlet and outlet, respectively, $K$; $Q$ is the heat rate, W·m$^{-1}$; $V_f$ is the fluid volumetric flowrate, m$^3$·s$^{-1}$; $\rho_f$ is the density of the fluid, kg·m$^{-3}$; $C_{pf}$ is the heat capacity of the fluid, J·kg$^{-1}$·K$^{-1}$.

Figure 1. Flow chart of parameter estimation.  

3.2. Model validation

To validate the numerical model, the reference data sets provided by Beier was used, which included the temperature at different radial positions and the average temperature of the inlet and outlet. The comparison between numerical values and experimental data is shown in figure 3. The maximum absolute error of the average temperature of the inlet and outlet is 0.84 ℃, and the maximum relative error is 2.34%. The maximum absolute error at $r=0.303$ m is 0.39 ℃, and the maximum relative error is 1.62%. Moreover, the farther away from the center, the smaller the error is. In general, the numerical simulation results are in good agreement with the experiment, and this model can be used to simulate in-situ TRTs.

Table 1. Parameters of the sandbox test reported by Beier et al.
### Parameters Description Value

| Parameter | Description                              | Value        |
|-----------|------------------------------------------|--------------|
| $r_b$     | Radius of borehole                       | 0.063 m      |
| $B$       | Width of square sandbox                  | 1.8 m        |
| $r_o$     | Outer radius of U-tube                   | 1.67 cm      |
| $r_i$     | Inner radius of U-tube                   | 1.3665 cm    |
| $D$       | Distance between centers of U-tube pipes | 5.3 cm       |
| $k_p$     | Thermal conductivity of pipe             | 0.39 W m\(^{-1}\) K\(^{-1}\) |
| $k_s$     | Thermal conductivity of sand             | 2.82 W m\(^{-1}\) K\(^{-1}\) |
| $k_g$     | Thermal conductivity of grout            | 0.73 W m\(^{-1}\) K\(^{-1}\) |
| $C_s$     | Volumetric heat capacity of sand         | 2.0E+6 J m\(^{-3}\) K\(^{-1}\) |
| $C_g$     | Volumetric heat capacity of grout        | 3.8E+6 J m\(^{-3}\) K\(^{-1}\) |
| $V_f$     | Average fluid volumetric flowrate        | 0.197 L s\(^{-1}\) |
| $Q$       | Average heat rate                        | 1056 W       |
| $T_0$     | Initial temperature                      | 22 ℃         |
| $L$       | Length of bore and U-tube                | 18.3 m       |

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**Figure 3.** Comparison of temperatures between numerical model and experiment.

3.3. *Simulation of TRT*
Based on this numerical model, a virtual TRT on an energy pile was carried out under specific conditions. According to relevant specifications and experience, the size of the energy pile, and thermal parameters of materials are set as shown in Table 2. The cross section of the calculation area is a square with a side of 5 m. Compared to in-situ TRT, the numerical model can simulate TRTs under different conditions and obtain artificial temperature data for parameter estimation. In addition, the thermal parameters input into the model are regarded as real values, which can be used to calculate the error of parameter estimation.

Table 2. Parameters of the virtual TRT.

| Parameters | Description                        | Value           |
|------------|------------------------------------|-----------------|
| \( r_p \)  | Radius of pile                     | 0.3 m           |
| \( r_o \)  | Outer radius of U-tube             | 1.25 cm         |
| \( r_i \)  | Inner radius of U-tube             | 1.02 cm         |
| D          | Distance between centers of U-tube pipes | 0.5 m       |
| \( k_p \)  | Thermal conductivity of pipe       | 0.42 W m\(^{-1}\) K\(^{-1}\) |
| \( k_1 \)  | Thermal conductivity of soil       | 1.3 W m\(^{-1}\) K\(^{-1}\) |
| \( k_2 \)  | Thermal conductivity of pile       | 2.95 W m\(^{-1}\) K\(^{-1}\) |
| \( a_1 \)  | Thermal diffusivity of soil        | 0.481E-6 J m\(^{3}\) K\(^{-1}\) |
| \( a_2 \)  | Thermal diffusivity of pile        | 1.229E-6 J m\(^{3}\) K\(^{-1}\) |
| \( V_f \)  | Average fluid volumetric flow rate | 0.8 L s\(^{-1}\) |
| \( Q \)    | Average heat rate                  | 1500 W          |
| \( T_0 \)  | Initial temperature                | 22 °C           |
| \( H \)    | Length of pile                     | 20.0 m          |

4. Parameter estimation and results

According to equation (1) and equation (2), \( T_f \) can be expressed as:

\[
T_f(t) = T_0 + q_s R_0 + \frac{q_1}{2 \pi k_1} \int_0^t e^{-k_2 t} \sum_{n=1}^{\infty} \int_0^r \left[ \int_x^{r_i} \int_{\psi_1}^{\psi_2} \frac{1-e^{-\lambda t}}{\lambda (\lambda+R(\lambda))} \left[ \frac{\lambda}{\lambda+R(\lambda)} \right] \int_0^r \left[ H(\lambda) \psi_1 - H(\lambda) \psi_2 \right] d \lambda \right] d \lambda \right] d \lambda
\]

(5)

According to the variation of the temperature difference between the pile surface and the fluid in the virtual TRT (figure 4), the heat transfer in the pile has basically entered the quasi-steady state after \( t=12 \) h, so the data from \( t=12 \) h to \( t=24 \) h were selected for parameter estimation. On the other hand, the real value of \( R_0 \) was calculated by the temperature difference at \( t=72 \) h, which is 0.127 m K W\(^{-1}\). RMSE is taken as the objective function, pattern search is taken as the optimization algorithm, and the algorithm stops when the number of iterations reaches 100. It is estimated that \( k_2=1.316 \) W m\(^{-1}\) K\(^{-1}\), \( a_2=0.650 \times 10^6 \) m\(^{3}\) s\(^{-1}\), \( R_0=0.119 \) m K W\(^{-1}\).

Substituting the estimated parameters into equation (6), the average temperature of fluid was calculated and compared with TRT data. The results are shown in figure 5, representing good agreement within the time range of \( t=12 \) h–24 h.
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**Figure 4.** Variation of the temperature difference between the pile surface and the fluid

**Figure 5.** Comparison of average temperature of fluid between IDCS model and virtual TRT.

For the traditional slope method, because of the limitations of the model and method, only the data after the time $t_b$ is valid:

$$t > \frac{5k_2^2}{a_2} = 260.4\text{h}$$

(6)

This is obviously unrealistic. In order to compare the parameter identification results of different methods under the same condition, the data of $t=12 \text{ h}–24 \text{ h}$ was also analyzed by the slope method. Meanwhile, the estimated parameters and relative errors (RE) obtained by the parameter estimation method based on ILS model, IHCS model and ISCS model are also listed in Table 3.

**Table 3.** Parameter estimation results by different methods.

| Method    | $k_2$ (W·m$^{-1}$·K$^{-1}$) | $a_2$($10^6$ J·m$^{-3}$·K$^{-1}$) | $R_0$ (m·K·W$^{-1}$) |
|-----------|-----------------------------|----------------------------------|----------------------|
|           | Value                      | RE                              | Value               | RE                              | Value              | RE                              |
| Slope method | 2.483                      | 91.00%                          | –                   | –                              | –                  | –                              |
| ILS model    | 1.025                      | 21.15%                          | 0.303               | 37.01%                         | 0.150              | 18.11%                         |
| IHCS model   | 1.000                      | 23.08%                          | 0.150               | 68.81%                         | 0.112              | 11.81%                         |
| ISCS model   | 1.016                      | 21.85%                          | 0.151               | 68.61%                         | 0.104              | 18.11%                         |
| IDCS model   | 1.316                      | 1.23%                           | 0.650               | 35.14%                         | 0.119              | 6.30%                          |

It can be seen that the results obtained by the proposed method based on IDCS model are accurate, especially the soil thermal conductivity, $k_2$. This is because the IDCS model considers the influence of the material inside the pile and the size of the pile, giving a more accurate description of the short-term heat transfer. In particular, $k_2$ has the greatest impact on the heat transfer performance and is the most critical factor in the design of energy piles engineering, while the effect of $a_2$ is relatively small. Although the linear fitting degree of the traditional slope method is very high, the error of $k_2$ is particularly large, which is of no practical significance. Using different methods, the magnitude of the RMSE can all reach a smaller value, so the objective function cannot be used as the only evaluation criteria for parameter estimation results. Of course, the accuracy of the soil thermal diffusivity, $a_2$, needs to be further improved.

In the process of parameter estimation, the sensitivity coefficient is an index to measure the
identifiability and uncertainty of the estimation results. The sensitivity coefficient is defined as the first partial derivative of $T_i$. Because the solution of IDCS model is relatively complicated, the sensitivity coefficient of parameters can be simplified as the first-order difference quotient when the difference of independent variable is close to zero:

$$SC_j = \frac{\partial T_i(\mathbf{P})}{\partial P_j} = \lim_{\Delta P_j \to 0} \frac{T_i \left(P_1, P_2, \ldots, P_j + \Delta P_j, \ldots, P_M \right) - T_i \left(P_1, P_2, \ldots, P_j, \ldots, P_M \right)}{\Delta P_j}$$  \hspace{1cm} (7)

Where $SC_j$ is the sensitivity coefficient of the $j$th parameter $P_j$, $\mathbf{P} = [P_1, P_2, \ldots, P_M]^T$; $M$ is the total number of parameters.

To avoid the differences in orders of magnitude and dimensions, the relative sensitivity coefficients $RSC_j$ are used:

$$RSC_j = P_j \frac{\partial T(\mathbf{P})}{\partial P_j}$$  \hspace{1cm} (8)

From the results shown in figure 6, the relative sensitivity coefficients of $k_2$ and $a_2$ increase with time. The value of $k_2$ is about three times that of $a_2$, indicating that $a_2$ has little influence on $T_i$. This means that in the process of parameter estimation, the change of $a_2$ can only cause a slight change in the value of the objective function, which explains why the estimation error of $a_2$ is relatively large. On the other hand, because of the relatively small sensitivity of $a_2$, the inaccurate result of $a_2$ will not produce large design errors during the design of GHEs.

![Figure 6. Relative sensitivity of $k_2$ and $a_2$ by IDCS model.](image)

5. Conclusions

This paper presents a new method to identify the thermal parameters required for the energy piles design. The latest IDCS model was adopted to consider the influence of pile material and pile size on short-term heat transfer. Based on the validated three-dimensional numerical model, artificial TRT data were obtained and parameters were identified, and the following conclusions are drawn:

- The proposed method can effectively utilize the early data in TRT and shorten the test time.
- Compared with the methods in previous studies, the proposed method is more accurate in
estimating the soil thermal conductivity, with a relative error of 1.23%. The estimation error of the thermal resistance in the pile is acceptable.

- Because the IDCS model ignores the thickness of the protective layer, there is still a certain error in calculating temperature at the pile surface, and the estimation accuracy of the soil thermal diffusivity needs to be improved

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