Estimating the thermal properties of soil and concrete piles from thermal response tests (TRTs) for energy piles with spiral tubes

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Abstract. Accurate estimation of the thermal properties of soil and concrete piles is critical for designing energy piles. This paper proposes an algorithm that can simultaneously estimate the thermal conductivities and diffusivities of soil ($k_s$ and $\alpha_s$, respectively) and concrete piles ($k_b$ and $\alpha_b$, respectively) using data from thermal response tests (TRTs). The outstanding feature of the algorithm is its use of a composite-medium cylindrical-surface heat source solution. The proposed algorithm is a theoretically complete short-term solution that considers the heat capacity of the concrete pile and the difference in thermal properties between the soil and concrete pile. Sensitivity analysis shows that the data of early-time TRTs reduce the linear dependence of the parameters, thereby allowing the simultaneous estimation of $k_s$, $\alpha_s$, $k_b$, and $\alpha_b$. The new algorithm is validated using the reported TRT data. Results show that the four parameters could be estimated with high accuracy by using the data sampled between 10 and 50 h. Moreover, $k_s$ and $k_b$ have relative errors of $11.05\%$ and $24.47\%$, respectively. In conclusion, the proposed algorithm is easy to implement and computationally more efficient compared with algorithms using numerical models. Thus, the use of this algorithm may potentially reduce the time and cost of TRTs.

1. Introduction

The widespread use of borehole ground heat exchangers (GHEs) is impeded by space requirements and the high cost of drilling, especially in locations with land constraints and expensive land prices. Given their low cost and high heat transfer rate, energy piles (EPs) provide an alternative to borehole GHEs. EPs are building piles in which heat exchange pipes are embedded. Compared with borehole GHEs, the outstanding characteristics of EPs include a large diameter and short depth; thus, the heat capacity ($C_b$) and short-time temperature responses of these piles are important considerations. Calculation of short-time responses requires detailed information on the thermal conductivity and diffusivity of the soil ($k_s$ and $\alpha_s$, respectively) and concrete piles ($k_b$ and $\alpha_b$, respectively). From the perspective of engineering applications, these thermal properties may be obtained from the literature, but engineering experience shows that the theoretical results are probably inconsistent with those reported. Thus, developing a procedure for estimating $k_s$, $\alpha_s$, $k_b$, and $\alpha_b$ is highly necessary.

Estimations of thermal properties play an important role in addressing the design of heat exchangers. To determine these parameters, engineers generally carry out in situ thermal response test (TRTs); the equipment used in these tests consists of two thermometers, an electric heater, a water pump, a flow meter, and a data logger (Figure 1). The water temperatures at the inlet and outlet of the heat exchanger
loop under a constant heating power are collected by using the thermometers. The collected data are then used in a parameter-estimation (an inverse problem) procedure to estimate the necessary thermal properties. The simplest algorithm estimates only $k_s$. Zarrella et al. [1] estimated $k_s$ by using an infinite line heat source model; however, the obtained estimates demonstrated large errors and indicated that a numerical model may achieve improved accuracy. Zarrella also found that unreasonable estimations of $k_s$ affect the pile length design and peak load of the heat pump such that the cooling and heating load requirements of the building are not met. Oliveira Morais et al. [2] explored the influence of precipitation and water table by applying an infinite line heat source model to data collected over 4 years of TRTs on unsaturated soils in the Brazilian region. Using finite cylindrical and moving infinite line heat sources, Lines et al. [3] investigated the effect of groundwater on $k_s$ estimates in Australia; however, the estimates of $k_s$ were consistently higher than the actual values. A number of studies estimating $k_s$ at different depths by using two-dimensional numerical models have also been reported [4].

**Figure 1.** Schematic layout of the components and installation of an *in situ* thermal response test device

Another method estimates both $k_s$ and the borehole thermal resistance $R_b$. Luo et al. [5] proposed a modified line heat source model with an equivalent radius and half-transfer rate to estimate the effective $k_s$ and $R_b$ and found that the model is especially applicable to large-diameter pile foundations. Yoon et al. [6] estimated the equivalent $k_s$ and $R_b$ by using a helical line heat source model and finite element method, respectively. In a numerical simulation of a 72 h-long TRT, Park et al. [7] concluded that estimation of the effective $k_s$ yields good results but that $R_b$ is only half that of the traditional model, which could overestimate the concrete thermal resistance. Related studies on the estimation of the effective $k_s$ and $a_s$ using solid cylindrical-surface heat source and coil models have been published [8].

A heat transfer model that could account for the effect of heat capacity is necessary to estimate the thermal properties of concrete piles. Hu et al. [9] proposed a composite cylindrical heat source model to estimate $k_s$ and the volumetric heat capacity of soil ($C_s$), which can consider $C_b$. Results showed that the model is suitable for short-term predictions but may be inaccurate for long-term performance analysis because it ignores the axial effect. Lan et al. [10] explored a hybrid composite-medium line heat source model and kept the volumetric heat capacity constant; the authors found that the relative error of the estimated values was below 5% after 100 min. Franco et al. [11] examined how the ratios of $k_b$ and $k_s$ affect the estimation results with errors of up to 50% by numerical simulation and clearly showed that the line heat source model should be used with caution because of its tendency to generate higher errors. While numerous related studies on this topic are available, the current literature lacks reports on algorithms that could simultaneously estimate $k_s$, $a_s$, $k_b$, and $a_b$. 
In this paper, we propose an algorithm that can estimate the parameters of $k_s$, $a_s$, $k_b$, and $a_b$ simultaneously. The most remarkable feature of this algorithm is its use of a composite-medium cylindrical-surface source model; this model is an analytical model that takes into account $C_b$, as well as differences in the thermal properties of the soil and concrete pile. Compared with the numerical model, the analytical composite-medium model provides a highly computationally efficient solution to the corresponding direct problem. The parameter-estimation algorithm is then validated with the in situ TRT data reported by Park et al. [12]. This paper also explores the sensitivity of the estimated parameters by using a sensitivity matrix. The results of this research provide deeper insights into the importance of early data from TRTs, as well as a computationally efficient algorithm for estimating $k_s$, $a_s$, $k_b$, and $a_b$ by using TRTs for EP.

2. Composite-medium cylindrical-surface heat source model

The heat transfer of EPs with a spiral tube is a complex transient heat conduction problem that could be solved by using the composite-medium cylindrical-surface source model to divide the process into two parts on the basis of the outer wall of the spiral tube. The composite-medium cylindrical-surface heat source model ignores radial heat transfer and simplifies the spiral tube into two concentric cylindrical surfaces. This approach does not markedly differ from the traditional spiral line heat source model but avoids the necessary complicated triple-integration calculations [13].

Heat transfer from the circulating fluid to the tube wall is a steady-state process, whereas heat transfer from the tube wall to the soils is a transient process. A cylindrical-surface source can be modeled on the centerline between the inner and outer walls of the tube when the spiral tube is considered as two concentric cylindrical surfaces. Therefore, the spiral tube wall temperature connects the two parts of the heat transfer model and can be described as:

$$T_f - T_b = q_l R_p$$

where $T_f$ is the average temperature of the circulating fluid, $T_b$ is the temperature of the spiral tube wall, $q_l$ denotes the heat transfer rate per unit time per unit length (W/m), and $R_p$ denotes the tube thermal resistance, which could be written as:

$$R_p = \frac{1}{2\pi k_p} \ln \frac{r_o}{r_i}$$

where $k_p$ is the thermal conductivity of the heat transfer tube and $r_o$ and $r_i$ are the outer and inner radii of the spiral tube, respectively.

When considering the heat transfer process of soils, the tube wall temperature response can also be expressed as:

$$T_b - T_0 = q_l G(t)$$

where $T_0$ is the undisturbed initial temperature of the soils and $G$, which is also called the $G$ function in the literature, is a function that represents the soil temperature response in the composite medium due to a unit step change in the heat exchanger load $q_l$. In this case, $G$ physically represents a time-dependent thermal resistance. For an EP with a spiral tube, $G$ is written as [14]:

$$G(t) = \frac{1}{2\pi k_b} \int_0^\infty \left[ 1 - \exp(-v^2 F_o) \right] J_0(v R_d) + J_0(v R_g) \frac{J_0(v R_p)(\varphi g - \psi f)}{v(\varphi^2 + \psi^2)} dv$$

where functions $\varphi$, $\psi$, $f$, and $g$ are defined as:
\( \varphi = akJ_0\left( ur_b \right)J'_0\left( ur_b \right) - J_0\left( ur_b \right)J'_0\left( ur_b \right) \)
\( \psi = akJ_0\left( ur_b \right)Y'_0\left( ur_b \right) - J_0\left( ur_b \right)Y'_0\left( ur_b \right) \)
\( f = akY_0\left( ur_b \right)J'_0\left( ur_b \right) - Y_0\left( ur_b \right)J'_0\left( ur_b \right) \)
\( g = akY_0\left( ur_b \right)Y'_0\left( ur_b \right) - Y'_0\left( ur_b \right)Y_0\left( ur_b \right) \)
\[
(5)
\]
where \( r_b \) denotes the radius of the concrete pile foundation, \( a \) and \( k \) are dimensionless variables \( k = k_s / k_b, a = \left( a_s / a_b \right)^{1/2} \), \( J_n \) and \( Y_n \) respectively denote zero-order Bessel functions of the first and second kind, \( J'_n \) and \( Y'_n \) are the derivatives of \( J_n \) and \( Y_n \), respectively, and \( r_A \) and \( r_B \) are the radius coordinates of points A and B, respectively (Figure 1).

Substituting Eq. (3) into Eq. (1) gives the circulating fluid temperature:
\[
T_f = T_0 + q_i \left[ G(t) + R_p \right]
\]
\[
(6)
\]
Eq. (6) is the solution to the direct heat transfer problem of an EP with a spiral tube that is derived from the composite-medium cylindrical-surface heat source model. The outstanding feature of this model is that it considers not only \( C_b \) but also the difference in the thermal properties of piles and soils. The composite-medium solution is theoretically a complete short-time solution and used in the following parameter-estimation method.

3. Parameter-estimation method

Parameter estimation usually involves some optimization problems. The first problem is the choice of the objective function to be minimized. The second problem is the approach to minimize the objective function. The third problem concerns the optimal experiment design.

3.1. Ordinary least-squares (OLS) method

The sum of squares of deviations, also called the OLS estimator, is the function commonly selected for minimization. The sum of squares of the deviations of the measured and calculated values is written as follows:
\[
S = \left( Y - T_f \right)^T \left( Y - T_f \right) = \sum_{i=1}^{n} \left( Y_i - T_{f,i} \right)^2
\]
\[
(7)
\]
where \( n \) is the total number of measurements, \( Y = \left[ Y_1, Y_2, \cdots, Y_n \right]^T \) is the observation vector representing the average temperature of the circulating fluid at \( n \) observed times, and the \( n \)-dimensional column vector \( T_f \) represents the calculated value obtained from the model equations. The optimization algorithm, that is, the Levenberg–Marquardt method, is used to find the parameter vector that minimizes the function. Figure 2 shows a flowchart of the parameter-estimation process.

The next problem is the optimization of the experiment design to obtain the best parameter estimates; this problem includes the selection of TRT data and parameter types. In theory, the minimized independent variables may be any combination of parameters, but any reasonable choice must rely on the analysis of sensitivity coefficients.
3.2. Sensitivity and identifiability

The sensitivity coefficient is defined as the first-order derivative of an independent variable (such as the temperature response \( T_f \)) with respect to an unknown parameter (such as \( k_s \)). In this paper, the sensitivity coefficient reveals the variation of \( T_f \) with the fluctuations of each estimated parameter. For comparison, the relative sensitivity coefficients are used for sensitivity analysis:

\[
X_{\beta} = \beta \frac{\partial T_f}{\partial \beta}
\]  

They can also be expressed in vector form:

\[
X_{\beta} = \begin{pmatrix}
\beta \frac{\partial T_{f,1}}{\partial \beta} & \beta \frac{\partial T_{f,2}}{\partial \beta} & \cdots & \beta \frac{\partial T_{f,n}}{\partial \beta}
\end{pmatrix}
\]  

where \( \beta \) denotes parameters that occur in the model equation. According to [15], the preferred choice for parameter estimation is a large and linearly independent sensitivity coefficient because smaller sensitivity coefficients indicate that the fluid temperature is insensitive to the variation of the parameters and will produce errors when inversion is performed.

The sensitivity coefficients of \( T_f \) with respect to several key parameters are calculated from the composite-medium cylindrical-source model via the finite difference method, and their time-varying features are shown in Figures 3–6.

Figure 3 reveals that the absolute values of \( X_{a_s} \) and \( X_{k_s} \) increase with the test duration. The sensitivity of \( T_f \) to \( a_s \) increases in the first 40 h and levels off at a much smaller value (approximately 9°C). By contrast, the variation in \( X_{k_s} \) ranges from approximately 25°C to larger than 40°C when \( k_s \) varies from 3.0 W/(m·K) to 1.8 W/(m·K). These results indicate that \( k_s \) affects \( X_{k_s} \) significantly and that the estimation of \( a_s \) is difficult because of the low sensitivity to \( T_f \).
Figure 3. Variation of the relative sensitivity coefficients $X_{ab}$ and $X_{kb}$

Figure 4 shows that the sensitivity coefficient $X_{ab}$ increases dramatically with a peak of approximately 6°C during the first 5 h and then steeply falls to approximate a small value. The variation of $X_{kb}$ in the late period (after 10 h) differs from that of $X_{ab}$. Specifically, $X_{kb}$ declines slightly and then levels off at values ranging from 9°C to 15°C. This result implies that parameter estimation is very sensitive to $ab$ in the first several hours and that the estimate of $ab$ is extremely important. Fortunately, compared with $ab$, $kb$ is a relatively more sensitive parameter for estimation in the late-time data of TRTs.
Figure 4. Variation of the relative sensitivity coefficients $X_{kb}$ and $X_{ab}$

$k_a$ and $k_b$ are much more sensitive than $a_s$ and $a_b$, and the late-time data of TRTs should be applied to evaluate soil properties (i.e., $k_s$, $a_s$). By contrast, the first several hours of the test are extremely important for $k_b$ and $a_b$, which means the TRT data in this period must be taken into account.

Figure 5 represents the sensitivity of $T_f$ to time. The variation of $X_t$ provides a basis for the selection of the time interval of the TRT data. The figure reveals that selecting a linear interval in the parameter-estimation process may be feasible.
Figure 6 depicts four sensitivity coefficients of an EP with a spiral tube; here, the in situ TRT data reported by Park et al. are used as a reference. An important finding in this system is the near-linear dependence of the sensitivity coefficients of $a_s$, $k_b$, and $a_b$ after 40 h. This result indicates that estimating these three parameters simultaneously and uniquely from measurements of $T_f$ versus $t$ would be difficult during this period. This deduction is drawn from the identifiability criterion that parameters cannot all be uniquely estimated if the sensitivity coefficients obtained over the range of observations are linearly dependent [15]. Therefore, the reasonable use of early-time TRT data is vital to improve the reliability of the parameter-estimation results.

Figure 6. Sensitivity coefficients of $k_s$, $a_s$, $k_b$, and $a_b$

Besides the observation from Figure 6, the linear dependence of the parameters can be confirmed by the singular value decomposition (SVD) of sensitivity matrices. Table 1 summarizes the results of SVD in different sampling instances. The purpose of this series of evaluations is to identify linear dependencies among $k_s$, $a_s$, $k_b$, and $a_b$. The table shows that singular values decay gradually to a small value and that the condition numbers decrease as the test duration increases from 24 h to 120 h. Smaller conditions reflect the higher identifiability of parameter estimation. The result reveals that, if only the late-time data of TRTs are used in the estimation process, determining $k_s$, $a_s$, $k_b$, and $a_b$ simultaneously would be nearly impossible. The nonlinear features obtained within short times ($t < 40$ h) can reduce the linear dependence of these parameters and, thus, improve their identifiability. This paper suggests estimating the four thermal properties simultaneously by using TRT data collected from early to late times.

Table 1. Singular value decomposition of sensitivity matrices.

| Time                   | Singular values | Condition number$^2$ |
|------------------------|-----------------|----------------------|
| $0 \leq t \leq 24$ h   | 632.93, 130.65, 13.95, 0.64 | 987                  |
| $0 \leq t \leq 48$ h   | 1050.12, 215.42, 24.32, 2.29 | 458                  |
| $0 \leq t \leq 72$ h   | 1428.33, 271.58, 31.39, 4.05 | 353                  |
| $0 \leq t \leq 96$ h   | 1781.01, 314.19, 37.05, 5.69 | 313                  |
| $0 \leq t \leq 120$ h  | 2114.31, 348.98, 41.92, 7.19 | 294                  |

$^1$ The columns of the matrices denote sensitivities calculated at the sampling instance.

$^2$ The condition number is the ratio of the maximum singular value to the minimum singular value.
4. Result and discussion

The parameter-estimation algorithm is validated by using the *in situ* TRT data reported by Park et al. for a 10 m-long EP with a spiral heat exchanger. These data are used because they are reliable and have relatively complete experimental descriptions given that TRTs on EPs with a spiral tube are scarce. Some details of the *in situ* TRT facility are reported in [12], and the key parameters employed in the experiments are listed in Table 2.

Table 2. Parameters of the *in situ* TRTs reported by Park et al. [12].

| Parameters | Description                                   | Value and unit |
|------------|-----------------------------------------------|----------------|
| $T_0$      | Initial undisturbed temperature               | 15 °C          |
| $r_o$      | Outer radius of the energy pile               | 0.2 m          |
| $L$        | Length of the energy pile                     | 10 m           |
| $r_b$      | Outer radius of the spiral tube               | 0.01 m         |
| $k_p$      | Thermal conductivity of the spiral tube       | 0.5 W m$^{-1}$ K$^{-1}$ |
| $k_s$      | Thermal conductivity of the soil              | 3.0 W m$^{-1}$ K$^{-1}$ |
| $k_b$      | Thermal conductivity of the concrete pile     | 2.5 W m$^{-1}$ K$^{-1}$ |
| $\rho_b$   | Density of the concrete pile                  | 2600 kg m$^{-3}$ |
| $\rho_s$   | Density of the soil                           | 2200 kg m$^{-3}$ |
| $C_p$      | Specific heat capacity of the soil            | 2500 J kg$^{-1}$ K$^{-1}$ |
| $C_b$      | Specific heat capacity of the concrete pile   | 900 J kg$^{-1}$ K$^{-1}$ |

The composite-medium cylindrical-surface heat source is proven to be able to predict the behaviors of heat exchangers over short periods, except in very short periods (15–30 min); it can also show more reasonable short-time responses than traditional solutions that ignore all heat capacities inside the concrete pile foundation. Because the contact area between the EP with the spiral tube and the concrete pile is quite large, heat transfer occurs smoothly and, therefore, the time required to achieve steady-state conditions increases. In this paper, the fluid temperatures measured from 10 h to 50 h are used to estimate $k_s$, $a_s$, $k_b$, and $a_b$.

First, the impact of the number of data on the estimate of $k_b$ is marginal, which may be explained by the high sensitivity of $k_b$ (Figure 6). For example, the estimate of $k_b$ increases from 1.77 W/m·K to 1.88 W/m·K when the number of the data varies from 50 to 120. By contrast, the number of data has a strong influence on the estimate of $k_s$. For example, the data sampled between 30 min, 5 h, and 10–50 h yield $k_s$ estimates of 1.40, 1.85, and 2.31 W/m·K, respectively.

The thermal properties of the soil and concrete pile play different roles in the underground thermal process. $a_b$ exerts an influence on the thermal process within the first several hours. As the testing time increases, the influence of $a_b$ decreases rapidly and becomes insignificant. This finding can be verified by the sensitivity of $a_b$ (Figure 4). By contrast, $k_b$ influences the heat transfer throughout the whole process (Figure 4). $k_s$ and $a_s$ have a great influence on the long-term thermal process because the sensitivities of the parameters increase with time (Figure 3). This result can be explained by the influencing range of the underground heat transfer, which increases gradually with time.

Figure 7 shows the estimation of $k_s$, $a_s$, $k_b$, and $a_b$ and a comparison between the *in situ* TRT data and the predictions obtained by using the estimated properties. The predicted and measured values match well. The residuals never exceed 0.3°C throughout the test period, which further confirms the reliability and accuracy of the simultaneous parameter-estimation results. The estimate of $k_s$ (2.6685 W/m·K) agrees with the measured value (3.0 W/m·K) with high accuracy and a relative error of 11.05%. The estimate of $k_b$ (1.8882 W/m·K) has acceptable accuracy (relative error, 24.47%) when compared with the measured value (2.5 W/m·K). This result is consistent with the findings of a previous sensitivity analysis, that is, the high sensitivity coefficients of $a_s$ and $a_b$ lead to the high accuracy of the estimate. Similarly, the relative sensitivity coefficient of $k_s$ is high, and the estimated $k_b$ is closer to the measured value than the estimated $k_b$. By comparison, the estimates of $a_s$ and $a_b$ have lower accuracy, with relative errors of 69.39% and 76.89%, respectively.
Several reasons may explain these unexpected results. First, the deviations observed are mainly due to the lower sensitivity coefficients of $a_s$ and $a_b$ compared with those of $k_s$ and $k_b$. The sensitivity coefficient of $a_b$ is smaller than that of $a_s$, which also leads to a larger deviation. Second, uncertainties in the experiments and the lack of precision of the estimation algorithm may contribute to the deviations observed. Because the experiments are performed outdoors, they are bound to suffer strong disturbances from the complex external environment. In addition, the accuracy of the measurement method cannot be evaluated; $a_s$ and $a_b$, in particular, do not directly give accurate experimental reference values and only provide $C_s$ and $C_b$. The ASHRAE handbook recommends that data collection be conducted at least once every 10 min [16]. Although the TRT data used in this work meet this requirement, such a test interval is slightly insufficient for the deep investigation of short-term temperature responses. Simplification of the model may also lead to deviations. Given the complexity of EPs with spiral tubes and their combination with pile foundations, the pure heat conduction model is influenced by thermomechanical coupling factors, which could lead to deviations in the temperature response.

The numerical model is widely employed to perform parameter estimation by using the TRT data of EPs with a spiral tube; this model can yield accurate but time-consuming results. Indeed, the calculation time was demonstrated to exceed 1 week when the simultaneous estimation of $k_s$ and $k_b$ was attempted by using a three-dimensional numerical model on a high-performance desktop computer [17]. Therefore, this paper is anchored on an analytical solution, that is, the composite-medium cylindrical-source model, to explore a parameter-estimation procedure for EPs with a spiral tube. Because the composite-medium model is applicable to short times, the new algorithm provides an alternative strategy by using early-stage TRTs data. The use of early data may obtain information on the key thermal properties required for the design of heat exchangers and find a reasonable minimum TRT period and data interval with which to improve the efficiency of the test. In addition, because $k_s$ and $k_b$ determine the long-term temperature response of heat exchangers, the results of these two estimates are still in line with expectations when prioritizing the accuracy of the thermal diffusivity coefficient backward. Optimization of the parameter-estimation algorithm and collection of experimental data with better control conditions will be further explored to validate the proposed algorithm in future work.

5. Conclusion

The short-time temperature response is an important factor that should be considered when designing an EP with a spiral tube. Thus, a feasible and reliable method for determining $k_s$, $a_s$, $k_b$, and $a_b$ must be developed. This paper presents an algorithm that could be used to estimate these four thermal properties simultaneously. The algorithm uses a theoretically complete short-term solution, that is, the composite-medium cylindrical-surface heat source model, which takes into account $C_b$ and the difference in the thermal properties of the soil and concrete pile. Sensitivity analysis shows that the use of early data from
TRTs can reduce the linear dependence of the parameters, thus providing a means to estimate $k_s$, $a_s$, $k_b$, and $a_b$ simultaneously.

Parameter estimation is performed by using the TRT data sampled between 10 and 50 h. The relative errors of the estimated $k_s$ and concrete pile are 11.05% and 24.47%, respectively, thereby indicating that the algorithm is reliable when prioritizing the thermal diffusivities of both backward. The analytical solution applied in the simultaneous estimation algorithm is computationally efficient and easier to implement compared with algorithms using numerical models. Therefore, the algorithm developed in this work may potentially reduce the time required to complete TRTs, which is an extremely important issue related to the cost and feasibility of these tests.

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