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Numerical sensitivity analysis of thermal response tests (TRT) in energy piles

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ABSTRACT

In recent years, energy pile systems have been developed as a cost effective alternative to traditional systems. An optimal design requires good characterization of the effective thermal properties of the soil and the system, through analysis of the results of thermal response tests (TRT). However, due to the size of foundation piles, accurate estimations require tests which are excessively long for practical applications. Hence, in most situations the analysis is carried out using the results of relatively short tests, which depend upon several factors, such as pile and ground thermal properties, pile geometry, pipe configuration, etc.

In this article we use detailed numerical simulations to reproduce the results of thermal response tests for synthetic energy pile systems with different material properties, dimensions and pipe configurations. We used the standard line heat source model to evaluate the results of the numerical simulations and to highlight the magnitude of the errors this type of interpretation may produce. We demonstrate that even in the absence of groundwater flow and soil heterogeneity, TRT results obtained using the line heat source model can be misleading and must be treated with care.

1. Introduction

Heating and cooling of residential and industrial buildings requires large amounts of energy, which indirectly account for a large proportion of greenhouse gases emissions [26]. In recent decades, low enthalpy geothermal systems have emerged as a renewable and environmentally friendly alternative to supply all or part of these energy requirements. These systems use the soil's ability to maintain a relatively stable temperature throughout the year, which, depending on the location and altitude fluctuates between 7 and 13 °C at 10–15 m deep [5]. The temperature difference between air and ground is used for heating or cooling purposes through heat exchanger systems such as Ground Source Heat Pumps (GSHP) [10].

Borehole Heat Exchangers (BHE) are low enthalpy geothermal systems that typically consist of a 10–20 cm diameter borehole that is 50–200 m deep, which contains a piping system that acts as a heat exchanger between the fluid inside the pipe –usually a mix of water and antifreeze fluid- and the ground [10]. The space between pipes and soil is filled with materials such as grout, concrete, or bentonite, to enhance heat flow from/to the soil [15]. The development of BHE systems has mainly occurred during the last 20 years in Europe, China and North America [10], and more recently in other regions (e.g. Ref. [33]. Several studies have demonstrated the feasibility of implementing this type of solution as part of heating systems of commercial and residential buildings (e.g. Refs. [4,8,11,16].

Piles made of concrete are used as foundations systems in buildings on soft or loose soil and also as embedded retaining walls. These piles naturally have a large area of contact with the surrounding soil, so that they can work as heat exchangers saving the time and expenses associated to the drilling and cementing of more traditional systems. In order to use them as heat exchangers, pipes are installed to carry the working fluid within the piles during the construction process [8]. Systems built this way are known as Energy Piles (EP). Although there are many similarities between BHE and EP systems, there are also important differences that arise from parameters such as the length of the installation, the diameter of the pile and the filling material which cannot be changed in EP systems to optimize their efficiency. Thus, EP systems can only

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partially meet the thermal demands of a project, but they can significantly contribute to reducing the energy costs of buildings. Although, in recent years there has been increasing interest in the study of EP systems (e.g. Refs. [4,8,14,16] more research to optimize their design, construction and operation is still needed.

Thermal Response Tests (TRT) are carried out in BHE systems to determine the ground thermal conductivity (λ_s) and borehole resistance, which controls the efficiency and long term sustainability of low temperature geothermal systems [12,35]. During TRTs, heat is injected into the system through the circulation of a heated fluid, while recording inlet and outlet fluid temperatures [15,35]. A constant temperature difference between the inlet and outlet is reached after some circulation time, which indicates that the system is sustaining constant heat extraction or an injection rate. Interpretation of the recorded data of temperature versus time to obtain values of thermal conductivity is typically performed using the Line Heat Source (LHS) model [17]. Although, the use of the LHS solution assumes several simplifications of the problem that are not always satisfied in practice, several studies [36,24] have concluded that its interpretation of TRT data for BHE systems is fairly accurate for evaluating the influence of key parameters such as soil heterogeneity, groundwater flow, installation depth or spacing between pipes [12,15,36]. However, interpretations based on the LHS model introduce significant errors for some specific cases [20,31,39], as demonstrated by studies that applied this model for the interpretation of synthetic tests performed through numerical simulations [36,24]. Moreover, the analysis of TRT is also affected by errors in the measurement of parameters, which can propagate and amplify [42]. estimated that such errors can be as large as 5% in the estimation of the thermal conductivity and up to 10–15% in the case of the borehole thermal resistance.

Correct estimation of effective thermal conductivity is necessary to optimize the design of energy exchangers for a specific location. According to [34]; an overestimation of λ_s can result in: estimations of fluid temperature that are lower and decrease faster than in practice, lower coefficient of performance (COP) of heat pumps, underestimation of operational costs due to higher real electric power consumption, and possible malfunctioning of the systems because of wrong dimensioning. On the other hand, an underestimation of thermal conductivity can result in designs that overestimate the size of BHE fields, with a subsequent higher initial investment. For example [34], discuss the possible practical impacts of errors in the estimation of the thermal conductivity for a typical BHE system. They demonstrate that an overestimation of λ_s by 38% results in a 43% increase in energy costs during operation compared with the original design. On the other hand, an underestimation by 21% can generate an increase of 15% in investment costs. Therefore, errors in the estimation of the effective thermal conductivity of the system can produce significant differences in the performance and costs of real BHE systems.

For simple pipes configurations, some of the simplifications made in the derivation of the LHS theory become valid sometime after the beginning of the test that directly depends on the square of the radius of the borehole [25,35]. Previous studies have found that for typical vertical borehole heat exchangers, which usually have diameters smaller than 20 cm, the minimum required duration of the test to obtain reliable results is 50 h [35,37]. Since EP systems have much larger diameters than typical BHE systems −about 1 m-, and therefore a much greater heat storage capacity, it is not always possible to perform TRTs in such systems in a reasonable and economically feasible time frame [13,35]; which represents a serious barrier for practical applications. The Ground Source Heat Pump Association [13] suggests building a BHE at a nearby site to carry out equivalent TRTs to address this issue. However, this is not always feasible, due to technical or economic limitations.

This study was based on an analysis of the TRT results of tests carried out in a research system at the campus of the School of Engineering at the University of Chile. The main objective of the system was to investigate the technical feasibility of constructing and operating geothermal systems as part of the foundation piles and anchors of large buildings. While analyzing the collected data, it became clear that LHS interpretation needed to be modified in order to be used for this type of system. Hence, the main purpose of this study is to identify how different factors have an impact on the results of TRTs performed in EP systems and affect the validity of traditional interpretation models. To accomplish this, we carried out a parametrical study based on highly detailed numerical simulations of synthetic TRTs in EP systems. We applied the LHS model to interpret the results of simulations to test its validity, quantify errors, and propose ways to extrapolate results of short TRTs to obtain reliable estimates of the performance of EP systems. While other numerical studies have focused their attention in the effects of groundwater flow [40], soil heterogeneity [29–32,36], thermal dispersivity [39], pipes placement [19,22,25], tube diameter and Reynolds number [27]in TRTs for traditional BHE systems, the main contribution of this study is to extend the analysis to evaluate the impact of other parameters such as the geometry of the pipes, the physical properties of the soil and filling material, considering typical dimensions of real EP systems. We expanded on the analysis carried out by Refs. [20]; who evaluated the impact of different thermal properties of the ground and the grouted material of energy piles for the estimation of the thermal borehole resistance. We focus our analysis on the estimation of thermal conductivity and consider other parameters such different tube placement, volumetric heat capacity, pile diameter and shank spacing.

2. Analytical interpretation based on the line heat source model

When interpreting the results of TRTs, it is often assumed that geothermal heat exchangers behave like a line heat source in an infinite, homogeneous and isotropic domain with uniform initial temperature. Furthermore, it is considered that the borehole instantly releases a finite amount of uniform and constant energy in a radial direction due to the temperature difference between the inlet and outlet sections of the pipe. Using these assumptions, it is possible to find an analytical solution to estimate the variation of temperature versus time during the transient regime. This conceptual and mathematical model, known as the Line Heat Source (LHS) model, is based on Kelvin's Line Source theory and has been the method of choice to interpret the behavior of BHE systems [17,23]. The model assumes that the temperature around the BHE system as a function of time t, and radial distance r from the borehole axis, can be calculated as:

$$T(r,t) - T_0 = \frac{q}{4\pi\lambda} E_1\left[\frac{r^2}{4\alpha t}\right] \tag{1}$$

where T [°K] is the ground temperature, T_0 is the initial ground temperature, q is the heat injection rate per meter of borehole length [W m^{-1}], λ is the volumetric thermal conductivity [W m^{-1} K^{-1}], α is the thermal diffusivity of the ground [m^2 s^{-1}], and E_1 denotes the exponential integral function. However, for small values of the argument of the function, i.e. large times or short distances from the source, the solution can be approximated by Refs. [17,33]:

$$T(r,t) - T_0 = \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right] \tag{2}$$

where γ is Euler's constant. The error of this simplification is less than 20% when r time t is greater than $\frac{1.2\ r^2}{\alpha}$, and less than 10% when t is greater than $\frac{1.8\ r^2}{\alpha}$. However, the criterion that is used in practice to apply the LHS model only considers times that are greater than $\frac{5\ r^2}{\alpha}$ [21,36,41].

T Thermal resistance per unit length between the fluid and the borehole wall,

$$R_b = \left(\overline{T}(t) - T(r_b,t)\right)/q \tag{3}$$

where r_b[m] is the borehole wall radius and $\overline{T}(t)$ is the average fluid temperature of the circulation fluid, and the average temperature is calculated according to

$$\overline{T}(t) = (T_{in} + T_{out})/2 \tag{4}$$

where T_{in} and T_{out} are the inlet and outlet temperature of the fluid, respectively. Then, $\overline{T}(t)$ can be expressed as a simple linear relation [9,35].

$$\overline{T}(t) = k\ln(t) + m \tag{5}$$

where

$$k = \frac{q}{4\pi\lambda} \tag{6}$$

$$m = \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right] + T_0 + qR_b \tag{7}$$

Equation (5) is often used in the interpretation of TRT results by plotting $\overline{T}$ versus the natural logarithm of time. Then, the slope of the curve is compared to (6) to obtain an estimation for the thermal conductivity of soil, λ_{LS},

$$\lambda_{LS} = \frac{q}{4\pi}\frac{[\ln(t_1) - \ln(t_2)]}{\left[\overline{T(t_1)} - \overline{T(t_2)}\right]} \tag{8}$$

In this last expression and according to the LHS model, q is constant and equal to

$$q = \rho C_W\, Q_W(T_{in} - T_{out})/H \tag{9}$$

where ρC_W [J m^{-3} K^{-1}] is the volumetric heat capacity of the fluid, Q_W [m^3 s^{-1}] is the fluid flow rate that circulates through the pipe, and H is the length of the borehole.

3. Numerical modeling approach

We use COMSOL Multiphysics® version 4.3a [6] for modeling of a synthetic EP system. COMSOL allows you to incorporate different flow and heat transport phenomena, which makes it a suitable tool to simulate these types of systems, which has motivated its use in other modeling studies of BHE systems (e.g. Refs. [3,18,24]. To simulate the heat transport that takes place during a TRT, we use COMSOL's Heat Transfer Module [7], which solves the general heat transport equation in each of the model domains through the following expression:

$$\rho\, C\frac{\partial T}{\partial t} + \rho\, C\cdot\boldsymbol{u}\cdot\nabla T = \nabla\cdot(\lambda\,\nabla T) + Q \tag{10}$$

where ρ is the material density [kg m^{-3}], C is specific heat capacity [J kg^{-1} K^{-1}], u is the flow velocity [m s^{-1}] –relevant only inside the pipe system-, and Q represents heat sources other than viscous heating. The model only contains the mechanisms of heat transfer by conduction and convection, neglecting radiation, which has been usually ignored in this type of analysis [4].

3.1. Conceptual model

In our simulations, we modeled an EP system as two water-filled pipes: an inlet downward flow pipe and an outlet upward flow pipe. These are embedded in a concrete cylinder of H = 28 m, that is in contact with the natural ground. The modeled domain is a symmetric 12 m diameter cylinder as shown in Fig. 1. The domain is comprised of four subdomains or regions: water, pipes, filling material (hereafter referred to as concrete) and natural soil.

According to (10) and considering the different materials in the system, the relevant properties to include in simulations are the thermal conductivity of the soil (λ_s), thermal conductivity of the concrete (λ_c), the volumetric heat capacity of the soil ($\rho_s C_s$) and the volumetric heat capacity of the concrete ($\rho_c C_c$). The water domain, λ and ρC depend upon temperature, with values assigned according to COMSOL's material library.

The condition of constant heat flow into the system was imposed through the following boundary condition

$$T_{down}(0,t) = T_{up}(0,t) + \Delta T \tag{11}$$

where $T_{down}(z,t)$ is the downward fluid temperature,$T_{up}(z,t)$ is the upward fluid temperature, and ΔT is the constant temperature difference as shown in Fig. 2. In this way, only ΔT is imposed in the model, while the inlet and outlet temperature evolves over time depending upon the initial fluid temperature, ΔT, and the heat dissipation rate of the system. Therefore, expression (11) represents the operation of a TRT system that uses a constant amount of fluid, which is continuously recirculated and that is heated between the outlet and inlet. Next, the continuity of the pipe between the downward and upward sections was modeled by imposing:

$$T_{down}(-H,t) = T_{up}(-H,t) \tag{12}$$

In addition, we only modeled the a boundary condition of outflow heat by convection at the end of the downstream (z = -H) and upstream (z = 0) pipes, according to

$$-n\cdot(\lambda\,\nabla T_{down}(-H,t)) = -n\cdot(\lambda\,\nabla T_{up}(0,t)) = 0 \tag{13}$$

We imposed adiabatic boundary conditions, i.e. no heat flow, on the other external surfaces of the domain. We also considered a constant initial temperature $T(z)=T_0$ and constant water velocity inside the pipes. Table 1 summarizes other geometrical and physical properties considered in all the simulated scenarios. In addition, shank spacing S (m), which corresponds to the distance between the axes of the pipes, was set equal to half of the pile diameter in all simulations.

To generate the numerical mesh, we first meshed the horizontal plane with a maximum distance between elements of 0.5 m and a minimum distance of 0.001 m, and we then create pentahedral elements repeating the previous mesh every 0.5 m in a vertical direction, generating a total of 120,498 elements. We refined the mesh around the pipes to accurately represent its geometry and the heat transfer that occurs around them (Fig. 1). Flow inside the pipes was simulated assuming laminar conditions, which is adequate for the range of Reynolds numbers considered.

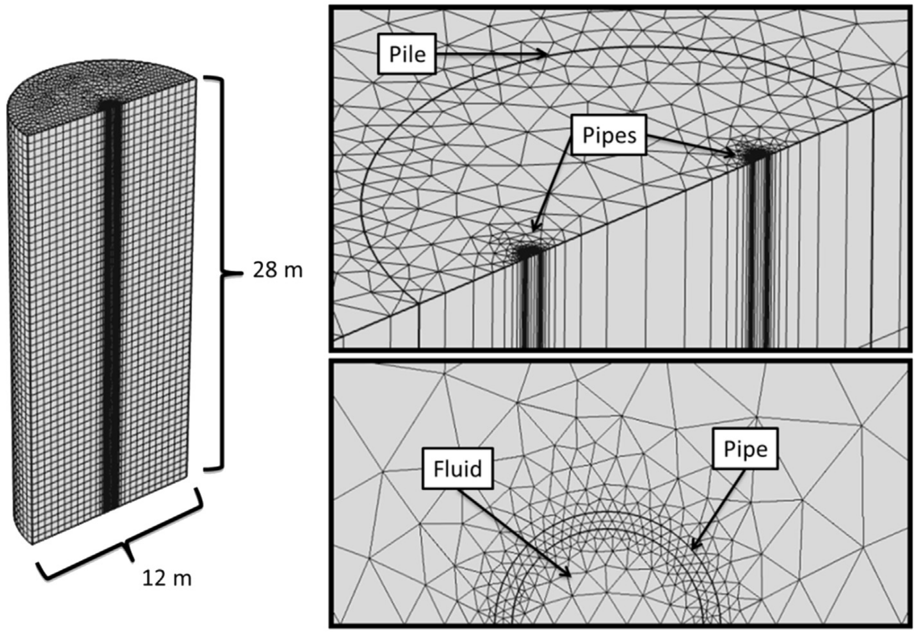

Fig. 1. Numerical mesh used to represent an energy pile.

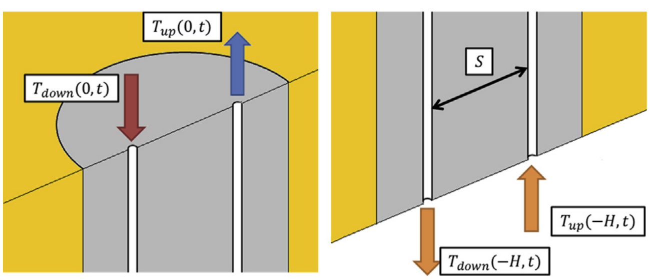

Fig. 2. Schematic illustration of the top (left) and the bottom (right) of the pile, where $T_{down}(z,t)$ is the down-flow pipe fluid temperature, $T_{up}(z,t)$ is the up-flow pipe fluid temperature and S is the distance between pipes also called shank spacing.

3.2. Dimensionless parameters used in data analysis

To test the validity of the LHS model to interpret the results of TRTs, we looked at the ratio between the calculated thermal conductivity estimated using the LHS interpretation of the results (λ_{LS}), and the value of the thermal conductivity used as input in the numerical simulations (λ_S). In that case, when λ_{LS}/λ_S is closer to 1, we assumed that the LHS is a valid model to interpret the results of the tests. According to the theory described in Section 2, it is expected that at long times this ratio will tend to be 1. To make the analysis independent of the dimensions of the problem, we plotted the results as a function of the dimensionless time (Fourier number), $Fo = t \cdot \alpha_c / r_b^2$, i.e. the product between time and thermal diffusivity of the concrete, divided by the square of the pile radius.

Table 1
Constant parameters in simulations.

Parameter	Value
d, pipe diameter [mm]	32
e, pipe thickness [mm]	2.9
S, shank space [m]	0.5
D, pile diameter [m]	1
T_0, initial temperature [°C]	16
Q_w, water flow [l/min]	5
ΔT, temperature difference between in and out pipes [°C]	2
λ_{pipe}, HDPE pipe thermal conductivity [W/mK]	0.4
ρC_{pipe}, HDPE pipe volumetric heat capacity [MJ/m^{3}kg]	2.16

4. Results and discussion

In this section we present the results of numerical simulations carried out to evaluate the validity of the LHS interpretation model on EP systems.

4.1. Differences between natural soil and filling material properties

One of the main limitations of the LHS model to interpret results of TRTs performed in EP systems, is that it neglects the difference in thermal dispersivity and heat storage capacity between the ground and the filling material of the pile. Variations in the soil's physical parameters do not immediately influence the observed outlet temperature due to the time needed for the heat dissipated from the pipe to reach the pile edge and the ground. However, for long times after the beginning of the test, it is reasonable to assume that the heat bulb has expanded beyond the limits of the pile and that the observed behavior of the system mainly reflects the soil's thermal properties. To confirm this hypothesis, we first evaluated the impact of the difference between soil and concrete thermal conductivity, measured as the ratio $\lambda^*=\lambda_s/\lambda_c$. To obtain ratios that are close to typical values found in real tests, we considered thermal conductivity of the soil as equal to 1.5 W/mK, and we varied the thermal conductivity of the filling concrete between 0.5 and 3.0 W/mK, which corresponds to typical values reported for these materials (e.g. Refs. [2,33]. Fig. 3 shows that, as expected and predicted by the theory explained in Section 2, estimations of the thermal soil conductivity based on the LHS model differ from the true value at early time ($F_0 < 1.0$) even in a completely homogeneous medium. For scenarios that consider different properties for the ground and the pile, the differences are still observable even for $F_0 > 1.5$. Moreover, for λ^*=0.5, which corresponds to the most realistic value considering the properties of real materials, the error is greater than 50% for the maximum simulated time. For this particular

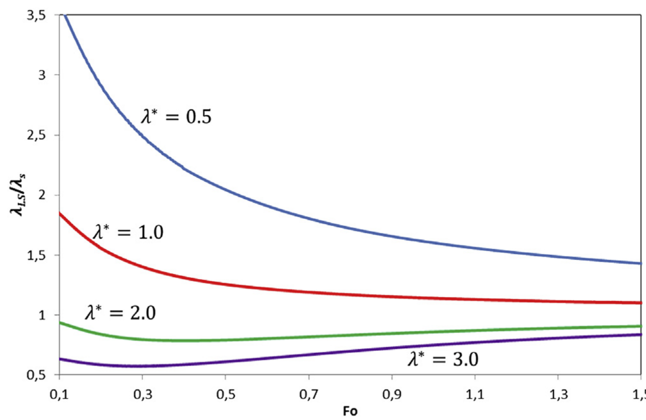

Fig. 3. Calculated dimensionless thermal conductivities based on the line-source model, λ_{LS}/λ_s, for different ratios of soil and concrete conductivities, $\lambda^*=\lambda_s/\lambda_c$. The ρC_s and ρC_c values were set equal to 2 MJ/m^3kg.

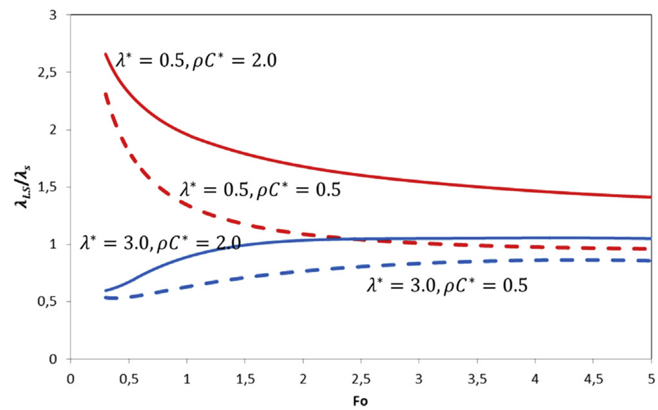

Fig. 5. Calculated dimensionless thermal conductivities based on the line-source model, λ_{LS}/λ_s, for two values of the ratio between soil and concrete thermal conductivities, $\lambda^*=\lambda_s/\lambda_c$, and heat storage capacity ratio, $\rho C^*=\rho C_s/\rho C_c$.

scenario, an overestimation of this magnitude in the soil properties can cause a reduction of the effective heat rejection rate of the pile system of about 10%. This means that a system designed according to the estimated parameters would be too large to meet a given heat extraction or injection capacity, with the consequent increase in investment and operational costs.

4.2. Volumetric heat capacity

Fig. 4 shows the results for scenarios with equal thermal conductivity, but different heat capacity for the soil and concrete, measured as $\rho C^*=\rho_S C_S/\rho_C\ C_C$. Since the volumetric heat capacity is associated with the amount of heat that the material can store per unit volume, it is consistent that for higher ρC^* heat dissipates faster in the concrete, which is interpreted as a higher λ_{LS}. For the case of highest volumetric heat storage capacity (ρC^*=2.0), the estimated λ_{LS} is up to 40% higher than λ_S even at $Fo = 1.5$. Heat transfer to the ground is also slower for the opposite case when $\rho_s C_s < \rho_c C_c$, due to the greater capacity of the concrete to store heat, which explains the underestimation of λ_s for $\rho C^* = 0.7$ at times $Fo > 1.2$.

Fig. 5 shows the results of TRTs for extreme values of λ^* and ρC^* that can be found in the literature. This figure shows that errors in the estimation of λ_s can be important even after a significant amount of time has elapsed since the beginning of the test. For

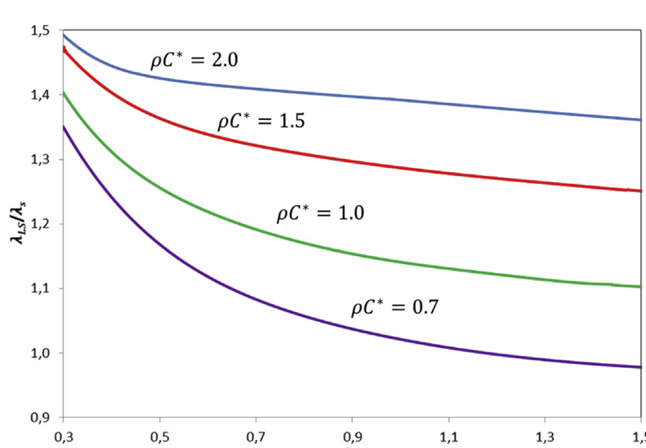

Fig. 4. Calculated dimensionless thermal conductivities based on the line-source model, λ_{LS}/λ_s, for different $\rho C^*=\rho C_s/\rho C_c$ values. The thermal conductivity of the soil and concrete, λ_s and λ_c, are equal to 2 W/mK.

example, if we perform a TRT for a 1 m diameter pile with $\lambda_c = 2$ W/mK and $\rho C_c = 2$ MJ/m^3 that lasts 100 h, which corresponds to $Fo = 1.44$, the error in the estimation of λ_s can be up to 50%. At early times, the difference between the values of λ_{LS}/λ_s, is due mainly to different values of the thermal conductivity ratio, while at later times the difference is mainly due to the heat storage capacity ratio. For example, if we perform a TRT for a 1 m diameter pile with $\lambda_c = 2$ W/mK and $\rho C_c = 2$ MJ/m^3 that lasts 100 h, which corresponds to $Fo = 1.44$, the error in the estimation of λ_s can be up to 50%.

4.3. Shank spacing

Fig. 6 shows curves of λ_{LS}/λ_S versus dimensionless time for different shank spacing (S) and λ^*=1 and λ^*=2. As expected, for homogeneous medium ($\lambda^* = 1$), the LHS approximation works best when there is the smallest separation between the pipes. However, the error of the LHS approximation increases for larger values of S. For example, for the maximum shank spacing (S = 0.8 m), the LHS overpredicts λ_s for approximately 30% at $Fo = 1.5$. The difference between the true value and the one estimated from the LHS approximation at short times, is mainly due to the time that is needed for heat to dissipate and both pipes to act as a single line heat source. During this initial period the system has the capacity to store heat in the space between the pipes. This error is in addition to the overestimation in calculating λ_{LS} that comes from the mathematical approximation of the integral exponential function.

On the other hand, for the case that considers higher ground conductivity than concrete ($\lambda^* = 2$), the LHS overestimates or underestimates the ground thermal conductivity depending upon the value of the shank spacing. For smaller spacing the LHS approximation tends to underestimate the ground thermal conductivity, because the initial effective thermal conductivity is closer to λ_c. Nevertheless, in cases where S is large (e.g. S = 0.8 m), pipes are located near the pile edge, and the response of the system is more influenced by the higher value of λ_s. Note that regardless of the value of S, the error in the estimation is less than 20% for $Fo = 1.5$ and $\lambda^* = 2$.

4.4. Pile diameter

The diameter of the pile is another factor that can potentially affect the validity of applying an LHS approximation when interpreting the results of TRTs in energy piles. Fig. 7 shows that the pile diameter directly affects the λ_s estimation, and that the time needed for the LHS theory to become valid can be very large for

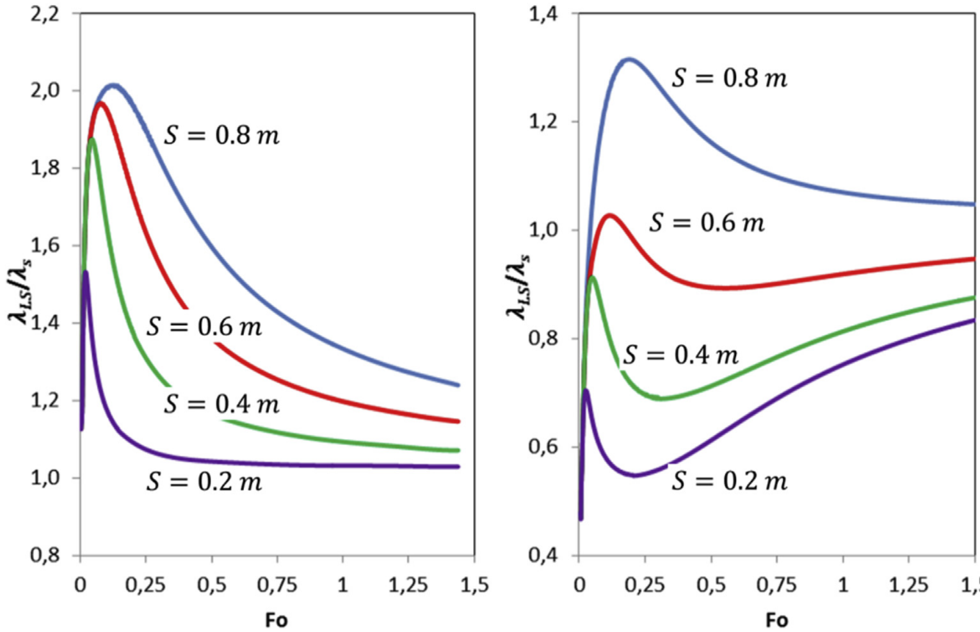

Fig. 6. Calculated dimensionless thermal conductivities, λ_{LS}/λ_s, based on the line-source model for a $D = 1$ m pile, for different shank space values, S, with $\lambda^* = 1$ (left) and $\lambda^* = 2$ (right). The heat storage capacity for soil and concrete, ρC_s and ρC_c, are 2 MJ/m^{3}kg.

large pile diameters. The application of the LHS model to interpret the test results produces large errors early on due to the initial available capacity in the pile to store heat. However, LHS becomes a good approximation with estimated values for the thermal conductivity λ_{LS}, within 10% of the true value for $Fo > 3$ in all the cases analyzed. Note that for a 1 m diameter pile, this value of F_0 is equivalent to 278 h, with $\lambda_c = 1.5$ W/Mk, $\rho C_c = 2$ MJ/m^{3}kg.

4.5. *Comparison between different pipe geometries: Helicoidal, Triple-U and U*

Finally, we analyzed differences in the interpretation of TRT results performed in systems with three different pipe geometries: U, Triple-U and Helicoidal shaped configurations, as shown in Fig. 8. The pipes in the Triple-U and Helicoidal configurations are of identical length, three times longer than for the U-shaped pipe. To evaluate the importance of the different geometries versus changes in other parameters, we considered two different sets of material properties defined in Table 2 for these simulations.

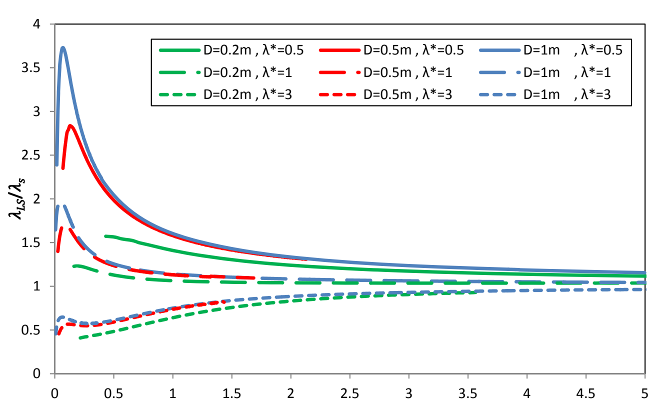

Fig. 7. Calculated dimensionless thermal conductivities based on the line-source model, λ_{LS}/λ_s, for different λ^* and D values. The ρC_s and ρC_c values are 2 MJ/m^{3}kg. In all cases the shank spacing, S, is equal to $D/2$.

Fig. 9 shows simulated outlet temperatures for the different scenarios. The outlet temperature for the Triple-U and Helicoidal configurations is lower than in the U-shaped configurations due to the longer pipes and, consequently, there is longer residence time of the fluid in the systems, which result in greater heat dissipation. On the other hand, there are also differences in the outlet temperatures of the Triple-U and Helicoidal systems caused by the different geometrical configuration but they are much smaller.

The interpretation of the outlet temperatures shown in Fig. 9 to estimate λ_s, produces a relatively large early error in the Triple-U and Helicoidal configurations as shown in Fig. 10. However, in all the situations analyzed, values of λ_{LS} converge relatively fast, and for times such as $Fo > 0.5$ the three curves are almost identical. This can be explained by considering that the thermal dissipation rates are equal after an initial period when the heat distribution inside the pile is not uniform. However, after the heat distribution inside the pile becomes homogeneous, the heat transfer rate to the surrounding ground only depends upon the thermal properties of the materials in the system. This analysis demonstrates that differences due to the geometrical configuration of the system are relatively small in comparison to the ones due to other parameters, for example pipe length.

5. Conclusions

We used detailed numerical simulations to reproduce synthetic thermal response tests in energy piles under different ideal conditions. The main conclusion of this analysis is that the results of TRTs in an energy pile are very complex, and t depend upon the ratio between the ground and concrete thermal conductivities, the rate of volumetric heat capacity between the soil and concrete, pile diameter, and shank spacing among others. The common criterion for the use of the LHS interpretation model, which requires tests runs of $Fo > 5$, can be too restrictive for practical applications. For example, for the set of parameters we used in our simulations, such criterion is equivalent to running the test for 218 h–1345 h, depending on the filling material properties on a 1 m diameter pile.

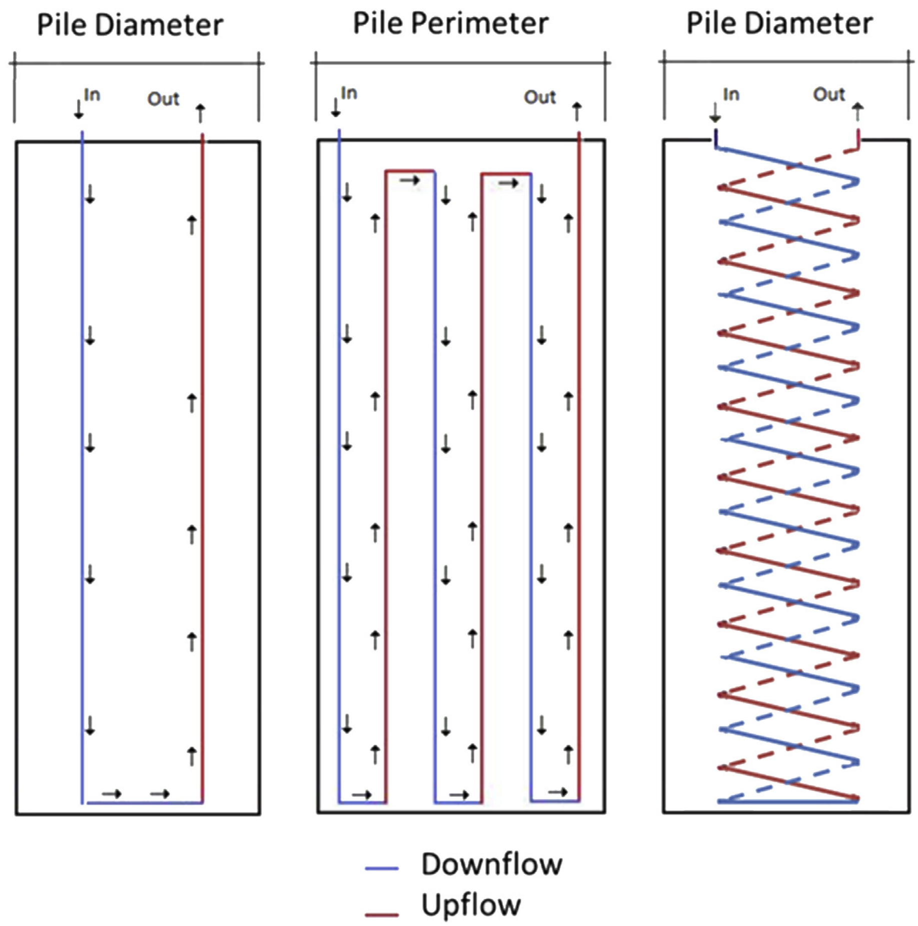

Fig. 8. U (left), Triple U (center) and Helicoidal (right) pipe geometries.

Table 2
Soil and concrete properties for cases a and b shown in Figs. 9 and 10.

Properties	Case a	Case b
λ_s[W/mK]	1.5	3
λ_c[W/mK]	1.5	1.6
ρC_s[MJ/m^{3}kg]	2	2.5
ρC_c[MJ/m^{3}kg]	2	2

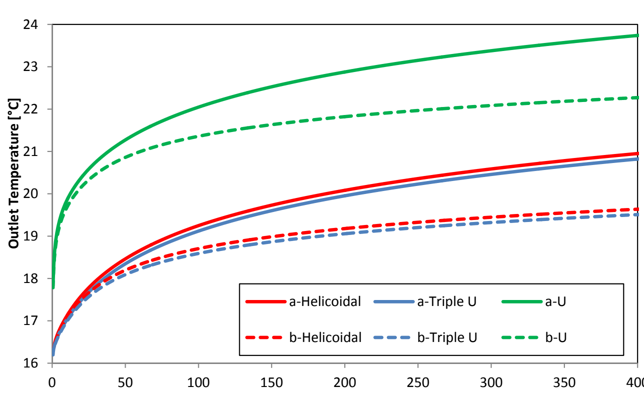

Fig. 9. Computed outlet temperature for a 400 h long TRT, in an Helicoidal (red), Triple-U (blue) and U (green) pipe configuration, for a) and b) cases defined in Table 2. All cases consider $D = 1$ m and $S = 0.5$ m between opposite pipes (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

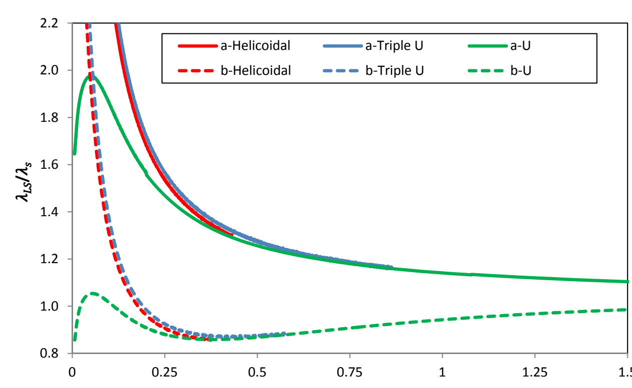

Fig. 10. Calculated dimensionless thermal conductivities based on the line-source model, λ_{LS}/λ_s, in a Helicoidal (red), Triple U (blue) and U (green) tube configuration, for a) and b) cases defined in Table 2. All cases consider $D = 1$ m and $S = 0.5$ m between opposite pipes (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Hence, in practical applications shorter tests are needed which accept that the common procedure to interpret the results using an LHS model can introduce large errors. For example, we demonstrated that there can be significant errors in the estimations of the thermal conductivity value for some combinations of material properties and pile dimensions. According to the analysis presented above, the factors that most influence the validity of the LHS model to interpret results of TRT are the ratio between thermal conductivities of the filling material and the ground and shank spacing and/or pile diameter. Errors associated with any of those parameters can be up to 50%. According to the situations analyzed, other factors such as uncertainty in values of the volumetric heat capacity for the filling material and the different geometry of the pipes produce smaller errors of the order of 20% or less for the simulated scenarios.

Finally, we would like to mention that the set of results generated in this study, summarized in different figures, can be used to estimate correction factors that should be used when interpreting results of TRT applied to energy piles. Without applying such correction factors one can introduce significant errors for tests that run for less than 160 h in a 1 m diameter pile, which corresponds to approximately $Fo = 1.5$. Hence, it is our hope that the results presented in this study will permit users to run shorter tests, while allowing for correct interpretation of the results to obtain optimal designs and correct cost estimations for new geothermal systems.

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