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# Counterbalancing ambient interference on thermal conductivity tests for energy piles

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ABSTRACT

Thermal conductivity tests on Energy Piles suffer from ambient interference on the recorded fluid temperatures. Such interference is observed as sudden fluid temperature increases or stabilizations which require advanced data processing techniques for reliable estimates of the effective ground thermal conductivity. This paper presents a modified testing procedure to eliminate the ambient interference observed in thermal conductivity tests for short ground heat exchangers including Energy Piles. The proposed testing technique relies on counterbalancing the ambient interference when heating the circulating fluid. Supported with a full-scale field experiment on an Energy Pile, the proposed testing technique showed a successful elimination of the ambient interference and an accurate estimate of the ground thermal conductivity using the simple infinite line source (ILS) model. Further, the estimated ground thermal conductivity is independent of the number of hours included in the data processing which offers the potential to reduce the testing duration and consequently the associated testing costs.



## 1. Introduction

The thermal energy stored in the shallow ground strata (<60 m) can be used to heat and cool buildings — known as ground-coupled systems (Brandl, 2006). The use of ground-coupled systems increases slowly despite the high thermal performance and low operational costs of such systems. This slow growth is attributed to the high initial installation costs of the ground heat exchangers, in the form of drilling or excavation costs. In recent years, this ground coupling concept has been expanded to the use of buildings' foundations as heat exchangers to reduce the initial installation costs. Circulation loops are embedded in the deep foundation elements required to structurally support buildings; thus, no additional drilling or excavations are needed. Vertical loops installed in pile foundations — known as Energy Piles — is an example for the use of foundation elements as heat exchangers. Similar to typical ground heat-exchangers, the thermal design of Energy Piles as heat exchangers necessities approximating the ground thermal properties (conductivity and diffusivity), and the thermal resistance of the pile (Kavanaugh and Rafferty, 1997). To estimate these parameters, thermal conductivity tests are performed on pre-production Energy Piles.

Thermal conductivity testing relies on the principle of evaluating thermal response of the geothermal heat exchanger to characterize its thermal properties. In these tests, the ground is subjected to a constant heating rate ($q$) over a period of time-typically, 60 W/m over 48 h (Pahud, 2007). The applied heating rate increases the temperature of the circulating fluid and consequently the ground. The applied heating rate as well as the temperature of the fluid entering and leaving the ground loop is recorded throughout the testing duration. The fluid temperature ($T_f$) at time ($t$) is related to the ground initial temperature ($T_o$), the temperature change at the pile-soil interface ($\Delta T_p$), the applied heating load ($q$), and the thermal resistance of the heat exchanger ($R_p$) as shown in Eq. (1) (Monzó, 2011);

$$T_f(t) = \Delta T_p(t) + q \cdot R_p + T_o \quad (1)$$

Various analytical models were available to estimate the temperature change at the heat exchanger-soil interface ($\Delta T_p$) (Claesson and Eskilson, 1987; Eskilson, 1987; Ingersoll et al., 1954). Due to its simplicity and reliable estimates, the infinite line source model (ILS) is the most commonly used model to estimate $\Delta T_p$ (Monzó, 2011). In this model, the heat exchanger is represented as an infinite line source (Carslaw and Jaeger, 1986; Mogensen,

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**Nomenclature**

| | |
|---|---|
| $b$ | $y$-intercept of the line at the origin |
| $c_A$, $c_B$ | coefficients for Churchill equation |
| $Cp$ | specific heat capacity, J/kg °C |
| $f_d$ | Darcy's friction factor |
| $h$ | convection heat transfer coefficient at the walls of the inner tube, W/m$^2$ K |
| $k$ | thermal conductivity, W/m K |
| $m$ | slope of the line |
| $N_u$ | Nusselt number |
| $P_r$ | Prandtl number |
| $Q$ | total heat exchange, W |
| $q$ | heating rate per unit length, W/m |
| $R$ | thermal resistance, m K/W |
| $R_e$ | Reynolds number |
| $r$ | radius, m |
| $T$ | temperature, °C |
| $t$ | time, s |
| $\Delta T$ | temperature change, °C |
| $t$ | time increment, s |
| $v$ | velocity, m/s |
| $V$ | mass flow rate, kg/s |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity, m$^2$/s |
| $\mu$ | dynamic viscosity, Pa s |
| $\rho$ | dry density of the grout, kg/m$^3$ |
| $\gamma$ | Euler constant = 0.5772 |

*Subscripts*

| | |
|---|---|
| *0* | initial |
| *air* | ambient air |
| *e* | external |
| *f* | circulating fluid |
| *g* | ground |
| *i* | internal |
| *in* | inlet fluid |
| *out* | outlet fluid |
| *p* | energy pile |
| *saturation* | thermal saturation |
| *t* | tube |
| *teff* | effective property for the tubes |
| *w* | water |

*Superscripts*

| | |
|---|---|
| * | inside the testing trailer |
| *air* | difference with ambient air temperature, °C |

1983). Using the ILS model, the temperature change at the pile-soil interface ($\Delta T_p$) can be estimated using Eq. (2).

$$\Delta T_p(t) = \frac{q}{4\pi k_g}\left[\ln\left(\frac{4\alpha_g t}{r_p^2}\right) - \gamma\right] \quad \text{for} \quad \frac{\alpha_g t}{r_p^2} \geq 5 \tag{2}$$

From Eqs. (1) and (2), the average fluid temperature ($T_f$) can be estimated as;

$$T_f(t) = \frac{q}{4\pi k_g}\left[\ln\left(\frac{4\alpha_g t}{r_p^2}\right) - \gamma\right] + q \cdot R_p + T_o \tag{3}$$

Rearranging and collecting terms in Eq. (3):

$$T_f(t) = \underbrace{\frac{q}{4\pi k_g}\left[\ln\left(\frac{4\alpha_g}{r_p^2}\right) - \gamma\right] + q \cdot R_p + T_o}_{\text{Independent of time } (t)} + \underbrace{\frac{q}{4\pi k_g}\ln(t)}_{\text{Time dependent}} \tag{4}$$

Theoretically, the first three terms on the right hand side of Eq. (4) are constant once the considered heat exchanger reaches thermal saturation. The time needed to reach thermal saturation ($t_{saturation}$) can be estimated using the applicability condition for the ILS model shown in Eq. (5), i.e. $t_{saturation} = 5r_p^2/\alpha_g$. The fluid temperatures over recorded over the thermal saturation time must not be included in the data processing especially when ILS model is used to avoid inaccurate estimates of the ground thermal properties. On the other hand, the last term in Eq. (4) varies with time ($t$). Thus, a linear form on Eq. (4) can be used;

$$y = m \cdot \ln(t) + b \tag{5}$$

where, $y$ average fluid temperature = $T_f(t)$, $m$: the slope of the line which is related to the average thermal conductivity of the ground = $q/4\pi k_g$, $b$: the $y$-intercept at the origin $= q/(4\pi k_g)[\ln(4\alpha_g)/r_p^2 - \gamma] + q \cdot R_p + T_o$, This formulation presents a log-linear relationship between the average fluid temperature ($T_f$) and the elapsed time ($t$) as shown in Fig. 1. Thus, the average thermal conductivity of the ground ($k_g$) and the average thermal resistance of the Energy Pile ($R_p$) can be estimated using the slope ($m$) and the $y$-intercept ($b$) of the best-fit line, respectively, as presented in Eqs. (6) and (7).

$$k_g = \frac{q}{4\pi m} \tag{6}$$

$$R_p = \frac{b - T_o}{q} - \frac{1}{4\pi k_g}\left[\ln\left(\frac{4\alpha_g}{r_p^2}\right) - \gamma\right] \tag{7}$$

As presented in Eqs. (6) and (7), injecting a constant heating rate ($q$) to the ground is necessary for accurate estimates of the ground thermal conductivity and the effective thermal resistance of the tested Energy Pile. One approach to impose a constant heating rate is to maintain a constant temperature difference between the inlet and the outlet fluids – commonly known as the Dutch thermal conductivity testing procedure (Witte et al., 2002). Constant temperature difference between the inlet and the outlet fluids ($\Delta T$) produce a constant calorimetric power applied to the circulating fluid as explained in Eq. (8).

$$\text{Calorimetric Power, Watts} \quad (q) = V \cdot C_p \cdot (T_{in}^* - T_{out}^*) \tag{8}$$

where, $V$ mass flow rate in kg/s = volumetric flow rate (m$^3$/s) × fluid density (kg/m$^3$), $C_p$: specific heat of the circulating fluid in J/kg °C, The inlet and the outlet fluid temperatures ($T_{in}^*$, and $T_{out}^*$) are typically measured inside the testing trailer as shown in Fig. 2. The fluid temperatures at the inlet and the outlet of the ground loop ($T_m$, and $T_{out}$) slightly differ from those measured inside the testing trailer ($T_{in}^*$, and $T_{out}^*$) due to the heat exchanged between the circulating fluid and the ambient air along the tubes connecting the testing trailer to the ground loop. The heat exchange with ambient air is unavoidable, however, its magnitude decreases with better tube insulation (Bandos et al., 2011). Consequently, the calorimetric power estimated using $T_{in}^*$, and $T_{out}^*$ measured inside the trailer does not represent the actual power injected into the ground during the thermal conductivity test.

The heat exchanged with the ambient air introduces a thermal power ($Q_{air}$) that is either injected into the system as a heat gain, or extracted from the system as a heat loss. The magnitude of $Q_{air}$ and its flow into or out of the system depend on the relative temperatures of the circulating fluid and the ambient air. For example, $Q_{air}$ is injected into the system (heat gain) if the fluid temperature is less than the ambient temperature. On the other hand, $Q_{air}$ is removed