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The average temperature of energy piles

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ABSTRACT: The geotechnical design of energy piles requires confirmation that the foundations can continue to carry safely the required load from the overlying structure and that no detrimental effects from the additional imposed temperature changes will occur. These additional design checks require assumptions to be made about the temperature changes within the pile. However, there is no universal approach for determining these, and routine application of over-conservative pile temperatures can lead to unrealistically adverse geotechnical design scenarios. This paper considers how the average temperature of a pile can be determined based on the analysis steps already carried out for the thermal design. The aim is to be able use the calculated fluid temperatures, along with readily available pile and ground parameters, to provide better assessments of the actual pile temperature so that the outputs of the geotechnical design can be improved. Two dimensional numerical simulations are used to determine the average pile temperature for different pipe, pile and concrete properties. The results of the simulations are compared with analytical approaches, allowing these to be validated for use on a routine basis. It is shown that the temperature of the center of the pile, which can be determined easily by analytical methods, can be used as a proxy for the average pile temperature.

INTRODUCTION

Energy piles, where foundation piles are equipped with heat transfer pipes to allow them to become part of a shallow ground energy system, are a technology of increasing interest owing to their carbon and energy savings benefits. The geotechnical design of energy piles requires confirmation that the foundations can carry safely the required load from the overlying structure and that no detrimental effects from the additional imposed temperature changes will occur (GSHPA, 2012). These additional design checks may be carried out by adapted load transfer methods, by numerical simulation or by design charts (e.g Knellwolf et al, 2011, McCartney & Rosenberg, 2011, Laloui et al, 2006, Bodas-Freitas et al, 2013). With the exception of full numerical simulation, which is computationally very expensive, most of these approaches require simplifying assumptions to be made about the heat transfer rate or temperature boundary conditions related to the pile. Load transfer methods tend to assume a homogeneous pile temperature change so it is important to be able to make an appropriate assumption regarding this value, which would be equivalent to the average pile temperature. However, current thermal design methods focus on delivery of the temperature of the heat transfer fluid as it enters and leaves the heat pump. This will always cover a greater range than the pile temperatures. Hence if extreme fluid temperatures are used to define the thermal load cases, an over-conservative design may result. Better means of determining the average temperature of the pile as part of the thermal design process are required.

The aim of this paper is to be able use the calculated fluid temperatures, along with readily available pile and ground parameters, to provide better assessments of the actual pile temperatures so that the outputs of the geotechnical design can be improved. Consequently, this paper considers how the average temperature of a pile can be determined based on the analysis steps already carried out for the thermal design. The average temperature is chosen as the most suitable parameter for use in predictions of expansion and contraction of the pile during heating and cooling. Two dimensional numerical simulations are used to determine the average pile temperature for different combinations of pipe, pile and concrete properties. The results of the simulations are compared with analytical approaches, allowing these to be validated for use on a routine basis.

THERMAL DESIGN

The thermal design of energy piles uses a variety of analytical solutions to calculate the temperatures of the heat transfer fluid entering and leaving the heat pumps (for example Eskilson, 1987, Hellstrom, 1989, Claesson & Hellstrom, 2011). These are typically determined by superposition of the temperature changes in the ground, across the pile concrete and between the fluid and the edge of the heat transfer pipes embedded in the concrete:

$$\Delta T_f = \Delta T_{ground} + \Delta T_{concrete} + \Delta T_{pipe} \tag{1}$$

The ground temperature change is normally calculated using a transient temperature response function (G_g) evaluated at a radial coordinate $r=r_b$, where r_b is the pile radius.

$$\Delta T_{ground} = \frac{q}{2\pi\lambda_g} G_g(t, r) \tag{2}$$

where λ_g is the thermal conductivity of the ground in W/mK, q is the applied thermal power in W/m and t is the elapsed time in seconds.

Traditionally $\Delta T_{concrete}$ and ΔT_{pipe} are calculated using thermal resistances and assuming a thermal steady state (Eq. 3 & 4). However, for large diameter energy piles a transient approach to the temperature change in the pile is preferable (Eq. 5).

$$\Delta T_{concrete} = T_p - T_b = qR_c \quad (3)$$

$$\Delta T_{pipe} = T_f - T_p = qR_p \quad (4)$$

$$\Delta T_{concrete} = T_b - T_p = qR_c G_c(t) \quad (5)$$

where R is a thermal resistance in mK/W and G_c is a transient response function. T_b and T_p are the temperatures at the pile edge and pipe edge respectively (see Figure 1).

In the following sections of the paper the thermal resistance values, which are standard input parameters for the design, will be used to determine an approximation for the average value of the pile temperature based on the fluid temperature which is a routine thermal design output.

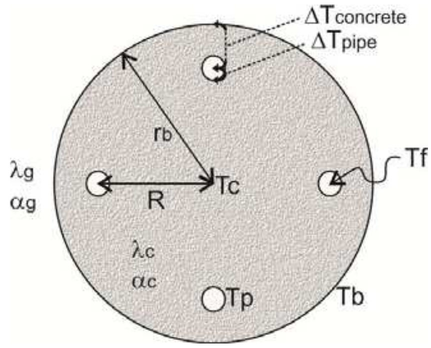

FIG. 1. Typical arrangement of an energy pile showing four pipes.

AVERAGE PILE TEMPERATURE BY ANALYTICAL SOLUTIONS

It is proposed that to determine the thermal design cases for the geotechnical analysis, the extreme fluid temperatures calculated from the thermal design may be used as a starting point for simple calculations to determine the extreme average pile temperatures.

Approach

It is hypothesized that the temperature of the center of the pile could be used as a proxy for the average temperature of the pile. This hypothesis will be tested subsequently by numerical simulation.

Equation 6 gives the change in temperature at the pile center (ΔT_c), after Bozis et al (2011). This assumes that the heat flux to each pipe, q_i, is an equal proportion of the total flux q, such that $q = q_i n_p$, where n_p is the total number of pipes.

$$\Delta T_c = \frac{q}{4\pi\lambda_c} Ei\left(\frac{R^2}{4\alpha_c t}\right) \quad (6)$$

where R is the injection radius, i.e. the distance of the heat transfer pipes from the center of the pile (Figure 1), and the subscript “c” indicates properties of the pile concrete. Ei is the exponential integral. The heating power, q, is variable over the lifetime of a pile, so it is time consuming to calculate the ΔT_c over the full design time sequence. It is instead desirable to determine the value at the extreme conditions only. To investigate how this might be done, the value of the pile center temperature is compared with the temperature values at the pile and pipe edge (T_b and T_p on Figure 1, respectively). For this comparison, the values for the pile edge temperature are determined using a line source approach (Eq. 7). To avoid limiting the time frame for which the results are valid, the full implementation of the exponential integral was used rather than the common log linear simplification.

$$\Delta T_b = \frac{q}{4\pi\lambda_g} Ei\left(\frac{r_b^2}{4\alpha_g t}\right) \tag{7}$$

The results from Eq. 7 were then input into Eq. 3 to determine the pipe temperature, additionally applying values of thermal resistance determined according to the methods of Loveridge & Powrie (2014) or Claesson & Hellstrom (2011). As Eq.6 is based on the thermal properties of the pile and Eq. 7 is based on the thermal properties of the ground, for the two approaches to be directly comparable it must be assumed initially that the pile and the ground have the same properties. The effect of different pile and ground properties will be tested subsequently by numerical analysis.

Results

Figure 2 shows example results of the calculation for the case of a 600 mm diameter pile with two 30 mm diameter pipes installed 75 mm from the pile edge. For ease of interpretation and general applicability of the results the calculations are presented using normalized temperatures and time:

$$\Phi \quad = \frac{2\pi\lambda_g}{q} \Delta T \tag{8}$$

$$Fo = \frac{\alpha_g t}{r_b^2} \tag{9}$$

The results assume a constant applied thermal power and so evolve to show a log-linear relationship after a period of time has elapsed. The temperature at the pipe edge starts at a non-zero value which is a reflection of the steady state resistance value used in Eq. 3. Consequently, the values at later times in Figure 2 should be considered when the whole pile is approaching steady conditions. In these circumstances, and for this specific example, the center pile temperature is approximately a quarter of the way between the pile edge temperature and the pipe temperature.

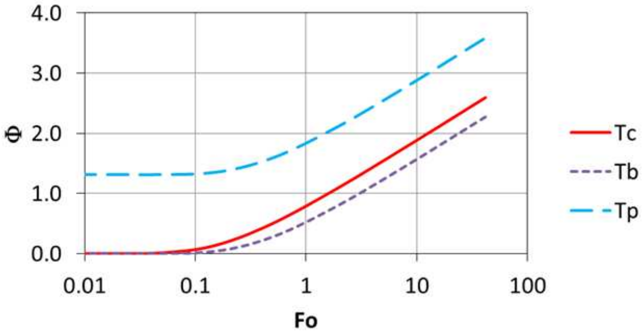

FIG. 2. Example temperature evolution from analytical calculation for 600 mm diameter energy pile with two 30 mm diameter pipes installed at 75 mm offset from the pile edge.

A parametric study was completed to investigate a range of pile sizes and pipe numbers, keeping the pipe size and offset from the pile edge constant (Figure 3) and maintaining evenly spaced pipe arrangements. In all cases the center pile temperature was between that of the pile edge and the pipe edges. In relative terms, the bigger the pile and the fewer the number of pipes, the closer the center pile temperature is to pile edge temperature. This corresponds to the case of the largest pile resistance where there is the biggest temperature difference between the pipe edge and the pile edge.

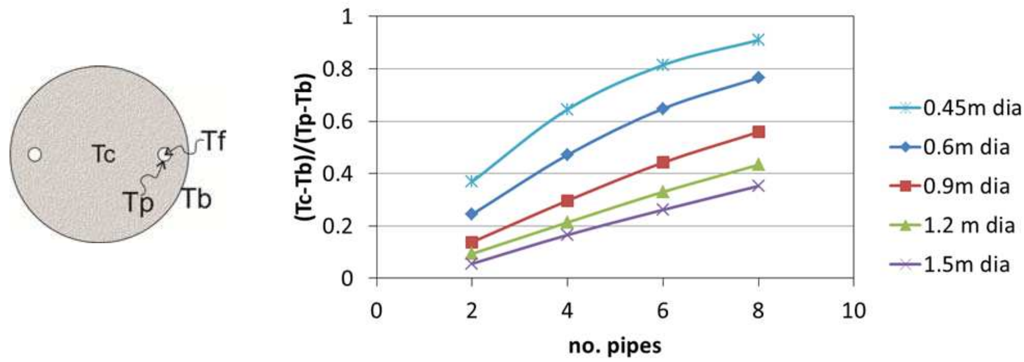

FIG. 3. Relative value of the center pile temperature for different pile sizes and numbers of pipes installed (assuming 30 mm diameter pipes installed at 75 mm offset from the pile edge).

Design Charts

The results of the parametric study are summarized in Figure 3. Such charts could be used to determine the center pile temperature based on the thermal design output, i.e. the fluid temperature. With the extreme fluid temperature values known, Eq. 3 and Eq. 4 can be used to determine T_p and T_b, from which T_c can be estimated from Figure 3. The only other input parameters are the pipe and pile concrete resistances (R_p and R_c), which should already have been estimated (from the geometry and design thermal properties) as input parameters to the thermal design, or can be determined according to the approaches of Loveridge & Powrie (2014) or Claesson & Hellstrom (2011).

NUMERICAL VALIDATION

The proposed approach set out above relies on a few important assumptions:

1. That the pile center temperature is a good proxy for the average pile temperature.
2. That the ground and pile thermal properties are equal.
3. That the pile is at a thermal steady state.

The first point is expected to be a reasonable assumption and will be tested in this section of the paper. However, it is known that both the relative pile and ground properties and the tendency of large diameter piles to not attain a steady state (especially at peak thermal load) will affect their short term thermal behavior. How this impacts on the average pile temperature is now the subject of investigation.

Model Details

For this initial investigation a two dimensional numerical model was built in COMSOL, as described in Loveridge & Powrie (2014). The model comprised a slice through the pile and surrounding ground. The pipes were not explicitly modelled and the pipe edge temperature and temperatures within the full domain are determined following application of a constant heat flux applied at the position of the pipe outer edge. Boundary conditions within the ground were sufficiently far away so as to not influence the simulation results. The simulation duration was 45 days, since 2D simulations are only appropriate for short time periods.

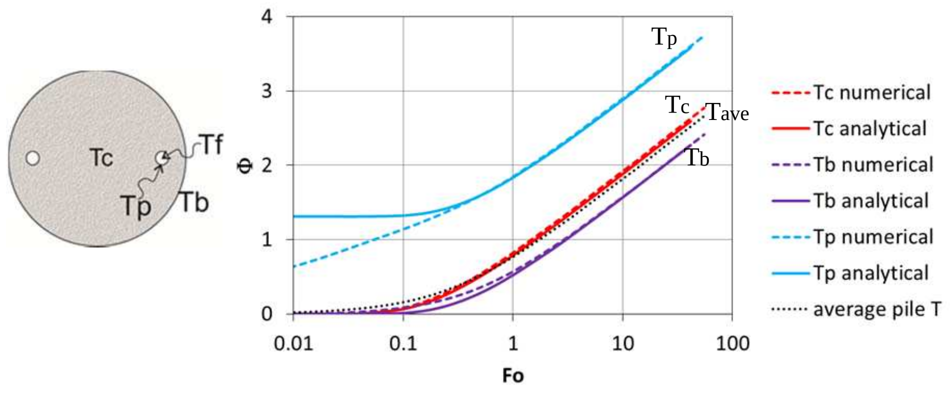

FIG. 4. Temperature evolution from numerical simulation (dashed lines) and analytical calculation (solid lines) for a 600 mm diameter energy pile with two 30 mm diameter pipes installed at 75 mm offset from the pile edge.

Figure 4 shows the model and analytical results for the case of a 600 mm piles with

30 mm pipes installed 75 mm from the pile edge, assuming that the ground and concrete thermal properties are the same. For the numerical model the average temperature at the pipe (T_p) and pile edges (T_b) are used for comparison. The results show good consistency between the two approaches and also that the average temperature of the pile (T_{ave}) is just below the temperature of the pile center (T_c). The difference is approximately 4%. Additionally, as the analysis was carried out for heat injection, and the center pile temperature is higher than the average pile temperature, this result is conservative. This suggests that the pile center temperature could make a good proxy for the average pile temperature.

Impact of Differing Ground and Concrete Properties

The model was then used to investigate the effect of the soil and ground thermal properties for two different pipe arrangements. When the conductivity of the ground becomes less than that of the pile concrete temperature changes are reduced. This means that all the pile edge, pile average and pipe edge temperatures bunch together. Conversely, when the pile concrete is less conductive than the ground, the temperature changes increase and spread out. The effect of these changes on the pile center and average temperature are summarized in Tables 1 and 2.

Table 1. Difference in Relative Value of Pile Center Temperature between Analytical and Numerical Approaches

	(Tc-Tb) / (Tp-Tb)			
Pile Arrangement	**Analytical $\lambda c=\lambda g$**	**Numerical $\lambda c=\lambda g$**	**Numerical $\lambda c=2\lambda g$**	**Numerical $2\lambda c=\lambda g$**
600mm pile, 2 pipes	0.22	0.27	0.27	0.28
600mm pile, 8 pipes	0.77	0.86	0.86	0.86

Table 2. Average Pile Temperature as Percentage of Pile Center Temperature

Pile Arrangement	Analytical $\lambda c=\lambda g$	Numerical $\lambda c=\lambda g$	Numerical $\lambda c=2\lambda g$	Numerical $2\lambda c=\lambda g$
600mm pile, 2 pipes	-	96%	98%	93%
600mm pile, 8 pipes	-	96%	97%	93%

It can be seen that for the numerical analyses, the calculated value of the pile center temperature is always slightly greater than for the analytical approach. However, no significant difference is apparent for the cases with different ground to pile conductivity ratios. In all cases the pile average temperature remained within 7% of the pile center temperature. As the pile center is higher than the average temperature in heat injection, again this indicates the results to be conservative with respect to geotechnical design. Therefore these initial findings suggest that the analytically determined pile center temperature would be both appropriate and safe if used to determine the thermal design cases for the geotechnical pile analysis.

Impact of Transient Thermal Load

The above analyses all assume that the pile is at a thermal steady state, which may not be the case in reality (Loveridge & Powrie, 2013). To investigate the impact of a time varying thermal load on the average pile temperature, the constant applied heat flux in the COMSOL model was replaced with one that was "on" for 12 hours a day and "off" for 12 hours a day. When the applied heat flux was "on" it was set at twice the value as previously so that the overall average thermal load was the same as in previous simulations.

The results of the transient thermal load simulation are shown in Figure 5. The analysis assumes a 600 mm diameter pile with two 30 mm diameter pipes installed at 75 mm offset from the pile edge with equal ground and concrete thermal properties. At peak loads there is large separation between the pile edge and the pipe temperatures. However, this reduces substantially during the "off" periods when there is no applied thermal load. Steady state conditions do not appear to occur within the pile concrete since $\Delta T_{concrete} = T_p - T_b$ is not constant. Of relevance for this study is the fact that the pile center temperature remains an acceptable proxy for the average pile temperature. However, what needs to be investigated is whether use of the center temperature calculated from steady state resistances will still give a useful indicator of the average pile temperature.

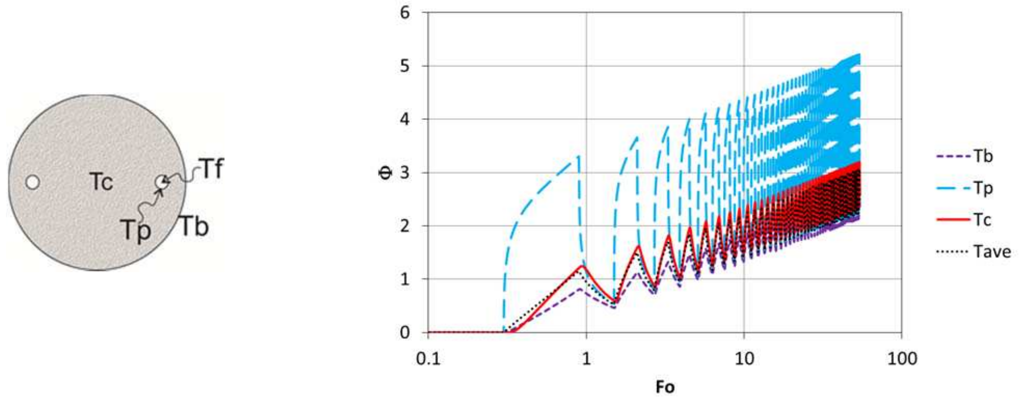

FIG. 5. Temperature evolution during transient thermal load for a 600 mm diameter energy pile with two 30 mm diameter pipes installed at 75 mm offset from the pile edge.

To assess this, the center of pile temperature has been calculated based on the maximum pipe edge temperature from the numerical simulation in Figure 5 and the results compared with the simulated value for the average pile temperature. The steps in the calculation are as follows, with results given in Table 3 below:

1. Read off simulated maximum normalized pipe edge temperature, $\Phi_{p\text{-}max}$
2. By application of Eq. 3 and Eq. 8, determine the calculated maximum pile edge temperature $\Phi_{b-max} = \Phi_{p-max} - 2\pi\lambda_g R_c$
3. For the calculated $\Phi_{b\text{-}max}$, determine $\Phi_{c\text{-}max}$ by reading off the design chart in Figure 3.
4. Compare the results with the simulated values of $\Phi_{c\text{-}max}$ and $\Phi_{ave\text{-}max}$.

Table 3. Calculated and Simulated Pile Temperatures under Transient Thermal Load (assuming *q=50* W/m, λ_g*=2* W/mK, R_c*=0.104* W/mK)

Normalized Pile Temperatures	Simulated Value (Transient)	Calculated Value (Steady State)
$\Phi_{p\text{-}max}$	5.22	
$\Phi_{b\text{-}max}$	2.67	3.91
$\Phi_{c\text{-}max}$	3.36	4.26
$\Phi_{ave\text{-}max}$	3.06	

Table 3 shows how the calculations assuming a steady state resistance overestimate the average temperature of the pile. The calculated normalized pile center temperature is 4.26 and which is approximately 25% more than the simulated pile center temperature and 40% more than the simulated average pile temperature. Nonetheless the calculated values remain both conservative and critically less than the simulated pipe temperature. As such, even in transient conditions, the steady state calculation of the pile center temperature, as a proxy for the average temperature, represents an improvement on simply applying the fluid or pipe edge temperatures as an input for the geotechnical design.

FURTHER WORK

This initial study has focused on numerical simulation of only a small number of pile cases. To increase confidence in the results a greater range of pile geometries need to be assessed such that the design chart presented in Figure 3 can be improved. Additionally, it is clear that the approach can be further developed to better account for transient conditions. This will be especially important for larger diameter energy piles. Validation using 3D simulation that accounts for the non-uniform heat flux distribution between the different pipes would also be beneficial.

CONCLUSIONS

To assess the thermo-mechanical effect of heating and cooling on energy piles it is necessary to make assumptions regarding the temperature changes that will occur within the pile. It is simple to use the extreme values of the fluid temperature for this purpose but the approach is conservative as a temperature gradient exists across the piles and the bounds to the average pile temperature will be reduced compared with the fluid temperature. This paper presents a simple approach to estimate the temperature at the center of the pile which has been shown to be a good proxy for the average pile temperature. Using the thermal resistances, which are a necessary design input parameter for the thermal design, along with the predicted fluid temperature, which is an output of that process, it is possible to calculate the pile edge and pipe edge temperatures. Using design charts these values can be converted to a value for the center pile temperature. The proposed approach has been tested against numerical simulation and shown to be appropriate for steady conditions. Under transient thermal loads the approach may be conservative for large diameter piles, but less conservative than simply adopting the fluid temperature values instead.

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