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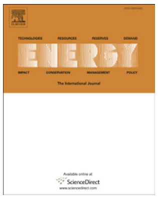

Influences on the thermal efficiency of energy piles

Francesco Cecinato [a, *], Fleur A. Loveridge [b]

[a] *University of Trento, Department of Civil, Environmental and Mechanical Engineering, Trento, Italy*
[b] *University of Southampton, Faculty of Engineering and the Environment, Southampton, UK*

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ABSTRACT

Energy piles have recently emerged as a viable alternative to borehole heat exchangers, but their energy efficiency has so far seen little research. In this work, a finite element numerical model is developed for the accurate 3D analysis of transient diffusive and convective heat exchange phenomena taking place in geothermal structures. The model is validated by reproducing both the outcome of a thermal response test carried out on a test pile, and the average response of the linear heat source analytical solution. Then, the model is employed to carry out a parametric analysis to identify the key factors in maximising the pile energy efficiency. It is shown that the most influential design parameter is the number of pipes, which can be more conveniently increased, within a reasonable range, compared to increasing the pile dimensions. The influence of changing pile length, concrete conductivity, pile diameter and concrete cover are also discussed in light of their energetic implications. Counter to engineering intuition, the fluid flowrate does not emerge as important in energy efficiency, provided it is sufficient to ensure turbulent flow. The model presented in this paper can be easily adapted to the detailed study of other types of geothermal structures.

1. Introduction

Increased use of renewable energy is required in the coming decades to contribute to a reduction in global energy use and also a reduction in carbon dioxide emissions. Ground source heat pump systems will make an important contribution to renewable energy as they lead to both energy efficiencies in buildings and are compatible with moving away from fossil fuels as lower carbon sources of electricity become available. However, ground source heat pump systems have a high up front capital cost meaning there is a pay back period of several years before the building owner sees the benefit of the energy efficiencies of the system. Consequently, any means to either reduce the capital cost of systems and/or increase their efficiency will be timely.

All ground source heat pump schemes comprise a series of ground heat exchangers forming a primary circuit and a building heating system forming the secondary circuit. As well as the heat pumps themselves, construction of the ground heat exchangers, where pipes must be cast into the ground, are also a significant capital cost. One way to reduce this cost, and also save on embodied energy, is to use the piled foundations of new buildings as the ground heat exchangers (e.g Ref. [32]), so called energy piles. This removes the requirement to make expensive special purpose excavations. In addition, the larger diameter of energy piles tends to mean they can be expected to have a greater energy capacity per drilled metre than other types of ground heat exchanger, such as boreholes [4]. While borehole heat exchangers have been in use and the subject of research for decades (e.g Ref. [29]), energy piles are only now becoming more common (e.g Ref. [1]). Consequently, the energy efficiency of piles used as ground heat exchangers has seen little research compared to other types of ground heat exchangers.

In fact, much energy pile design is currently carried out using methods developed for borehole ground heat exchangers. In such cases it is usually beneficial to install two rather than one U-loops of heat transfer pipes and to separate the up and down legs of the U-loops with spacers to prevent thermal interactions (e.g Ref. [2]). With energy piles there is the scope for inclusions of many more pipes within the pile cross section, but little available guidance as to optimum spacing or arrangements. It is factors like these, along with pile size, thermal properties and heat transfer fluid flowrate that will influence the thermal behaviour and ultimately the energy efficiency of the pile. While some studies of these factors exist,

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* Corresponding author. Tel.: +39 0461 282585.
E-mail addresses: francesco.cecinato@unitn.it (F. Cecinato), Fleur.Loveridge@soton.ac.uk (F.A. Loveridge).

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there is currently no overarching framework to help engineers make design decisions.

2. Background

Initial studies into energy piles were carried out by Brandl [5]. For smaller diameter energy piles he characterised thermal output in terms of Watts per metre length of the pile, but used Watts per square metre for larger diameter piles (≥600 mm) reflecting the expected beneficial effects of larger surface areas of bigger piles. The internal thermal aspects of energy piles are often taken into account by a lumped parameter known as thermal resistance. A low thermal resistance means more efficient thermal transfer to the surrounding ground. As thermal resistance encompasses both geometry and material property effects, it is convenient in many respects, but can mask which of these parameters is most important. Guidance for determining pile thermal resistance can be found in Ref. [27] and [20]. The former publication suggests that larger diameter piles are only more efficient if the opportunity to install more pipes is taken. The latter contains a more detailed study showing the importance of the pile concrete thermal properties and the position of the pipes within the pile. However, the study is limited to two dimensions and therefore does not include the influence of pipe flow condition and the potential for pipe-to-pipe interactions.

Ref. [16] investigated experimentally the importance of the number of heat transfer pipes and their connections. Parallel U-loops were seen to be slightly more efficient than series U-loops and the study also confirmed the potential for greater heat transfer with more pipes and faster fluid flow conditions. It has also been shown that the flow conditions are of greater relative importance when there are only few pipes [4]. Recently there has also been interest in the potential for greater energy efficiency from using spiral coil type heat transfer pipes rather than vertical pipes installed as U-loops (e.g Refs. [24,34]). However, practically spiral coils are rarely installed as they are limited to use in scenarios where the pile reinforcement cage, to which the coils must be fixed, is installed in one piece.

To investigate further how the design of energy piles can be adjusted to increase their energy efficiency this paper presents a numerical sensitivity study covering the key factors that will control the pile thermal behaviour: pile diameter and length, concrete cover, concrete thermal conductivity, number and diameter of installed pipes, fluid flow velocity. Numerical methods are common in ground heat exchanger research (e.g Refs. [13,33]) and allow consideration of many more configurations that can be addressed in practical experiments. However, most models are produced to consider specific case studies (e.g Refs. [14,18,28]) and do not take the opportunity to study the important general problem of optimisation guidance for designers. Distinct from previous work this study allows the relative importance of the design key parameters to be compared so that practical recommendations can be made regarding where designers should focus their efforts to increase the energy efficiency of their energy piles scheme. The results of the analysis therefore allow development of an overarching framework for efficient thermal design of energy piles. For simplicity, this study is limited to rotary bored piles with vertical pipes (or U-loops) installed as this is the most common approach globally for equipping energy piles.

3. Model description

3.1. Theoretical background

The proposed numerical model aims at realistically reproducing the main processes behind the heat transfer phenomenon, taking place in geothermal structures. In this case it is applied to energy piles, but would be equally applicable to other energy geostructures. Three principal components of a geothermal system are identified as the heat exchanger fluid within the pipes, the grout/concrete filling the space between the pipes and the ground, and the soil/rock surrounding the heat exchanger. The corresponding three main heat transfer mechanisms are thermal convection between the fluid and the pipe wall, thermal conduction in the grout/concrete, and thermal conduction in the ground.

The above depicted situation provides a simplified representation of reality where additional thermal phenomena may occur, such as thermal radiation at the soil surface and convective heat transfer in the pore water, when the groundwater is flowing. While the role of radiant heat exchange is generally deemed to be negligible in all but the coarsest of soils [15,26], the potential importance of groundwater convection makes the model realistically applicable to cases of low-permeability, or dry, soils or rocks. However, if the groundwater at a specific site is known to be in static conditions, the model can be also applied to high-permeability water-saturated geologic materials.

A general form of the convection–diffusion equation that applies to the heat exchanger fluid, neglecting the contribution of friction heat dissipated by viscous shear, is

$$\dot{T} - \nabla(D\nabla T) + v\nabla T = S \tag{1}$$

where T the temperature, D the fluid thermal diffusivity, v the fluid velocity and S the temperature sink term. The first term on the left hand side of Equation (1) represents the time rate of change of temperature, the second term represents heat diffusion in the circulating fluid along the pipe, and the third term is linked to the convective spatial temperature change due to fluid circulation. The sink term represents the convective heat transfer between the fluid and the pipe wall.

By introducing the standard expressions of diffusivity and convective heat transfer, Equation (1) can be expressed in terms of heat flux quantities, as

$$\rho_f c_{pf}\dot{T} - \nabla\left(\lambda_f \nabla T\right) + \dot{m}c_{pf}\nabla T = h\Delta T \tag{2}$$

where ρ_f and c_{pf} the fluid density and specific heat capacity, λ_f the fluid thermal conductivity, $\dot{m} = \rho v A$ the mass flowrate, A the pipe cross-sectional area, h the ‘film’ (or convective heat transfer) coefficient, and $\Delta T = (T_s - T_f)$ the temperature difference between the solid interface (pipe wall) and the fluid.

Equation (2) can be simplified for the purposes of our analysis, by assuming that (i) convection due to fluid flow occurs as a quasi-static phenomenon, and (ii) conductive heat transfer along the flow direction can be neglected compared to both the radial heat transfer at the fluid/pipe wall interface and the convective transfer.

The above simplifying hypotheses correspond to neglecting the first two terms of Equation (2), and were shown to yield accurate results for the purposes of vertical ground heat exchangers simulation [7]. It should be remarked that ignoring the first term of Equation (2) implies neglecting temperature variations due to the temperature front propagating along with fluid flow. This may lead to inaccurate modelling of the very early stage of circulation, if a sharp temperature discontinuity is imposed at the inlet pipe, limited to the time span required for the temperature front to reach the outlet (of the order of a few seconds to a few minutes, depending on the flowrate and circuit length). This approximation is acceptable since the typical time span of interest for our simulations is several order of magnitudes larger (a few days). Furthermore, as shown in Section 4, the simulation results obtained