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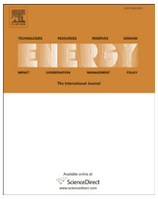

Finite cylinder-source model for energy pile heat exchangers: Effects of thermal storage and vertical temperature variations

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ABSTRACT

A mean integral solution to the FCS (finite cylindrical source) model for ground heat exchangers that takes into account the heat capacity inside the borehole or foundation and allows estimation of temperature field for an arbitrary borehole configuration is presented as a single integral. Approximate expressions for the average temperature over a wide range of time values are derived analytically in the vicinity of both sides of the finite cylindrical surface of heat source. Exact and approximate results for the mean temperature are compared to those calculated at the mid-depth from the exact solution of the same FCS model.

1. Introduction

A GCHP (ground coupled heat pump) is one of a sustainable energy technologies for heating and cooling buildings. GCHPs are based on borehole heat exchangers, consisting of a U-loop tube buried in the ground and connected to a heat pump through which a heat transfer fluid is circulated.

Although GCHP systems provide renewable energy to buildings, long-term financial benefit and space requirements prevent their widespread. One possible method for reducing their cost is to place tubes of heat exchangers in foundation piles, which are connected through the larger pipes to the heat pump, as Fig. 1a illustrates. Foundation heat exchangers are an alternative to more expensive borehole heat exchangers used in ground coupled heat pump systems, and it becomes increasingly common to utilize foundation piles as energy piles [5,22,23]. Fig. 1b shows GCHP systems with vertical U-loops or spiral coils integrated in energy piles, which provide both the structural support and cooling/heating to the buildings. These pile heat exchangers are normally used in combination with borehole heat exchangers for heating purposes.

Recently, innovated GCHP systems in foundation piles have attracted interest of geotechnical engineers [1,12,14]. Geotechnical analysis of the expansion or contraction of the pile involves studying the transient heat transfer process within the pile and through the ground surrounding it. Design of energy pile is to account for thermal stress and thermal energy storage when using numerical and analytical methods. In the thermal design simulation models of GHEs (ground heat exchangers) are necessary for sizing and energy calculations [24]. Some software programs are based on an infinite cylinder or line heat source models [7], which are appropriate models for short-time applications and describe the heat transfer between the ground and the heat sources presented in Figs. 1a and 2b.

Kelvin's ILS (infinite line source) model is used for evaluation of response test data because of its simplicity and speed [20]. In the lack of such a simple solution for cylindrical heat source, this model is used for analysis of energy pile test [4]. Both infinite CHS (cylindrical heat source) and line-source models assume that the resistance at the inside the surface of cylinder is the same as in steady-state conditions, when solving transient problem for a field of GHEs or a single pile [25]. To account for the thermal storage capacity inside the pile, the hollow cylinder-source model was extended to the solid one, which accounts for both the inner and outer heat exchange [17]. However, these infinite-source models

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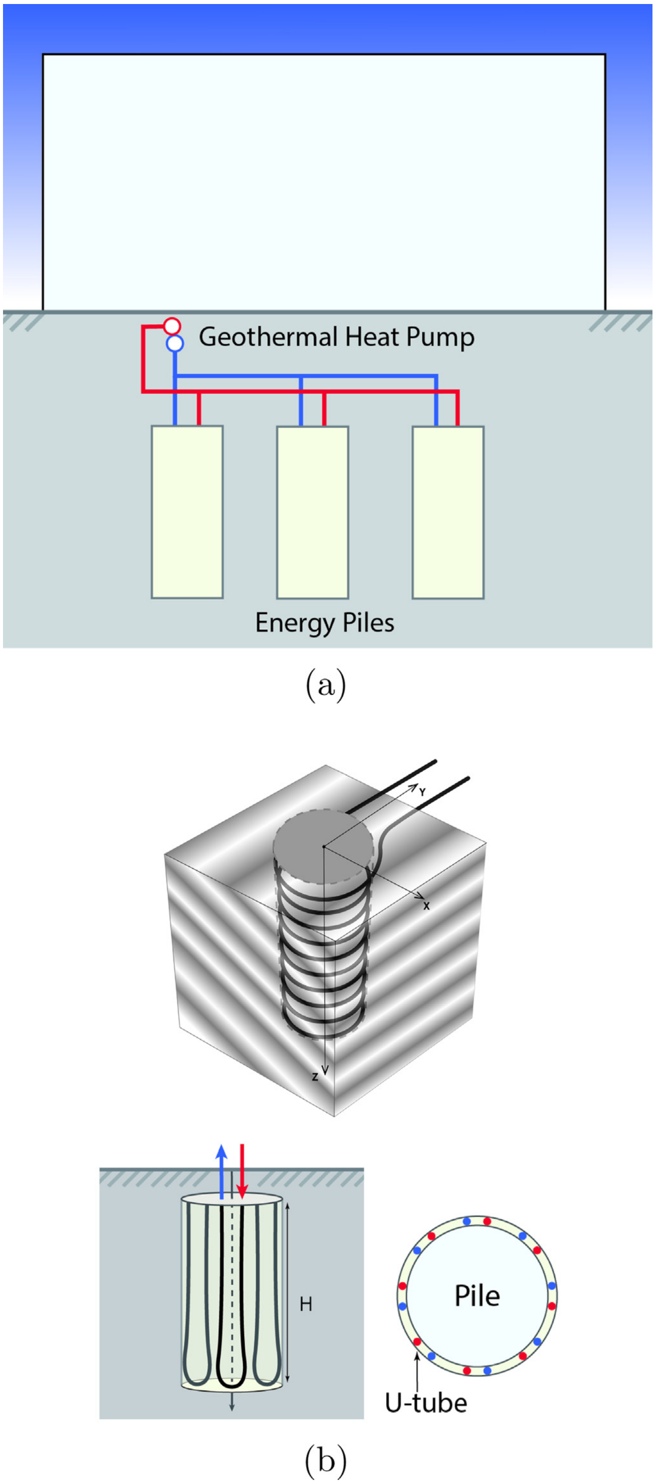

Fig. 1. (a) Scheme of a GCHP system with energy piles; (b) Thermo-active foundations with vertical U-tubes and spiral shaped pipes.

are based on integral calculation and their use requires rather lengthy simulations.

To reduce computational efforts, one may utilize empirical time-dependence of the temperature distribution obtained by parameter-estimating the results from the infinite hollow [3] or solid cylindrical source models [17]. However, their usage is limited to few values of the radius for temperature response evaluation at the boundary or outward it. Instead, an analytical solution from the infinite solid cylindrical source of heat of finite-curvature would be valuable for estimating field test results. In addition, asymptotic form of the solution may give insight for the early thermal behavior, where results of the geothermal probes as the pile data are often difficult to interpret [12,19].

Infinite-source models have some limitations. For the long-time periods the vertical temperature variations or finite size effects need to be taken into account; otherwise the approximation to the ground temperature does not reach a steady-state value. This is not the case neither for the FLS (finite line-source) model [7] nor for the FCS (finite solid cylinder-source) model [17]. In both models temperature around the GHE is evaluated at its mid-point. In the FLS model one makes use of the so-called *g*-function introduced by Eskilson [9]; which represents the thermal response factor of the borehole at the mid-point to a heat pulse and is used when modeling the 3-D (three dimensional) temperature distribution of a multiple borehole pattern.

However, there is growing interest in a modeling framework for the accurate estimation of the temperature around the GHE by averaging over its thermo-active length as proposed by Ref. [28]. The integral mean temperature analysis in geothermal applications has been developed further [2,10,15] as it is a more reasonable than the mid-point one. Accordingly, the integral mean temperature approach was suggested as a base of new methodology for simulation of heat pump energy consumption in multiple borehole field [6]. Codes developed for use with boreholes are also used for pile design applications.

The *g*-function methodology implies multiple energy piles or borehole heat exchangers arranged in regular patterns [21]. These systems were studied with the duct ground heat storage model [13] in TRNSYS simulation software that neglects thermal storage in the borehole wall interior [22]. However, use of the pre-computed *g*-functions is limited to the symmetric configurations of deep boreholes, while a single shallow pile or piles in irregular arrangements, like open rectangular, double “L” configurations, require specific use of solution for single heat source [21].

Furthermore, the *g*-function usage assumes steady-state thermal resistance of borehole. Typically, one applies this steady-state approximation after few hours, when a heat pulse from the cylindrical wall of radius r_b reaches its center, i.e. $t > r_b^2/\alpha$ [13]. The finite solid cylinder – source model overcomes these steady-state limitations and accounts straightforwardly for the depth to radius ratio of the energy pile, AR $= H/r_0$.

The steady-state thermal resistance assumption is widely used for the inside of the GHEs, though inner thermal capacity as well as the outer one is important and both of them must be simultaneously taken into account [6].

Typical energy piles are more shallow than BHEs, and have a depth to radius ratio from 10 to 50 with heat flow distributed over contact area which is 10^4 times larger than that for borehole. That is the reason for studying further vertical temperature variations, using integral mean temperature approach both inside and outside of the heat exchange interface between pile grout and ground. The integral mean temperature method has proved to be practical for boreholes [10] but it would be also desirable if such a lumped approach could be applied to the piles with much larger aspect ratio than boreholes.

However, in the absence of a solution in the form of one-integral for the mean thermal response factor, temperature is assessed at the mid-point of the depth in the frame of the solid cylindrical model [17]; otherwise the mean temperature estimation requires numerical calculation of a complex double integral, which is computationally rather expensive [18].