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A composite cylindrical model and its application in analysis of thermal response and performance for energy pile

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ABSTRACT

Energy pile is a special vertical heat exchanger with the advantage of saving land area for buried pipe in recent years. Based on the composite line source model and cylindrical model, this paper presents a composite cylindrical model, and the heat capacity of pile in the borehole in ground source heat pump system (GSHP) was considered in the model. The model can be used in energy pile with a large diameter. It was validated by comparing to a 3-D numerical model which had been compared with a measured data set. The thermal performance of various layout forms of heat exchangers in energy pile was analyzed. In addition, the model was applied to a project of thermal response test (TRT) to estimate the thermal property parameters of soil. The simulation results showed that the composite cylindrical model have a better agreement from start of the test with measurement data. The model gives a new simulation tool in analysis of performance and TRT for energy pile.

1. Introduction

Geothermal energy is increasingly used through the ground-source/coupled heat pump (GSHP/GCHP) in many countries. GSHP provides an efficient and environment friendly way of heating and cooling for buildings. The common ground heat exchangers (GHEs) are vertical borehole heat exchanger and horizontal heat exchanger. A typical problem of GCHPs is that large land area is required for installing GHEs, which is unavailable or expensive in some urban areas. Recently, utilization of pile foundations of buildings as ground heat exchangers attracts much attention for reducing cost and land area for buried pipe and enhancing heat transfer [1–4]. In this case the foundation pile is called energy pile or pile ground heat exchanger.

The main materials used in construction of bearing or friction piles that have been used in geothermal energy pile include precast or cast in situ reinforced concrete, steel and grout. And concrete energy piles represent the majority used around the world [4]. In a cast in situ energy pile (EP), multiple branches of U-shaped polyethylene pipe have been tied up on the reinforcement cage of the pile.

Some researchers have investigated the heat transfer process and various capacities associated with energy piles. Gao et al. [1] carried out an in-situ performance test and performed numerical investigation to specify the design of an energy pile in an actual engineering. Bozis et al. [2] developed a methodology for comparative evaluation of design alternatives of cast in situ EPs. The methodology is based on the implementation of the line source theory to the specific geometry of the EPs.

Li and Lai [3] presented new temperature response functions (G functions) for pile ground heat exchangers with spiral coils and for borehole ground heat exchangers with single or double U-shaped tubes. Hamada et al. [5] described three tests on system characteristics of space heating operation in an air conditioning with an energy pile system. Hwang et al. [6] suggested an estimation method to determine the thermal and hydraulic properties of the ground to accurately design the heat exchanger of energy pile system based on geotechnical investigation for designing the building's foundations.

Park et al. [7] conducted short-term field thermal response tests (TRTs) for the precast high strength concrete (PHC) energy piles installed in partially saturated weathered granite soil deposit, in which two types of heat exchangers were considered: W and 3U-shaped heat exchangers. Man et al. [8] presented a new "solid" cylindrical source model which considered both the radial dimension and the heat capacity of the borehole or the pile. Park et al. [9] made numerical and analytical case study of thermal response test with energy pile and indicated that analytical models, including modified solutions in the study, overestimated temperature rises outside the pile. The discrepancies might be induced by

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Nomenclature

c_s	ground heat capacity (J/(kg K))
c_g	heat capacity of the backfill material (J/(kg K))
d_i	inside diameter of the tube (m)
d_o	outside diameter of the tube (m)
D	distance between two legs of the U tube (m)
d_b	diameter of the borehole or pile (m)
d_w	effective diameter of the single tube (m)
F_o	Fourier number
K	coefficient of heat exchange between fluid and inside of the tube W/(m^2 K)
q	constant heat injection rate (W/m)
r	radius (m)
R_b	thermal resistance of borehole or pile (K m/W)
R_f	thermal resistance of convective heat transfer (K m/W)
R_s	thermal resistance of soil outside of the borehole (K m/W)
R_w	thermal resistance between the fluid and the radius of undisturbed soil (K m/W)
T_f	mean fluid temperature in the borehole heat exchanger (°C)
T_0	undisturbed ground temperature (°C)

Greek letters

γ	Euler's constant = 0.5772
λ_g	thermal conductivity of the backfill material (W/(m K))
λ_p	thermal conductivity of the tube (W/(m K))
λ_s	soil thermal conductivity (W/(m K))
ν	viscosity of the fluid (m^2/s)
ρ_s	soil density (kg/(m^3)
ρ_g	density of the backfill material (kg/(m^3)
τ	time (s)
α	thermal diffusivity (m^2/s)

the assumption of homogeneous thermal property in the analysis domain or lack of appropriate method for back-calculation of effective thermal property.

Katsura et al. [10] carried out field tests of heating and heat extraction of a GSHP system using 25 steel foundation piles of 8 m long as ground heat exchangers. Performance of GSHP systems with steel foundation piles in long term was predicted with the developed tool. Li and Lai [11] presented several analytical solutions to the heat conduction problem in infinite or semi-infinite anisotropic media with line, spiral-line or cylindrical-surface heat sources. These solutions were applied to the analysis of heat transfer by borehole and pile ground heat exchangers. Katsura et al. [12] developed a tool which can evaluate performance of GSHP systems with multiple ground heat exchangers on a short term hourly basis with random layouts, including ground temperatures.

Loveridge and Powrie [13] presented new pile temperature response functions (G-functions) which were designed to include the transient response of the pile concrete. As an update of the previous works of Eskilson, the G-functions took into account typical pile heat exchanger geometries. By means of numerical analyses, Loveridge and Powrie [14] found that the key controlling factors for pile concrete thermal resistance are the thermal conductivity of the concrete, the number of heat exchange pipes and the amount of concrete cover to those pipes. Zarrella et al. [15] presented a new model to analyze energy piles with n-U-tubes and helical pipe. The numerical models consider the axial heat conduction in the ground and pile.

Zarrella and De Carli [16] presented a numerical model CaRM-He to analyze the thermal behavior of the helical heat exchanger of short length. Gustafsson et al. [17] studied the common U-pipe arrangement in a groundwater-filled borehole heat exchanger by a three-dimensional steady-state CFD model. Go et al. [18] suggested a new model for the borehole thermal resistance of coil PHC pile. They examined the effect of groundwater advection on the long-term ground temperatures and found groundwater advection attenuates the average temperature rise in the ground.

The heat transfer in GHEs is usually analyzed in two separated regions: the soil region outside the borehole and the region inside the borehole. The heat conduction must be treated as a transient process in the soil region, while the thermal process in the borehole is commonly approximated as a steady-state heat transfer due to the much smaller dimensions and heat capacity.

Energy pile is a special vertical heat exchanger. The diameter of the pile is usually much larger and the depth is shorter than those of vertical boreholes. Since the energy pile has such particularity the transient heat transfer period is much longer than that in vertical borehole. Thus the error would be large if the conventional model is still used which assumes the heat transfer process in the borehole is a steady one. Until now the suitable analytical model for the energy pile, especially for the short-term unsteady behaviors inside borehole, is less and need to be studied.

This paper presents the development of a new composite cylindrical model for energy pile. The main advantage of the model is that it can reflect the transient heat transfer in the early period of thermal response for energy piles. So it provides a suitable method for the analysis of performance, especially the simulation tool of TRT in energy pile. First, the composite cylindrical model for energy pile was developed while the heat capacity of the pile was considered in the model. Then the analytical model was validated through comparison of the results of the model and that of a 3-D numerical analysis. And the 3-D numerical model had been verified in a TRT. Next the performance of some energy piles with different layout of heat exchanger was analyzed. Finally the model was applied to an engineering case of energy pile. The results of mean water temperature calculated by composite cylindrical model and that by line source model were also compared and the advantages of the developed model were discussed.

2. Development of the composite cylindrical model

2.1. The composite line source model

Bixel and van Poollen [19] developed a composite line-source model. As shown in Fig. 1 [20], the U tube with two legs was replaced by a single tube with an equal borehole resistance. The effective diameter of the single tube was d_w. The thermal resistance of the tube wall and the thermal resistance between the fluid and inside wall of the tube which were relatively small were merged with the borehole resistance corresponding to the effective diameter d_w. The treatment of double U tube was similar to that of single U tube.

The borehole resistance can be interpreted the comprehensive thermal resistance between inside wall of tube and borehole wall [21].

$$R_b = \frac{1}{2\pi\lambda_g} \ln \frac{d_b}{d_w} \tag{1}$$

On the basis of line source theory [22], the soil temperature is written as:

$$T(r,\tau) - T_0 = \frac{q}{4\pi\lambda} \int_{r^2/4\alpha\tau}^{\infty} \frac{e^{-u}}{u} du = \frac{q}{4\pi\lambda} E_1 \left[\frac{r^2}{4\alpha\tau} \right] \tag{2}$$