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Influences of ground saturation and thermal boundary condition on energy harvesting using geothermal piles

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ABSTRACT

The paper highlights an important distinction between heat transfer mechanism in dry and saturated soil. The effects of two site-specific conditions (e.g., soil saturation and thermal insulation at ground surface) on pile-soil heat exchange and ground temperature response are investigated through a series of thermal tests under laboratory-controlled conditions. Soil temperature data recorded during model tests are compared with soil thermal response predicted using a numerical pile-soil heat exchange model. Moreover, effective thermal conductivity values for the pile-soil system are derived employing equivalent line source model that utilizes circulation fluid temperature recorded during the laboratory tests. Such derived effective thermal conductivity values are compared with soil thermal conductivity values obtained from element thermal conductivity tests. Analysis of recorded soil temperature data and readings from pore pressure transducers during the thermal loading tests identify the possibility of temperature-induced pore fluid flow and convective heat transfer in saturated soil surrounding a ground heat exchanger.

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1. Introduction

Near-surface geothermal energy harvesting through ground-coupled heat exchangers is an innovative way to partially meet energy demand of and foster sustainable energy use in residential and commercial buildings. Different forms of ground heat exchangers (GHEs) are used in practice (closed- and open-loop systems with horizontal and vertical loops); their suitability depends on local geology, climate, heat exchange demand and the type of application [1–8]. Embedment of heat exchange loops within foundations and other structures in contact with ground (e.g., retaining and diaphragm walls, basement slabs and walls, tunnel lining) helps in reducing the installation cost of shallow geothermal heat exchange systems [9]. Piles with embedded heat-exchange loops have been successfully employed as building foundations in different countries in Europe (e.g., Germany, Austria, Switzerland), U.K., Australia and Asia (e.g., China, Japan) [9–13]. The use of such piles, commonly referred to as geothermal piles, has also drawn significant attention of the building and construction industry in U.S.

Fitting to their increasing popularity, geothermal piles have undergone significant research and development in recent years [14]. Many of these studies focused on different aspects of pile-soil heat exchange because quantification of time-dependent evolution of pile and soil temperature due to thermal loading is critical to assess the amount, rate and efficiency of energy harvesting and to ensure structural integrity of geothermal piles [15–24]. Heat exchange analysis for other forms of GHEs (e.g., geothermal borehole, horizontal ground loop) are also common in literature [25–28]. A bulk majority of such thermal analysis of GHEs consider heat conduction as the primary heat transfer mechanism within the ground. Nevertheless, published research on heat transport in porous media indicates that free (or natural) convection and temperature-induced pore fluid flow may as well play roles in heat transfer within saturated and partially-saturated porous media [29–34]. Hossain and Wilson [35], and Hossain et al. [36] studied natural convection flow induced by non-isothermal boundaries. The effects of ground water flow (advection) and heat convection on thermal response of ground surrounding the heat exchangers have also been reported in the literature [37–42]. In recent studies, Go et al. [43], and Choi and Ooka [44] investigated the effects of rainfall infiltration and natural convection on heat transfer in saturated and unsaturated porous medium. These studies identified the need for consideration of free convection in heat exchange analysis and thermo-hydro characterization of ground for improved performance assessment of GHEs. From a series of soil-column (1.2-m-long and 110-mm-diameter) tests with a heating source placed at one end of the column, Chen et al. [45] reported evolution of volumetric water content with heat transport in the moist soil.

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Change in soil moisture content during laboratory measurement of soil thermal response has also been reported in literature [46–48].

From past studies, it is evident that temperature-induced changes in soil moisture content may trigger complex changes in heat and fluid flow characteristics of ground surrounding the geothermal heat exchangers, and such change in thermo-hydro characteristics will eventually affect thermal performance of GHEs. However, the influences of free convection and coupled heat and moisture movement on operative thermal conductivity of a GHE-soil system has not been reported in the literature. Several research investigated performance of geothermal piles and other forms of GHEs through analytical and numerical models and field- and laboratory-scale tests; nonetheless, direct comparison of theoretical predictions and recorded data are scarce in literature. This is due to uncertainties (due to inherent variability and lack of measured data), challenges (associated with reproducing test conditions in the simulation) and limitations (due to mismatch between practical test condition and model assumptions) associated with the assignment of field boundary conditions and values of input parameters in the theoretical model. Moreover, field tests are site-specific and are often subjected to uncertainties that are difficult to quantify and incorporate in the numerical model. In contrast, material properties and boundary conditions can be measured and ascertained, under laboratory-controlled environment, with relative ease. Hence, a series of fully controlled laboratory tests can be advantageous over field tests for better understanding of the physical processes involved in GHE-soil heat exchange.

This paper demonstrates, using data gathered from laboratory-controlled thermal performance tests on a model geothermal pile, the effects of two site-specific conditions – soil saturation and thermal insulation at ground surface – on pile-soil heat exchange, ground temperature response and operative thermal conductivity of a GHE-soil system. The paper also compares ground thermal response gathered from laboratory thermal tests on and numerical simulations of a model geothermal pile installed in both dry and saturated sand. The objective is to gather and provide evidence of the existence of free convection and temperature-induced fluid flow in saturated granular medium surrounding GHEs. Pore pressure fluctuation data recorded during thermal operation of a model geothermal pile installed in saturated sand are reported. This is a unique contribution, for that it provides evidence of temperature-induced pore pressure development and dissipation (which in turn indicates to the possibility of temperature-induced pore-scale fluid flow in granular medium) in saturated sand surrounding a heat exchanger pile. Moreover, data gathered during the thermal tests on the model pile allows quantification of operative values of thermal conductivity of the GHE-soil system for both dry and saturated test bed condition.

2. Thermal loading tests on model geothermal pile

We performed a series of laboratory-controlled thermal performance tests on a model concrete pile (0.1-m-diameter, and 1.38-m-long) installed in dry and saturated sand bed. The model geothermal pile was equipped with an embedded U-shaped poly-vinyl chloride (PVC) circulation tube with inner and outer diameters, respectively, equal to 12 and 15.8 mm. A constant-temperature water bath circulated heat carrier fluid (1:1 laboratory standard mixture of ethylene glycol and distilled water) through the circulation tube embedded within the model pile (Fig. 1a). The test bed of standard F50 Ottawa sand was prepared within a large soil tank (1.83 × 1.83 × 2.13 m) through air pluviation. We decided the tank dimensions based on a few preliminary numerical analyses such that thermal loading on the model pile could be continued for at least a few days (7 and 4 days, respectively, for dry and saturated sand) before the occurrence of any temperature change at the tank boundaries. The air pluviation technique was designed and calibrated to maintain uniformity and to achieve the desired relative density across the sand bed [20]. Upon reaching the desired sand layer thickness (= 0.61 m from the tank bottom), a clamp arrangement held the model pile in position and we continued sand raining to achieve pile embedment depth $L_p = 1.22$ m. Kramer et al. [20] presents vivid descriptions of the test setup, sand bed preparation and custom-built thermal conductivity test setup that we used to determine the thermal conductivity values for sand and concrete. Note that the thermal conductivity values obtained from

Nomenclature

A	Area (m^2)
C_p	Specific heat (J kg^{-1} K^{-1})
D_R	Relative density (%)
Fo	Fourier number (–)
h	Convective heat transfer coefficient (W m^{-1} K^{-1})
K	Hydraulic conductivity (m s^{-1})
k	Thermal conductivity (W m^{-1} K^{-1})
k_{eff}	Effective thermal conductivity of GHE-soil system (W m^{-1} K^{-1})
L_p	Pile length (m)
L_H	Heat source length for use in the line source model (m)
n	Porosity
$\dot{m}$	Mass flow rate (kg s^{-1})
P	Power output (W)
r	Radial coordinate (m)
r_t	Radius of circulation tube (m)
r_p	Pile radius (m)
t	Time (s)
T	Temperature (°C)
T_a	Ambient air temperature (°C)
T_{avg}	Temperature in the medium above ground surface (°C)
T_f	Fluid temperature (°C)
T_g	Ground temperature (°C)
T_{in}	Temperature at circulation tube inlet (°C)
T_m	Mean temperature of circulation fluid (°C)
T_{out}	Temperature at circulation tube outlet (°C)
ΔT	Difference in fluid temperature between inlet and outlet points of the circulation tube (°C)
v	Circulation velocity of the heat carrier fluid (m s^{-1})
z	Depth (m)

Greek symbols

α	Thermal diffusivity (m^2 s^{-1})
κ	Permeability (m^2)
$\Delta\theta$	Initial temperature difference between fluid inlet point and ground (°C)
ρ	Mass density (kg m^{-3})
λ	Slope of mean circulation fluid temperature versus ln(t) plot
μ	Dynamic viscosity (Pa s)
ν	Kinematic viscosity (m^2 s^{-1})

Subscripts

c	Concrete
f	Fluid
g	Ground
p	Pile
s	Soil
t	Circulation tube

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