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An experimental and numerical approach to derive ground thermal conductivity in spiral coil type ground heat exchanger

Seok Yoon [a,1], Seung-Rae Lee [a,*], Gyu-Hyun Go [a], Skhan Park [b]

[a] *Department of Civil and Environmental Engineering, KAIST, Daejeon 305-701, South Korea*
[b] *Research and Development Institute, Lotte E & C, Seoul 137-903, South Korea*

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This paper presents an experimental and numerical study on the evaluation of thermal response test (TRT) results observed in a precast high-strength concrete (PHC) pile and a general conventional vertical type borehole with spiral coil type ground heat exchangers (GHEs). Field TRTs were carried out on a PHC energy pile and a general vertical type borehole, and an equivalent ground thermal conductivity was estimated using the spiral coil source model. The PHC energy pile and conventional vertical type borehole were numerically modeled using a three dimensional finite element method for the estimation of borehole thermal resistance and the comparison with the TRT results. Based on the results, this paper suggested a method to evaluate the ground thermal conductivity using the infinite line source model and the results were compared with those of the spiral coil source model.

1. Introduction

Among various renewable energy resources, the use of geothermal energy has been regarded to be the most efficient way of space heating and cooling [1]. Geothermal energy has a great potential as a directly usable type of energy, especially in connection with ground coupled or ground source heat pump (GSHP) systems. Hence, GSHP systems combined with various types of ground heat exchangers (GHEs) have been widely applied since early 20th century [2]. Recently, as a multi-purpose vertical GSHP system, an energy pile foundation has been invented and used. It can provide dual functions to buildings: structural foundation function as well as GHE [3,4].

Compared to a general conventional vertical borehole of which length reaches to two or three hundred meters [5], an energy pile foundation has shorter length in a range of several tens of meters at most [6–8]. In Korea, most energy piles have relatively short length of less than 20 m because of the shallow depth of the bedrock location. Therefore, if the same type of heat exchanger (U or multi-U shaped) is used, lower heat exchange capacity is obviously expected in the energy pile because of the smaller heat exchange area. For that reason, to compensate for the shallow installation depth of the energy pile, a spiral coil type GHE can be used to enhance the heat efficiency by increasing flow path of circulating fluid and area for heat exchange with a surrounding grout material [9–11].

The ground thermal conductivity is one of the most important factors in the design process of GSHP systems in conventional vertical type boreholes as well as in energy piles [12–14]. The ground thermal conductivity can be derived simply by applying the infinite line source model to the field thermal response test (TRT) results. However, it is known that it is not accurate to use the infinite line source model in the spiral coil type GHEs [4,9,15]. Therefore, different kinds of analytical models adequate for the spiral coil type GHEs have been introduced. These models are very complicated and make it inconvenient to derive the ground thermal conductivity [4,9,15].

This paper presents in-situ experimental test and numerical study results to derive the ground thermal conductivity used in the design of PHC pile and conventional vertical type borehole. A PHC energy pile with a spiral coil type GHE was installed in Suwon city and a conventional vertical type borehole with a spiral coil type GHE was constructed at Incheon International Airport site in South Korea. Field TRTs were conducted to measure the ground thermal response, and the ground thermal conductivity was derived by using spiral coil source

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[*] Corresponding author. Tel.: +82 42 350 3617; fax: +82 42 350 7200.
E-mail address: srlee@kaist.ac.kr (S.-R. Lee).
[1] Current address: Department of Civil and Environmental Engineering, KAIST, 291, Gwahakro, Yuseong-gu, Daejeon 305-701, South Korea.

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Nomenclature

A	pipe cross section area (m^2)
c	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
d_h	average hydraulic diameter (m)
E_i	exponential integral
f_D	coefficient of friction
h	coil depth (m)
h_p	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
N	number of coil turns
Q	heat injection (W)
q_l	heat rate per length of borehole ($W\ m^{-1}$)
R_b	borehole thermal resistance ($m\ K\ W^{-1}$)
r	radius (m)
r_o	coil radius (m)
T	temperature (K)
T_b	borehole wall temperature (K)
T_f	fluid temperature (K)
$T_{f,av}$	average fluid temperature (K)
T_o	initial ground temperature (K)
T_p	pipe temperature (K)
t	time (s)
t', u'	integral variable
u	vector in x, y, z Cartesian coordinates
x', y', z'	integral variable
Z	wall perimeter of the pipe (m)
Greek letters	
α	thermal diffusivity ($m^2\ s^{-1}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ	density ($kg\ m^{-3}$)
w	wave number (m^{-1})
θ	variation of temperature (K)
ω	wave number (m^{-1})

model [15]. In addition, the PHC pile and vertical type borehole under a field condition were numerically modeled using a finite element method coupled with a computational fluid dynamics (CFD) analysis. With the borehole thermal resistance value obtained by the numerical analysis and analytical solution of a spiral coil type GHE proposed by Park et al. [15], the ground thermal conductivity value derived by the infinite line source model was compared with that estimated by the spiral coil source model.

2. Experimental setup

2.1. Setup of vertical type GHE

In this study, a vertical type borehole with a spiral coil type GHE was installed in a partially saturated landfilled runway area of Incheon international airport in South Korea. The vertical borehole depth is 30 m with a diameter of 300 mm. A PB (polybutylene: manufactured by Aikang Remetech Co. in South Korea) pipe (inner/outer diameter ratio of the pipe = 0.016/0.02 m) was used for the GHE. The spacing of coil is about 6 cm, and the diameter of coil is 28 cm. Fig. 1 shows the spiral coil type GHE which was installed in the borehole and a schematic GHE diagram. Resistance temperature detector (RTD) sensors were installed at inlet and outlet of the ground heat exchanger in the TRT equipment to measure the temperature variation during the TRT. The ground was composed of silt (3.5 m thick), clay (19 m thick), weathered granite soil (12.5 m thick) and weathered rock (from top to bottom). The groundwater table was about at 3.5 m below the ground surface. The N value of Standard penetration test (SPT) was in a range of 9/30–33/30 in the partially saturated landfill ground. Here, N indicates the number of blows (the numerator) required to penetrate to the desired depth in centimeter (the denominator) [16]. Fig. 2 shows drill log of the test site in vertical type GHE. The average void ratio was 0.95 and the water content was between 30 and 35%.

2.2. Setup of energy pile

A field TRT was conducted using a PHC pile at the construction site of the 154 kV Substation in Suwon city. The same size of PB pipe used in the conventional vertical system was also installed at the inside wall of the PHC pile using cement grout. The spacing of coil is 5 cm similar to the conventional vertical system, and the diameter of coil is 22 cm. The cement grout rather than bentonite grout was applied to increase the adhesive force with PHC pile. The grout was cured for more than 28 days. The depth of PHC pile is 12.8 m, and the inner and outer diameters of pile are 245 mm and 400 mm, respectively. The heat exchanger configuration is schematically shown in Fig. 3. The only difference between energy pile and vertical type GHE is to add PHC pile around the borehole. Spacers were used to maintain a constant distance between the pipes to minimize the thermal interference. RTD sensors were also installed at inlet and outlet of the GHE to measure the fluid temperature variation during the TRT. Ground investigation of the test site revealed that the soil was composed of weathered granite soil and soft rock. The SPT results showed that the weathered granite soil is medium-dense to dense with N values ranging from 19/30 to 50/12. The groundwater table was found to be at 4.5 m below the ground surface. Fig. 4 shows drill log of the test site in energy pile.

3. Numerical analysis

A finite element analysis program coupled with a CFD (computational fluid dynamics) module implemented in COMSOL Multiphysics [17] was used in order to simulate the TRTs conducted in the energy pile and vertical type borehole considering the configuration of spiral coil type GHE. The governing equation of the numerical model based on the convection current and conduction is expressed by Eq. (1) [18].

$$\rho A c\frac{\partial T}{\partial t} + \rho c A u\cdot\nabla T = \nabla\cdot A\lambda\nabla T + f_D\frac{\rho A}{2d_h}|u|^3 + Q + Q_{wall} \tag{1}$$

Here, Q refers to the regular heat injection and Q_{wall} refers to the heat source which is formed through the heat exchange across the pipe wall. A is the pipe cross section area available for the flow, T is the temperature, c represents the specific heat capacity, and ρ is the density.