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Thermal transfer behavior in two types of W-shape ground heat exchangers installed in multilayer soils

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Abstract. This paper presents an experimental and numerical study on the evaluation of a thermal response test using a precast high-strength concrete (PHC) energy pile and a closed vertical system with W-type ground heat exchangers (GHEs). Field thermal response tests (TRTs) were conducted on a PHC energy pile and on a general vertical GHE installed in a multiple layered soil ground. The equivalent ground thermal conductivity was determined by using the results from TRTs. A simple analytical solution is suggested in this research to derive an equivalent ground thermal conductivity of the multilayered soils for vertically buried GHEs. The PHC energy pile and general vertical system were numerically modeled using a three dimensional finite element method to compare the results with TRTs'. Borehole thermal resistance values were also obtained from the numerical results, and they were compared with various analytical solutions. Additionally, the effect of ground thermal conductivity on the borehole thermal resistance was analyzed.

Keywords: ground thermal conductivity; borehole thermal resistance; ground heat exchanger; thermal response test; numerical analysis

1. Introduction

Recently, the need for renewable energy sources is constantly increasing with the advent of global warming and the depletion of fossil energy. Geothermal energy has great potential as a directly usable type of energy, especially in connection with ground source or ground coupled heat pump (GCHP) systems, to achieve energy-efficient spaces for cooling and heating (Johnston *et al.* 2011). The GCHP systems use the ground as a heat source or reservoir, as it provides a relatively constant temperature. It releases heat energy during winter, while it absorbs heat energy in summer (International Energy Agency 2010). GCHP systems are available as both open and closed systems. The open system exchanges heat to/from aquifer water, while the closed system exchanges heat to/from the ground by a fluid circulating in heat exchange pipes. The closed system can be largely divided into vertical and horizontal types depending on the way that the exchange pipes are installed. The horizontal system requires the installation of a large number of GHEs parallel to the

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ground surface at a shallow depth, and this type requires larger land space (Park *et al*. 2013). The vertical system, in which the GHEs are installed vertically into the ground to a depth of tens or hundreds of meters, can involve high initial construction costs.

As an alternative, the usage of piles under a raft foundation as energy piles has recently become more common (Brandl 2006, Cui *et al*. 2011, Choi *et al*. 2012). It has the advantage of a relatively low initial investment cost with little additional installation cost during the construction process. Comparing to a conventional vertical-type GHE system, the energy pile has relatively larger diameter and shorter length. In Korea, most energy piles are shorter than 20 m due to the shallow depth of the bedrock in many locations.

Some of the current research on energy piles has focused on the development and performance evaluations of ground heat exchangers using PHC pile foundations (Hamada *et al*. 2007), and analyses of their thermal behavior (Brandl 2006). Some of the characteristics of GHEs, such as the pipe configurations including pipe types, the thermal properties of the pipes used, and the operating conditions, can affect the performance of the energy piles (Choi *et al*. 2011, Pahud *et al*. 1996, Lee 2011). Gao *et al*. (2008a) studied the heat exchange rates for various GHEs installed in energy piles using experimental and numerical analyses. They showed that for energy piles with the length of 20~30 m, the W-type GHE with a moderate medium flow rate (0.342 m^3/h) appeared to be the most efficient. Recently, coil type GHE is being increasingly used because spiral coil configuration has the advantage of larger heat transfer area (Park *et al*. 2013).

The ground thermal conductivity and the borehole thermal resistance are the most important factors in the design of a GCHP system either for conventional vertical GHEs or for energy piles. The ground thermal conductivity and borehole thermal resistance are affected by many factors, such as the porosity, particle size distribution and water content of the soil and the in-situ pressure (Park *et al*. 2012). For vertically buried GHEs, the GHE or piles are normally penetrated through several layers of soils. Most available GHE models are developed for the case of single layer of soil in which the GHEs are modeled by a line source heat (Ingersoll *et al*. 1954). Therefore, comprehensive coupled finite element analysis is required to analyze the heat exchange behavior of GHEs installed in multilayered soils. Yoon *et al*. (2012) proposed an equivalent heat conductivity model for the multilayered soils for vertically buried GHEs.

This paper presents in-situ experimental tests and numerical case studies to investigate the ground thermal behavior and borehole thermal resistance for PHC piles and conventional GHEs. A PHC energy pile with a W-type GHE was installed in Suwon city and a conventional vertical GHE with a W-type GHE was constructed at Incheon International Airport site, which is in the northwestern corner of South Korea (see Fig. 1). Field TRTs were carried out to measure the ground thermal conductivity and the results were compared with an analytical solution. In addition, the PHC pile and vertical GHE under a field ground condition were numerically modeled using a finite element method coupled with a computational fluid dynamics (CFD) analysis. The borehole thermal resistance values were also calculated by a numerical analysis and the results were compared with various analytical solutions. Finally, the effect of the ground thermal conductivity on the borehole thermal resistance was assessed by means of a numerical analysis.

2. Experimental setup

2.1 Setup of energy pile

A field TRT was conducted using a PHC pile at the construction site of the 154 kV Substation

Fig. 1 Location of GHEs installed in Suwon and Incheon

in Suwon city. A polybutylene pipe (the inner/outer diameter ratio of the pipe = 0.016/0.02 m) was installed on the inside wall of the PHC pile using cement grout with a cement-to-water ratio of 0.5. The grout was cured for more than 28 days. The heat exchanger configuration is shown in Fig. 2. Spacers were installed to maintain a constant distance between the pipes to minimize thermal interference, as shown in Fig. 3(a). Temperature sensors were installed at inlet and outlet of the heat exchanger, and inside the grout as well to measure the temperature variation of the grout during the thermal response test. Resistance temperature detectors (RTD) were installed at the inlet and outlet of the pipe within the thermal response equipment, and FBG (Fiber Bragg Grating) optical multiplexing sensors were installed in the grout inside the pile (Yoon *et al*. 2011). Table 1 summarizes the specifications of the TRT equipment. Ground investigation of the test site revealed the soil was composed of weathered granite soil and soft rock. Standard penetration test (SPT) showed that, the weathered granite soil is medium-dense to dense with *N* values ranging from 19/30 to 50/12, which indicate the number of blows (the numerator) required to penetrate to the desired depth in centimeter (the denominator). The groundwater table was found to be at 4.5 m below ground surface, and no noticeable flow of ground water was observed during the tests. Figs. 3(a)-(f) show the major construction process during the installation of the energy pile before conducting the thermal response test.

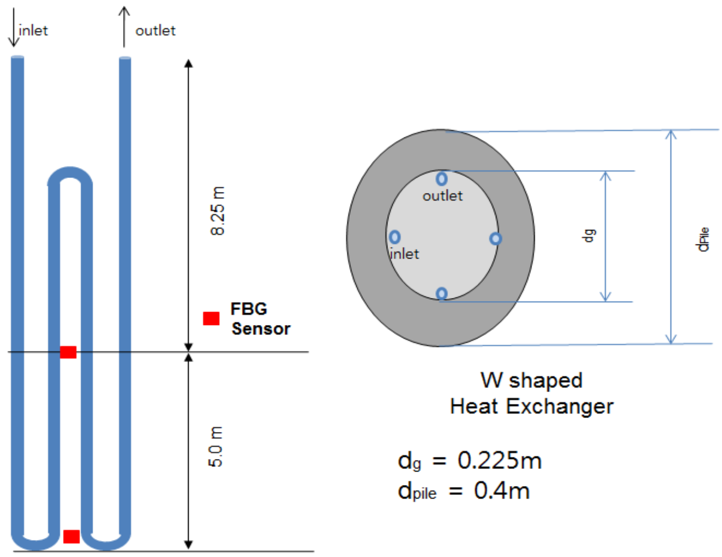


Fig. 2 Dimensions of energy pile with W shape GHE

(a) Production of GHE (b) Installation of GHE into piles (c) Attachment of sensors

(d) Cement grouting (e) Heat conservation of pipes (f) Connection to TRT equipment

Fig. 3 Construction process of energy pile

Table 1 TRT equipment

Item	Specification
Heater	Capacity 5kW
Water Tank	20L (SUS 304)
Flow rate range	2～20 lpm
Pump	40 m head, 100 lpm
Sensor	RTD

2.2 Setup of vertical-type GHE

In this study, a general vertical-type GHE, a grouted vertical borehole used as a GHE (with W loops instead of commonly used U loops), was also installed in a partially saturated landfilled runway area of Incheon international airport. The borehole is 50 m deep with a diameter of 150 mm. W-type polybutylene pipe (inner/outer diameter ratio of the pipe = 0.016/0.02 m) was used for the GHE, the same shape as used in the energy pile. The GHE configuration is shown in Fig. 4. 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 level was at 3.5 m below the ground surface. The SPT *N* value range was 9/30~33/30 in the partially saturated landfill ground. The average void ratio was 0.95 and the water content was between 30~35%.

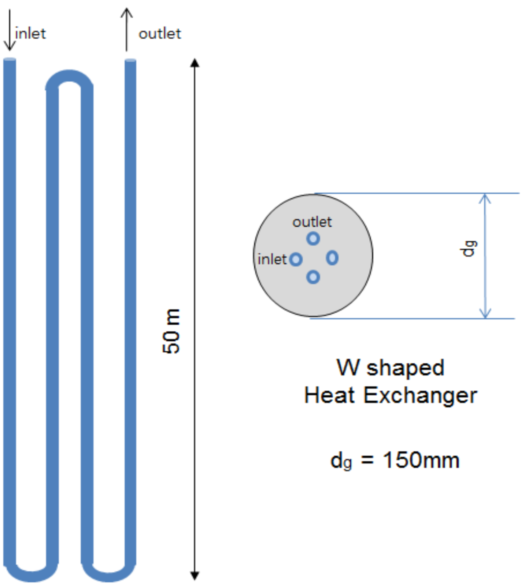


Fig. 4 Dimensions of W-shaped vertical GHE

3. Numerical simulation of thermal response test

In this research, a finite element analysis program coupled to a CFD module by COMSOL Multiphysics was used to analyze the thermal behavior of the energy pile and vertical GHE according to the heat exchanger form and arrangement. The governing equation of the numerical model based on the convection current and conduction is expressed by Eq. (1) by Incropera *et al.* (1996).

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

Here, Q refers to the regular heat injection and Q_{wall} refers to the heat source formed through the heat exchange across the pipe wall. The term $f_D \frac{\rho}{2d_h}|u|^3$ represents the thermal loss caused by viscosity. C_p represents the specific heat capacity, and ρ is the density. Also, d_h is the average hydraulic diameter, f_D (non-dimensional) refers to the coefficient of friction, and u represents the tangential velocity. A computational fluid dynamics (CFD) analysis is performed with a Newtonian fluid model (Eq. (1)) with the dynamic properties of a certain fluid, after which the result can be coupled with the heat conduction equation of a solid mass through Eq. (2).

$$Q_{wall} = hZ_{eff}(T_{ext} - T_{fm}) \tag{2}$$

Here, T_{ext} is the temperature of the pipe wall, which comes from the heat conduction equation of the solid mass; and T_{fm} is the fluid temperature in the pipe. Also, hZ_{eff} is the effective value of the heat transfer coefficient and Z is the wall perimeter of the pipe. Fig. 5 shows the finite element model for the thermal response test simulation. The form and arrangement of the energy pile (Suwon city) and vertical GHE (Incheon city) are shown in Figs. 2 and 4, respectively.

The ground condition at the test site in Suwon city is separated into unsaturated and saturated layers based on the underground water level, and the pile's lower half is in the rock layer. The thermo-physical properties used in the numerical analysis are shown in Table 2. The thermal conductivity of soil 1, which is the soil above ground table, was measured using a non-steady-state probe TP-08 manufactured by Hukseflux. The thermal conductivity of the soil below ground water table, soil 2, was determined using the thermal conductivity equation for decomposed granite soil according to the on-site moisture content and unit weight proposed by Park *et al.* (2012). Also, a value of 3.24 W/m·K is assumed for the thermal conductivity for the soft rock (Park *et al.* 2012). The material properties of the cement grout, PHC pile, PB pipe, and circulating water were referred from previous studies (Jeong *et al.* 2010).

Table 3 also shows the thermo-physical properties used in the numerical analysis in Incheon city. As the ground was mainly composed of weathered granite soil and weathered rock, the thermal conductivity of the rock was assumed to be approximately 2.5 W/m·K (Kavanaugh and Rafferty 1997). For the finite element model, a free tetrahedral mesh was used with a maximum element size of 0.590 m and a minimum element size of 0.025 m. On the other hand, the mesh element of the heat exchanger wall surface was formed using the wall layer function built into the Comsol Pipe module rather than creating a direct mesh. The temperature of the circulating water was derived using the function obtained based on the thermal response test data (see Fig. 6).

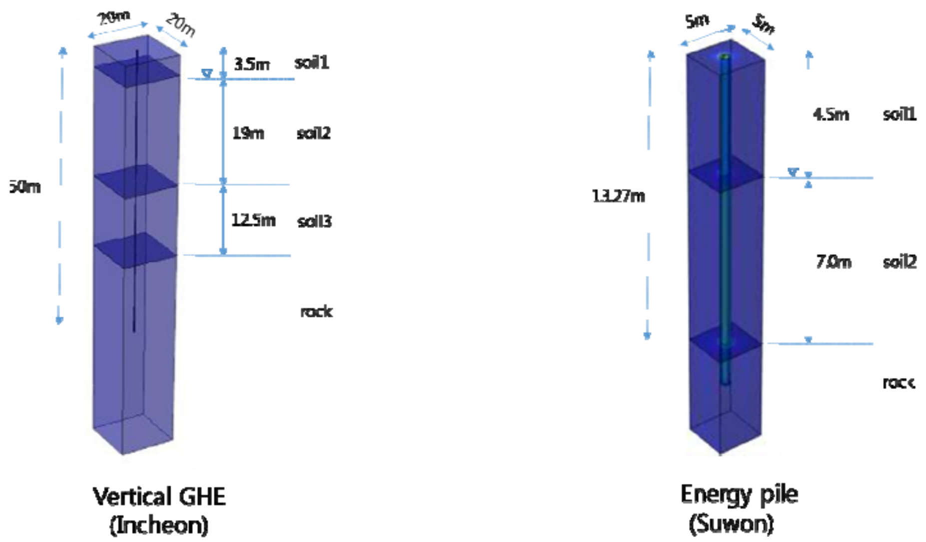


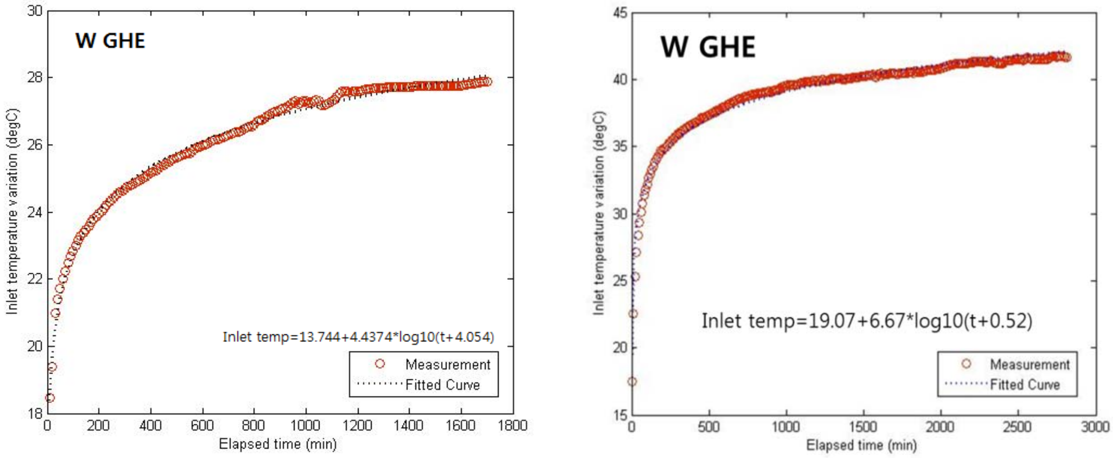
Fig. 5 Finite element model for the numerical simulation

Table 2 Basic thermal properties of materials for numerical simulation of energy pile

Materials	Thermal conductivity (W/m·K)	Specific heat capacity (J/kg·K)	Density (kg/m³)
Soil 1	1.10	1160	1800
Soil 2	2.40	1280	2140
Rock	3.24	823	2640
Cement grout	2.02	840	3640
PHC	1.62	790	2700
Polybutylene pipe	0.38	525	955
Circulating water	0.57	4200	1000

Table 3 Basic thermal properties of materials for numerical simulation of vertical GHE

Materials	Thermal conductivity (W/m·K)	Specific heat capacity (J/kg·K)	Density (kg/m³)
Soil 1	0.21	800	1600
Soil 2	2.30	1300	2100
Rock	2.40	1280	2140
Bentonite grout	2.50	879	2640
Polybutylene pipe	0.9	380	1580
Circulating water	0.38	525	955



(a) Energy pile (Suwon) (b) Vertical GHE (Incheon)

Fig. 6 Comparisons between measured soil temperatures and predictions

4. Analytical solution

4.1 Heat transfer mechanism of GHEs

In the GHE system, heat is extracted from or released to the surrounding ground through the circulating fluid. The heat transfer mechanism of a ground heat exchanger is quite complex and conjugated due to the various heat transfer mechanisms involved inside and outside GHEs. Soil is a multi-phase system involving complex heat transfer mechanisms, but heat transfer in soil occurs mainly through conduction (Brandl 2006), whereby energy is passed from one region of a medium to another by molecular transfer. According to Fourier's law, the heat flux through an arbitrary area (A) during time (t) can be written as

$$q = \frac{Q}{At} = \frac{\dot{Q}}{A} = -\lambda \frac{\partial T}{\partial x} \tag{3}$$

where λ is the thermal conductivity and $\partial T/\partial x$ is the temperature gradient. The GHE can be treated as a line source considering that the radius of the borehole is much smaller than its length. The change in the ground temperature at distance (r) from the line source after a time duration (t) and the constant heat injection rate per active length of the borehole (q) can be approximated by a line-source model (Morgensen 1983).

$$T_{(r,t)} - T_{(t=0)} = \frac{q}{4\pi\lambda}\left(\ln(4\alpha t / r^2) - \gamma\right) \tag{4}$$

In this equation, γ is the Euler constant, which is normally 0.5772, and α is the ground thermal diffusivity. The error can be up to a maximum of 2.5% for $\alpha t/r^2 \geq 20$ and 10% for $\alpha t/r^2 \geq 5$ (Roth *et al*. 2004). By selecting two points on a linear part of the curve of the mean circulating fluid temperature, i.e., the average fluid temperature between the inlet and outlet versus time in semi-natural logarithmic scale under a steady-state condition, the ground thermal conductivity can be approximated using the following equation.

$$\lambda = \frac{Q}{4\pi L}\left(\frac{\ln t_2 - \ln t_1}{T_{f,av,2} - T_{f,av,1}}\right) \tag{5}$$

Here, t_i is the time ($t_2 > t_1$) and $T_{f,av}$ is the mean fluid temperature between inlet and outlet. Also, using Eq. (4), at time t, the temperature difference (ΔT_{AB}) at two locations A and B at the same depth $h < L$, but at a different distance, for instance r_A and r_B from the center line of the borehole, can be obtained as follows

$$\Delta T_{AB} = \frac{q}{2\pi\lambda}\ln(r_B / r_A) \tag{6}$$

Therefore

$$\lambda = \frac{q}{2\pi\Delta T_{AB}}\ln(r_B / r_A) \tag{7}$$

Selecting point A at the side of the borehole, e.g., point b, when $r_A = r_b$ (r_b is the radius of the borehole), Eq. (7) can be rewritten as

$$\lambda = \frac{q}{2\pi\Delta T_{bB}}\ln(r_B / r_b) \tag{8}$$

4.2 Analytical model of multi-layered soils

Soil in the ground is normally non-homogeneous, especially in the vertical direction along GHEs. An analysis of heat transfer in the multi-layered soil can be achieved using a numerical method. In this section, an equivalent thermal conductivity of multi-layered soils will be derived using the line source model to analyze the heat flow in the multi-layered soils. In considering a GHE borehole in two-layered ground soils, the length of the borehole is h_1 in the top layer and h_2 in the bottom layer. Select two points, P_1 and P_2, from each layer of the soil with the same distance R from the center line of the borehole, as indicated in Fig. 7. Assuming $t = 0$, the temperature T_0 along the borehole is uniform when considering a one-dimensional heat flow in the horizontal direction only. From Eq. (8), we can obtain at the time t the temperature difference between P_1 and the borehole side (ΔT_1) and P_2 and the borehole side (ΔT_2). The temperature difference can be assumed to be constant.

$$\Delta T = \frac{Q_1}{2\pi h_1 \lambda_1}\ln(R / r_b) = \frac{Q_2}{2\pi h_2 \lambda_2}\ln(R / r_b) = const \tag{9}$$

The total heat flux is equal to the sum of each layer.

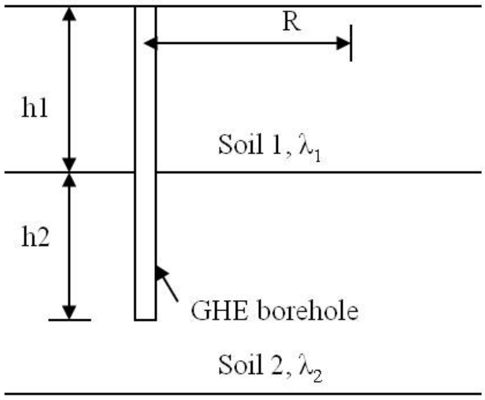


Fig. 7 Indication of a GHE borehole in a two-layered soil system

$$q = q_1 + q_2 \tag{10}$$

Assuming that the equivalent heat conductivity of the two-layered soil within the depth of the borehole is λ_e and substituting Eq. (10) into Eq. (9), we have

$$\Delta T 2\pi h_1 \frac{1}{\ln(R/r_b)} h_1 + \Delta T 2\pi h_2 \frac{1}{\ln(R/r_b)} h_2 = \Delta T 2\pi \lambda_{eq} \frac{1}{\ln(R/r_b)} (h_1 + h_2) \tag{11}$$

Therefore

$$\lambda_{eq} = \frac{(h_1\lambda_1 + h_2\lambda_2)}{(h_1 + \lambda_2)} \tag{12}$$

4.3 Analytical model of borehole thermal resistance

The borehole thermal resistance is one of the key factors in the design process of the GCHP system. The thermal characteristics of a GHE are determined by its effective borehole thermal resistance (R_b) (Florides and Kalogirou 2008). This is defined by the temperature difference between the fluid (T_f) and the borehole wall ($T_{b,av}$) under a steady-state condition divided by heat injection rate per unit length (q), as expressed in Eq. (13).

$$R_b = \frac{T_f - T_{b,av}}{q} \tag{13}$$

4.3.1 Conventional series sum method

In the series-sum model, the borehole thermal resistance for a W-type GHE can be estimated by summing the convective resistance of the fluid R_{fluid} (Eq. (15)), the conductive resistance between the pipe and grout R_{pipe} (Eq. (16)), the thermal resistance of the grout R_{grout} (Eq. (17)), and the thermal resistance of the pile R_{pile} (Eq. (18)), as depicted in Eq. (14). In a general vertical GHE, the thermal resistance of the pile is excluded.

$$R_b = R_{fluid} + R_{pipe} + R_{grout} + R_{pile} \tag{14}$$

$$R_{fluid} = 0.25 \cdot \frac{1}{\pi d_i h_i}, \quad \text{where } h_i = \frac{0.023\,\text{Re}^{0.8}\,\text{Pr}^n\,\lambda_f}{d_i} \tag{15}$$

$$R_{pipe} = \frac{\ln(d_o / d_i)}{8\pi\lambda_p} \tag{16}$$

$$R_{grout} = \frac{1}{2\pi\lambda_g}\ln\frac{d_g}{d_e} \tag{17}$$

$$R_{pile} = \frac{1}{2\pi\lambda_{pile}}\ln\frac{d_g}{d_{pile}} \tag{18}$$

Here, d_o is the outer diameter of the pipe, d_i is the inner diameter of the pipe, d_e is the equivalent diameter of the pipe, d_g is the grout diameter (i.e., the inner diameter of the pile), d_{pile} is the outer diameter of pile, λ_p is the thermal conductivity of the pipe, λ_g is the thermal conductivity of the grout, λ_{pile} is the thermal conductivity of the pile and h_i is the convective heat transfer coefficient of the fluid circulating in the pipe. Re is the Reynolds number of the circulating fluid, Pr is the Prandtl number, n = 0.4 for heating and n = 0.3 for cooling, and λ_f is the thermal conductivity of the fluid. In a vertical-type GHE, d_g becomes the diameter of the borehole as the pile is not considered.

The thermal resistance of the grout is the largest factor in the overall borehole resistance, whereas the fluid resistance contributes less than one percent to the overall steady-state borehole resistance for a turbulent flow (Young 2001). Therefore, an exact estimate of the grout resistance is very important for a reliable calculation of the borehole thermal resistance. For the calculation of the grout resistance, various formulas have been proposed, such as Eqs. (19) and (20). Shonder and Beck (1999) applied $\sqrt{n}d_0$ as the equivalent diameter (d_e), with n being the number of pipes. Eq. (19) used to be referred to as the equivalent diameter (EQD) method when calculating the thermal resistance of grout.

$$R_{grout} = \frac{1}{2\pi\lambda_g}\ln\frac{d_g}{d_0\sqrt{n}} \tag{19}$$

$$R_{grout} = \frac{1}{\lambda_g \beta_0 (d_g / d_0)^{\beta_1}} \tag{20}$$

However, the EQD model oversimplifies multi-legged or coaxial heat exchange pipes by considering them to be a single pipe. Hence, if the geometry of the pipe arrangement is complex or asymmetric, the above model may not give a reasonable estimation of the borehole thermal resistance. On the other hand, Remund *et al*. (1999) considered the shank distance between the pipe legs as an important factor for an estimation of the thermal resistance; they introduced shape factors β_0 and β_1, as presented in Table 4, for which the borehole configurations corresponding to cases A, B, and C are shown in Fig. 8. Therefore, Eq. (20) was known as the shape factor (SF) method.

4.3.2 Multipole method

A multipole method to compute the conductive heat flows to and between pipes in a borehole is used to estimate the borehole thermal resistance (Bennet *et al*. 1987). Here, the method was extended to the case of a composite region such as the grout and surrounding soil. Once the pipes are imbedded inside the borehole with an internal boundary at the borehole wall, the thermal resistance channel will be generated in a steady state. It is composed of two different types of thermal resistance: the thermal resistances between the pipes and the borehole and the resistance between two pipes. As the pipe's numbers increase (or as the number of sources increases) the thermal resistance channel becomes more complex and it becomes more difficult to account for the thermal channel. However, the multipole method provides a quick and accurate way to obtain the thermal resistance using a well-established computer program, e.g., EED (Earth Energy Designer). As depicted in Eq. (21), the borehole resistance defines the relationship between the heat flow rate and the fluid temperature.

Table 4 Shape factors for various configurations

Type	Configuration	β_0	β_1
	A	27.683	-0.9411
W type	B	21.359	-0.6031
	C	25.518	-0.3921

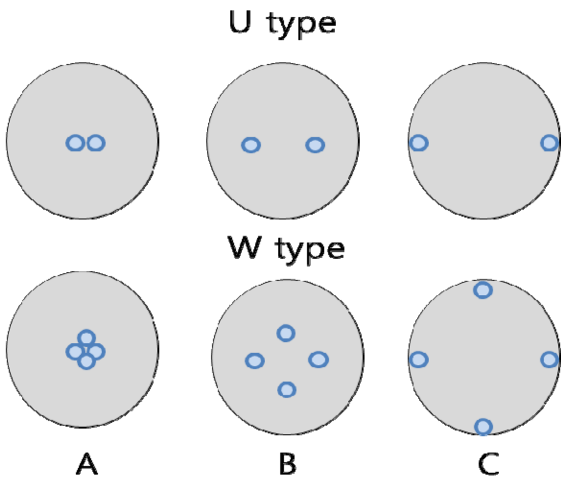


Fig. 8 Locations of GHEs in boreholes

$$T_{fn} = T_{b,av} + \sum_{n=1}^{N} q_n \cdot \hat{R}^o{}_{m,n} + \mathrm{Re} \cdot \left[\sum_{\substack{n=1 \\ m \neq n}}^{N} \sum_{j=1}^{J} P_{n,j} \cdot \left(\frac{r_{pn}}{z_m - z_n} \right)^j + \sigma \cdot \sum_{n=1}^{N} \sum_{j=1}^{J} P_{n,j} \cdot \left(\frac{r_{pn} \cdot \overline{z_m}}{r_b^2 - \overline{z_m} \cdot z_n} \right)^j \right] \quad (21)$$

In this equation, j denotes the order of the multipoles, J is the number of multipoles, N is the number of pipes in the borehole, $T_{b,av}$ is the average borehole wall temperature, T_{fm} is the fluid temperature in pipe m, q_n is the heat flux per unit length of pipe n, λ_g is the grout thermal conductivity inside the borehole, λ is the ground thermal conductivity outside the borehole, $P_{n,j}$ is the strength of the multipole factor, r_b is the borehole radius, $r_{p,n}$ is the outer radius of pipe n, and z represents the complex coordinate as $x + yi$. In the energy pile system, r_b is the outer radius of the pile and the radius of the grout in the general vertical-type GHE. Here, σ is a dimensionless parameter for the two thermal conductivities that can be defined by Eq. (22).

$$\sigma = \frac{\lambda_g - \lambda}{\lambda_g + \lambda} \quad (22)$$

Eq. (23) represents the thermal resistance between the pipe and the borehole wall, while Eq. (24) is used to determine the thermal resistance between two pipes. Also, Eq. (24) is the sum of the thermal resistance of the pipe wall and the fluid boundary layer. Like the second formula in Eq. (25), the thermal resistance is used as the dimensionless quantity β_m, which takes any non-negative value such that $0 \leq \beta_m \leq \infty$. Next, the ultimate borehole resistance is finally obtained by the superposition of each component. Thus, once the borehole resistance is determined, the fluid temperatures can be estimated with a given borehole wall temperature.

$$\hat{R}^o{}_{m,n} = \frac{1}{2\pi\lambda_g} \left\{ \beta_m + \ln\left(\frac{r_b}{r_{pm}} \right) + \sigma \cdot \ln\left(\frac{r_b^2}{r_b^2 - r_m^2} \right) \right\} \qquad m = 1, \ldots, N \quad (23)$$

$$\hat{R}^o{}_{m,n} = \frac{1}{2\pi\lambda_g} \left\{ \ln\left(\frac{r_b}{r_{mn}} \right) + \sigma \cdot \ln\left(\frac{r_b^2}{\left| r_b^2 - z_n \overline{z_m} \right|} \right) \right\} \qquad \begin{matrix} m \neq n \\ m, n = 1, \ldots, N \end{matrix} \quad (24)$$

$$\begin{aligned} R_{pm} &= \frac{1}{2\pi\lambda_p} \cdot \ln\left(\frac{r_{pm}}{r_{pm} - d_{pw}} \right) + \frac{1}{2r_{pm} \cdot h_p} \\ \beta_m &= 2\pi\lambda_g R_{pm} \end{aligned} \quad (25)$$

Here, $\hat{R}^o{}_{m,n}$ is the borehole thermal resistance when $J = 0$, R_{pm} denotes the thermal resistance of pipe m, and d_{pw} is the thickness of the pipe wall. Also, h_p is the convective heat transfer coefficient by Rohsenhow *et al*. (1985).

5. Result and discussion

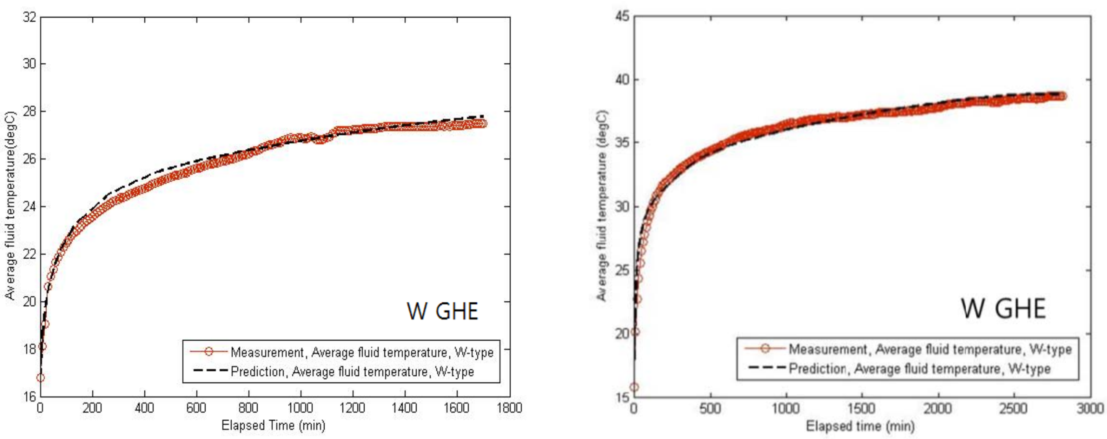
5.1 Comparion of TRTs and simulation results

TRTs were conducted on the energy pile in Suwon and the vertical GHE in Incheon. The TRT in the energy pile was performed for 30 hours. The temperatures of the circulating water in the inlet and outlet of the GHE and the grout were measured at 10-minutes intervals. Generally, for the closed vertical type, the thermal response test must continue for more than 48 hours. However, in this experiment, the temperature of the circulating water reached almost a steady state within 30 hours; therefore, the test was conducted for 30 hours. The initial temperature of the ground was 16.8°C, and this reading was obtained with a no-heating-load operation for the initial 30 minutes before the heater was used. The average flow rate was 16 *lpm* and the temperature difference during the TRT between the inlet and the outlet was 0.75°C. Also, the average fluid temperature distribution of the inlet and the outlet was between 16.80 and 27.52 °C during the TRT. A TRT was also conducted on the vertical GHE in Incheon, lasting 48 hours. Heat-free water circulation was performed for 30 minutes to equalize the soil and circulating fluid temperatures. The initial temperature of the ground after the heat-free water circulation was 15.85°C and the average fluid temperature distribution of the inlet and the outlet was between 15.85 and 38.63°C during the TRT. Also, the average flow rate was 7.1 *lpm* and the temperature difference between the inlet and the outlet was 6.05°C during the TRT. Additionally, both of the two site conditions were simulated and calculated using a numerical model, and the results were compared with the experimental results.

5.2 Ground thermal conductivity and borehole thermal resistance

Fig. 9 shows the test results and the numerical analysis values of the circulating fluid temperature with respect to time. The experimental values and numerical analysis predictions are in good agreement. Using the simplified equation of the infinite line source model of Eq. (5), the ground thermal conductivity was estimated. These results were 2.32 W/m·K and 2.15 W/m·K for the energy pile in Suwon and the vertical GHE in Incheon, respectively. The data for initial 9 hours for the energy pile and 12 hours for the vertical GHE were excluded to choose linear portion of Eq. (5). The equivalent thermal conductivity using Eq. (12) was also determined to be 2.07 W/m·K and 2.24 W/m·K for the energy pile in Suwon and the vertical GHE in Incheon, respectively. The ground thermal conductivity values obtained from the TRTs were found to be in good agreement with the actual equivalent values, varying by approximately 5~10%. Thus, the experimental results agree well with the analytical solution by Eq. (12) suggested by this research. As shown in Fig. 2, FBG sensors were attached to measure the grout temperature during the TRT in the energy pile. Fig. 10 shows the temperature variation of the grout during the TRT in the energy pile. Although the temperature value at a depth of 8m showed a difference of about 0.5°C between the experimental and numerical results, the other depth test measurement value was very similar to that of the numerical analysis. This occurred most likely because the temperature sensor at a depth of 8m for the W-type was not installed at a precise location. Also, after acquiring the pile wall temperature value under the steady-state condition, as shown in Fig. 11, through a numerical analysis, Eq. (13) was used to calculate the borehole thermal resistance, and the values were 0.118 m·K/W and 0.209 m·K/W for the energy pile in Suwon and the vertical GHE in Incheon, respectively. Although these results were not obtained from accurate experiments as temperature sensors were not installed on the borehole wall surface, when considering that the measured values of the circulating water temperature and grout temperature are consistent with the numerical analysis values, the borehole thermal resistance value obtained through the numerical analysis using the borehole wall temperature is demonstrated to be similar with the actual experimental value. FBG sensors were installed to measure the grout temperature in the energy pile, but theywere not applied to the vertical-type GHE due to the construction condition. The borehole thermal resistance values from the numerical results were compared to those of various borehole thermal resistance models. In the energy pile system, there is other resistance media, i.e., the PHC pile as well as the pipe and grout. Therefore, the equivalent thermal resistance of the grout could be considered, as depicted in Fig. 12. From Fig. 12, the equivalent thermal conductivity can be derived via Eq. (26), as the portion of the grout is composed of the grout itself and the pile. In this equation, r_g is the radius of the grout, and r_{pile} is the outer radius of the pile.

$$\lambda_{eq} = \frac{\left(r_g + r_{pile}\right)}{r_g/\lambda_g + r_{pile}/\lambda_{pile}} \tag{26}$$



(a) Energy pile (Suwon) (b) Vertical GHE (Incheon)

Fig. 9 Temperature variation of fluids

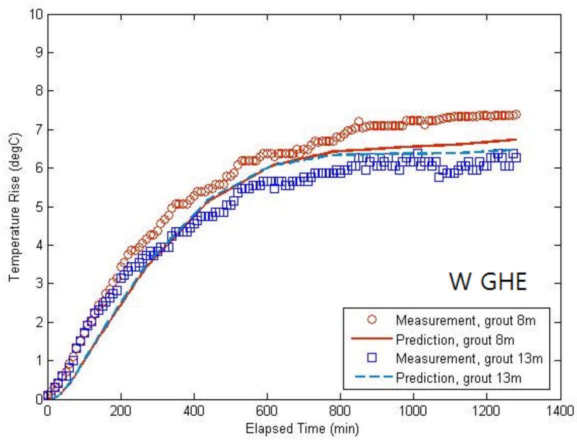
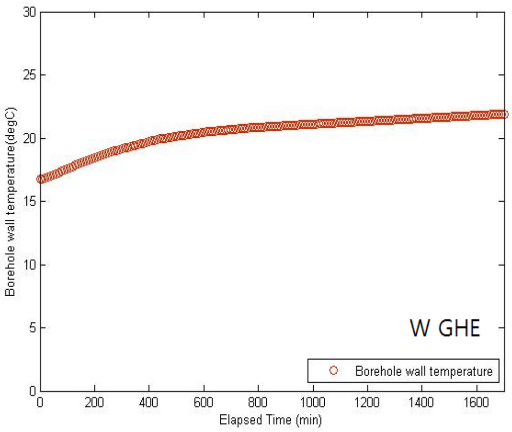
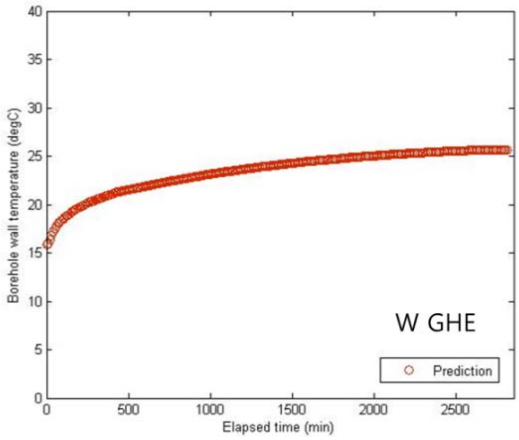


Fig. 10 Temperature variation at the grout in the energy pile



(a) Energy pile (Suwon)



(b) Vertical GHE (Incheon)

Fig. 11 Temperature variation at the borehole wall

As the W-type GHE in the energy pile was installed quite close to the inner wall of the pile, B case shape factors were used to calculate the borehole thermal resistance when using the SF method.

However, regarding the vertical type, it was constructed as an intermediate form between the A and B cases. Thus, the coefficient applied to the shape factor in the W type was determined by means of interpolation between the values of the A and B cases from Table 4. The analytically and numerically determined borehole thermal resistance values are shown in Table 5. The comparison revealed that the SF method overestimates the borehole thermal resistance and that the EQD and multipole methods produce similar results to those determined experimentally. In the vertical GHE, the borehole thermal resistance values obtained by the multipole and EQD methods were nearly identical to the value calculated by the numerical analysis. The relative error between these values was less than 1~2%. On the other hand, in the energy pile, the relative error between the numerical analysis and the analytical solution, i.e., the results of the multipole and EQD methods, was greater than 10%. There were a few construction errors such as the pouring of grout or the inappropriate positioning of the W-type GHE. Also, the SF method showed relative error levels of 23 to 28%. It

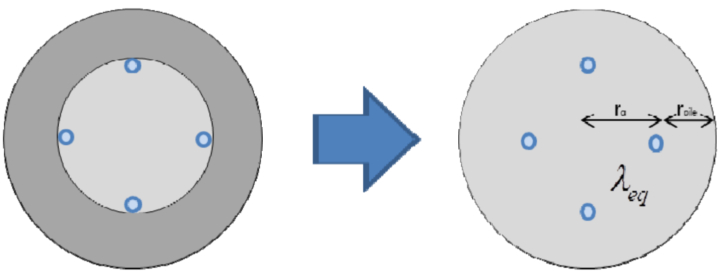


Fig. 12 Diagram of borehole in the energy pile

Table 5 Summary of borehole resistance values

Borehole thermal resistance	Numerical analysis (based on TRT)	Multipole method	Series	
			SF	EQD
Energy pile	0.118	0.105	0.151	0.106
Vertical GHE	0.209	0.208	0.258	0.205

*SF: Shape factor
*EQD: Equivalent diameter

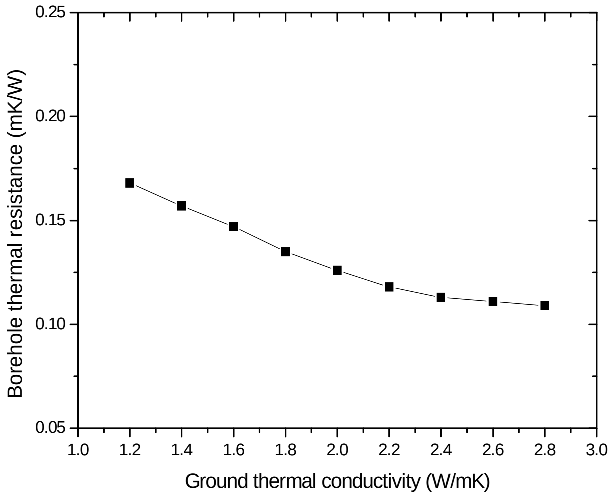


Fig. 13 Variation of the borehole thermal resistance

is thought because the SF method is based on the borehole wall temperature as measured from experiments and because there were a few measured temperature locations. As the borehole wall temperature can be affected by many factors such as the ground water table and the pipe configuration, it is necessary to consider the whole area of the borehole wall when measuring the borehole wall temperature.

5.3 Effect of ground thermal conductivity on borehole thermal resistance

For the energy pile in Suwon, an analysis of the effect of the ground thermal conductivity on the borehole temperature was conducted. A numerical analysis was performed under the same condition shown in Fig. 5 and Table 2 while varying only the ground thermal conductivity from 1.2 W/m·K to 2.8 W/m·K. Instead of a TRT analysis, a constant inlet temperature of 30°C was assumed to simulate a cooling condition in summer. Under the continuous operation of 100 hours, the borehole thermal resistance was calculated with the average temperature of the borehole wall and the average fluid temperature between the inlet and the outlet using Eq. (13) under a steady-state condition. The borehole thermal resistance was inversely proportional to the ground thermal conductivity, as shown in Fig. 13. However, above a ground thermal conductivity of 2.0

W/m·K, there was a negligible decrease in the borehole thermal resistance with an increase in the ground thermal conductivity. As the EQD and SF methods do not consider the effect of the ground thermal condition, it can be considered that the EQD and SF methods can be applied to a ground condition which has higher thermal conductivity. As a result, it is also feasible that the EQD and multipole methods showed similar borehole thermal resistance values based on the TRTs, in which the ground thermal conductivity was more than 2.0 W/m·K. However, it is clear that the borehole thermal resistance is affected by the ground thermal conductivity, especially for a dry ground condition or at a location above the ground water table. It is considered that the multipole method may be more adequate if GHEs are installed in the dry ground condition at a shallow depth, as such a location can take into consideration the effect of the thermal conductivity of the ground.

6. Conclusions

This paper presented an experimental and numerical case study to measure the ground thermal conductivity and borehole thermal resistance. A PHC energy pile and a general vertical GHE were installed and TRTs were conducted in each case. The following conclusions can be drawn from the TRTs and numerical analyses.

(1) The ground thermal conductivity values from the TRTs were 2.32 W/m·K and 2.15 W/m·K for the energy pile in Suwon and the vertical GHE in Incheon, respectively. The equivalent thermal conductivity was also determined to be 2.07 W/m·K and 2.24 W/m·K for the energy pile in Suwon and the vertical GHE in Incheon, respectively. The ground thermal conductivity values obtained from the TRTs were found to be in good agreement with the actual equivalent value with variation of approximately 5 to 10%. Thus, the experimental results agree well with the analytical solution derived from the equations. Therefore, it was determined that the ground thermal conductivity could be obtained from a TRT. Also, the equivalent ground thermal conductivity can be obtained via the ground thermal properties using a simple equation of the equivalent ground thermal conductivity. In other words, once the ground thermal properties are known, the equivalent ground thermal conductivity can be estimated using the simple equation proposed in this study.

(2) Because the borehole thermal resistance is an important design factor in the geothermal design, like the ground thermal conductivity, the borehole thermal resistance values of the energy pile and the vertical GHE were calculated through a numerical analysis based on the TRT results. The circulating water temperatures from the TRTs were in good agreement with the numerical analysis result. The SF method overestimated the borehole thermal resistance and the EQD and multipole methods produce a results similar to that of the numerical analysis, in which the ground thermal conductivity exceeded 2.0 W/m·K. However, the simulation results showed that the borehole thermal resistance was clearly affected by the ground thermal conductivity. Although there was a negligible decrease in the borehole thermal resistance when the ground thermal conductivity exceeded 2.0 W/m·K, it should be noted that the borehole thermal resistance is affected by the ground thermal properties when the ground thermal conductivity is less than 2.0 W/m·K. Accordingly, the multipole method can be more precise in predicting the borehole thermal resistance because it can directly consider the ground thermal properties, whereas the EQD and SF methods cannot consider the thermal conditions of the ground.

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