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

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ABSTRACT

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.

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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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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].

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

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.

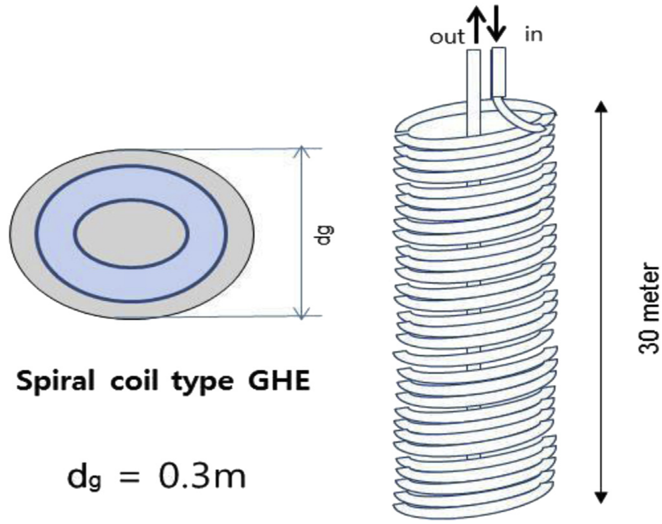


Fig. 1. Spiral coil type GHE and a schematic diagram.

Depth (m)	Layer	Description	USCS^{+}	SPT^{++} blow count
3.5	Reclamation soil *Groundwater table*	·Light brown color ·Medium-texture gravel ·Medium dense	GP	20/30
20.7	Sedimentary soil	·Pinkish gray color ·Silt clay ·Saturated ·Very weak	CL	9/30 20/30 24/30 27/30 33/30
29	Weathered granite soil	·Light brown color ·Medium sand ·Saturated ·Medium hard	SM	27/30 36/30 28/30 50/12
	Weathered granite rock	·Light brown color ·Intermediately weathered ·Saturated		

$^{+}$ Unified Soil Classification System
$^{++}$ Standard Penetration Test

Fig. 2. Drill log of the test site in vertical type GHE.

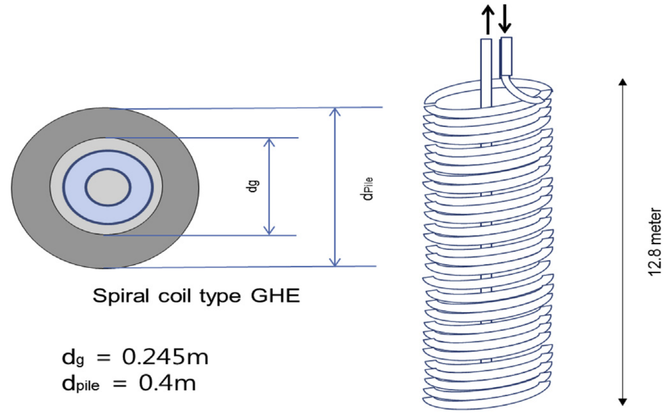


Fig. 3. Dimension of energy pile with spiral coil type GHE.

Also, d_h is the average hydraulic diameter, f_D (non-dimensional) refers to the coefficient of friction, u represents the tangential velocity, and λ is the thermal conductivity. A CFD analysis was performed with a Newtonian fluid model (Eq. (1)) with the dynamic properties of a certain fluid, after which the result could be coupled with the heat conduction equation of a solid mass through Eq. (2).

$$Q_{wall} = (h_p Z)_{eff}\left(T_p - T_f\right) \tag{2}$$

Here, T_p is the temperature of the pipe wall, which comes from the heat conduction equation of the solid mass, and T_f is the fluid temperature in the pipe. Also, $(h_p Z)_{eff}$ is the effective value of the heat transfer coefficient, and Z is the wall perimeter of the pipe. Fig. 5

Depth (m)	Layer	Description	USCS	SPT[++] blow count
4.5	**Weathered granite soil** *Groundwater table*	Brown color Medium dense silty sand Unsaturated	SP	19/30 26/30
11.5	**Weathered granite soil**	·Brown color ·Dense silty sand ·Saturated e=0.45/ w=16.7%	SP	45/30 50/25 50/21 50/17 50/12 50/8
	Weathered granite rock	·Brown color ·Intermediately weathered ·Saturated		

[+] **Unified Soil Classification System**
[++] **Standard Penetration Test**

Fig. 4. Drill log of the test site in energy pile.

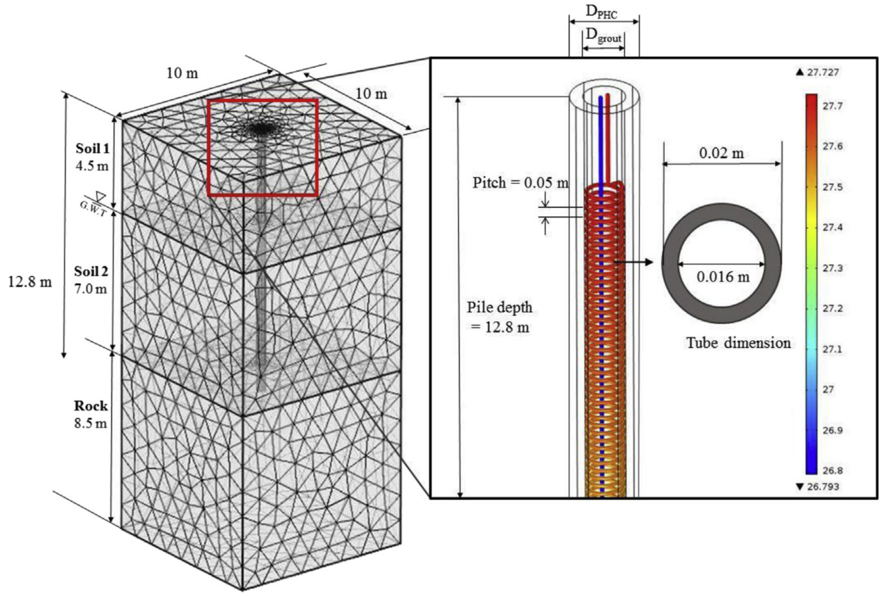


Fig. 5. Finite element model of energy pile for the numerical simulation.

represents the finite element model of energy pile for the thermal response test simulation. The form and arrangement of energy pile and vertical GHE are shown in Figs. 1 and 3, respectively.

Table 1 summarizes the thermo-physical properties used in the numerical analysis in Incheon city. The material thermal properties were referred from previous studies including the ground condition [16]. For the finite element model, a free tetrahedral mesh was used. On the other hand, the mesh element of the heat exchanger wall surface was formed using the wall layer function which was built into the COMSOL Pipe module rather than creating a direct mesh. The inlet temperature of the circulating water was derived using the function obtained based on the thermal response test data (see Fig. 6). The ground condition at the test site in Suwon city is separated into unsaturated and saturated weathered granite soil layers by the groundwater table, and the pile's lower half is in the rock layer. The thermo-physical properties used in the numerical analysis are also shown in Table 2.

4. Analytical solution

4.1. Spiral coil source model

It is known that it is not accurate to use the infinite line source model in the spiral coil type GHEs. Therefore, different kinds of analytical models adequate for the spiral coil type GHEs have been reported [4,9,15]. Recently, Park et al. [15] presented an advanced spiral coil source (SCS) model providing exact solutions by developing a mathematically more efficient analytical solution for the spiral coil type GHE. The SCS model considers three dimensional shape effects and the radial dimension effect of spiral coil type GHEs using Green's function. Because of the limitation in computation and the complicated formula, the model used an error function (see Eq. (3)) to improve and simplify the computation for engineering applications. The solution for SCM model is expressed as Eq. (3) [19].

$$\begin{aligned}\Delta T_{SCS}(u,t) &= \frac{q_l}{\rho c}\int_0^t\int_0^\infty \tilde{G}\left(u,t;x'=r_0\cos(\omega z'),y'=r_0\sin(\omega z'),z',t'\right)dz'dt' \\ &= \frac{q_l}{(4\pi\alpha)^{3/2}\rho c}\int_0^t \frac{1}{(t-t_0)^{3/2}}\int_0^h \exp^{\frac{F(x,y,z')}{4\alpha(t-t')}}\left(\exp^{\frac{(z-z')^2}{4\alpha(t-t')}} - \exp^{\frac{(z+z')^2}{4\alpha(t-t')}}\right)dz'dt' \\ &= \frac{q_l}{4\pi\lambda}\int_0^h \frac{erfc\left(A_-\left(u,z'\right)/2\sqrt{\alpha t}\right)}{A_-(u,z')} - \frac{erfc\left(A_+\left(u,z'\right)/2\sqrt{\alpha t}\right)}{A_+(u,z')}\Bigg]dz'\end{aligned} \tag{3}$$

with

$$F\left(x,y,z'\right) = x^2+y^2+r_0^2-2xr_0\cos\left(wz'\right)-2yr_0\sin\left(wz'\right)$$

$$A_\pm(u,z') = \sqrt{F\left(x,y,z'\right)+(z\pm z')^2}$$

Here, x', y', z' are the integral variables, and u is the vector in x, y, z Cartesian coordinates. Also, r_0 is the coil radius, t is time, $w = 2N\pi/h$

Table 1
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/m^3)
Soil1	0.21	800	1600
Soil2	2.30	1300	2100
Soil3	2.40	1280	2140
Bentonite grout	0.9	380	1580
Polybutylene pipe	0.38	525	955
Circulating water	0.57	4200	1000

indicates the wave number, and $\mathrm{erf}(\xi) = 2/\pi \int_0^\xi e^{-u^2} \mathrm{d}u$ denotes the error function. The detailed procedure and assumption for the spiral coil source model is given in the reference [15].

The thermal resistance inside a borehole has a significant impact on the performance of GHE [6,19,20]. In most of analytical models, the heat transfer inside the borehole region is assumed to be a steady state process. Then the borehole thermal resistance (R_b) can be defined by Eq. (4).

$$R_b = \frac{T_f - T_b}{q} \tag{4}$$

where T_f is the average fluid temperature and T_b is the borehole wall temperature. As the temperature and heat rate are time-dependent, this formulation disregards the heat capacitive effects of the borehole [21].

4.2. Infinite line source model

Many analytical models to describe the heat transfer behavior outside the borehole have been reported. The Kelvin infinite line source model is the most widely used to explain the heat transfer mechanism. The ground is regarded as an infinite medium with a uniform

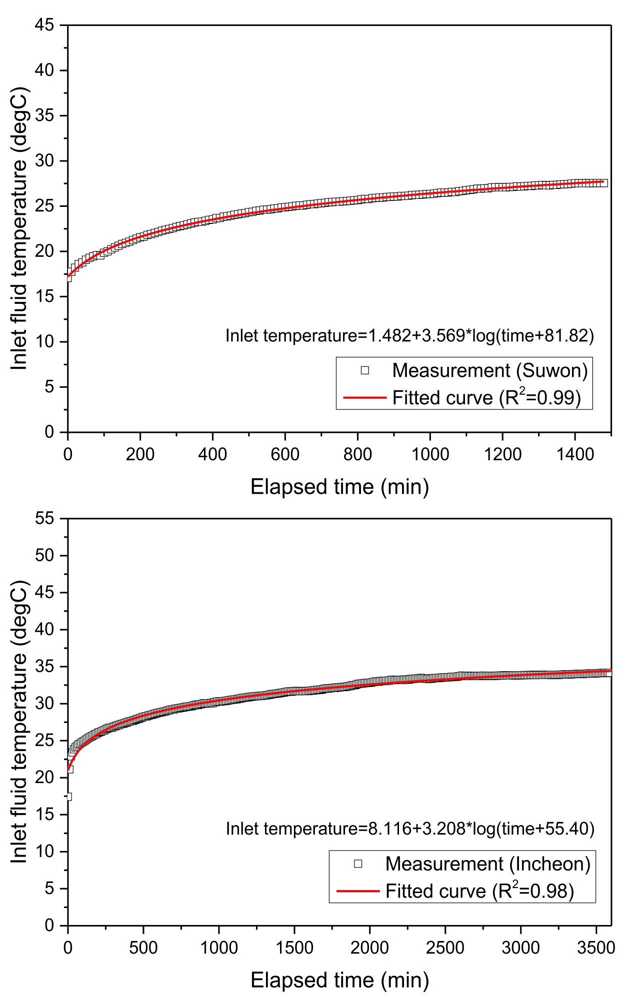


Fig. 6. Comparison between measured temperatures and predictions.

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/m^3)
Soil1	1.10	1160	1800
Soil2	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

temperature, in which the borehole can be assumed as an infinite line source [22–24]. The change in the ground temperature at a distance (r) from the heat source with a constant heat injection rate per length (q_l) during the time (t) is given by Eq. (5).

$$T(r,t) - T_o = \frac{q_l}{4\pi\lambda}\int_{\frac{r^2}{4at}}^{\infty}\frac{e^{-u}}{u}du = \frac{q_l}{4\pi\lambda}E_i\left(\frac{r^2}{4\alpha t}\right) \tag{5}$$

Here, T_o is the initial ground temperature, α is the thermal diffusivity of ground, and λ is the thermal conductivity of ground. E_i is the exponential integral, and u is the independent variable. 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 values versus time in a semi-natural logarithmic scale under a steady-state condition, the ground thermal conductivity can be approximated using the following equation.

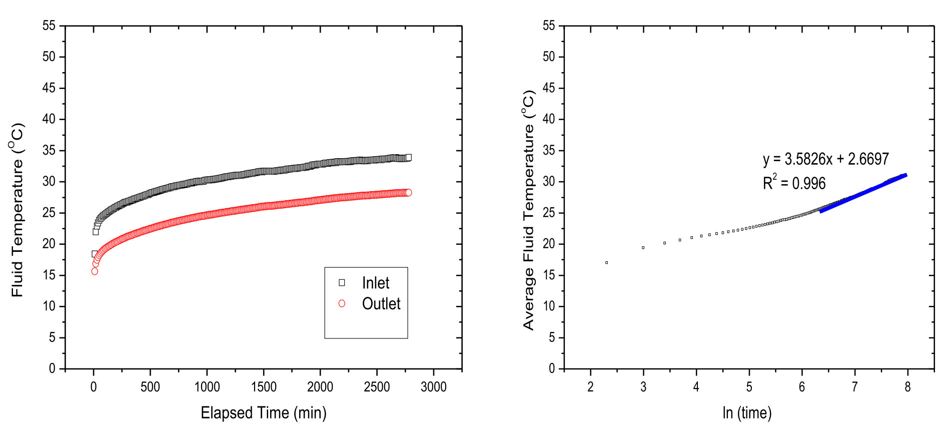
$$\lambda = \frac{q_l}{4\pi}\left(\frac{\ln t_2 - \ln t_1}{T_{f,av,2} - T_{f,av,1}}\right) \tag{6}$$

For the above expression, the maximum error is 2.5% when $at/r^2 \geq 20$ and 10% when $at/r^2 \geq 5$. It means that the accuracy increases as the thermal front reaches beyond the borehole wall [12,21].

5. Results and discussion

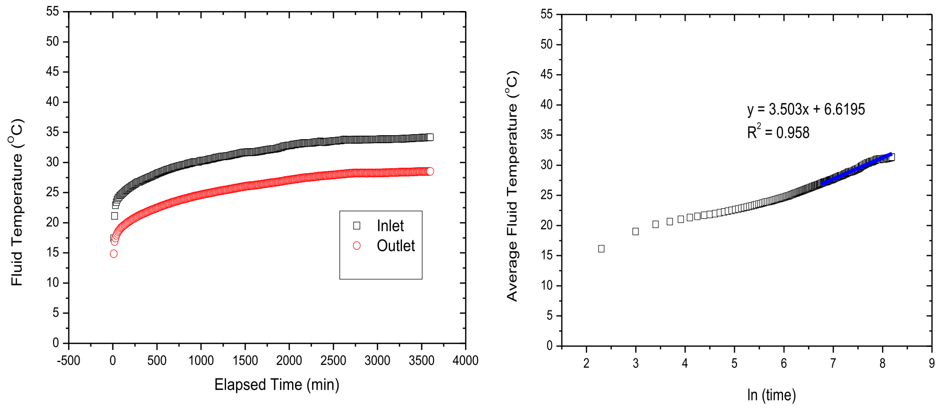
5.1. Experimental results

In this study, first, an in-situ TRT was conducted by installing a spiral coil type GHE on a vertical type borehole in Incheon. In the beginning, the TRT was conducted for 48 h [25,26] just as when vertical type borehole is used, and the temperature of the circulating water was measured at 10 min intervals. The initial temperature of the ground was determined through a no-load operation for 10 min before operating the heater, and the measured temperature was 16.14 °C. Fig. 7 depicts the change of circulating water temperature according to the TRT time when using spiral coil type GHE. As it can be seen in Fig. 7(a), the circulating water temperature rises at a constant rate for 48 h of TRT. Since the area of contact between the spiral coil type GHE and the grout is large, it was determined that the heat transfer occurred much more smoothly, and hence the time to reach the steady state increased. Thus, the conditions considered in calculating the ground thermal conductivity for the spiral coil type GHE should not be the same as the conditions employed for the conventional vertical type GHE. Therefore, the TRT was conducted again for approximately 65 h to ensure the steady state condition. Fig. 8 plots the temperature distribution of fluids measured from the 65 h TRT results. It can be observed that the quasi-steady state was reached after approximately 20 h.



(a) Temperature variation *vs* time (b) Temperature variation *vs* *ln* (time)

Fig. 7. Temperature variation of fluids for vertical type GHE (48 h).



(a) Temperature variation vs time (b) Temperature variation *vs ln* (time)

Fig. 8. Temperature variation of fluids for vertical type GHE (65 h).

Furthermore, the energy pile was used to perform in-situ TRT under the same conditions for the conventional vertical borehole. The 12.4 m depth of the energy pile was relatively shallow in comparison to the vertical type GHE, and consequently the time to reach the steady state was short. In order to apply for Eq. (6), the TRT should be conducted for more than 100 h. However, the TRT was conducted only for about 30 h because it already reached the almost steady state condition in 30 h. Fig. 9 shows the temperature distribution of the circulating water measured through the energy pile TRT results.

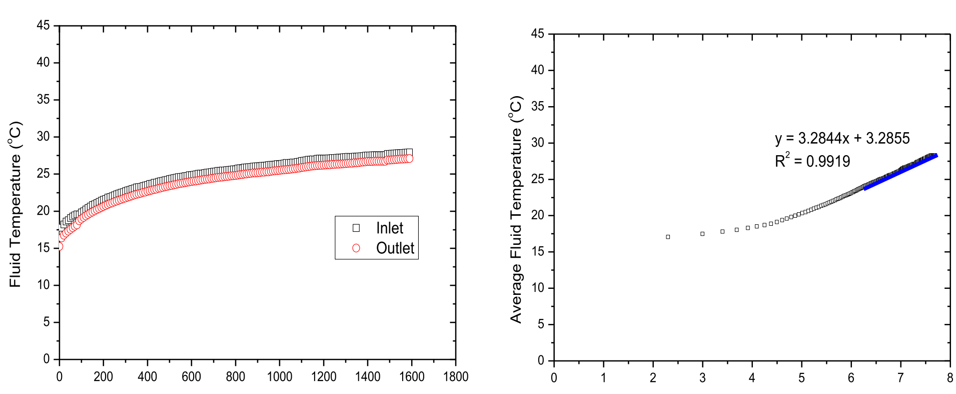
5.2. Borehole thermal resistance

Fig. 10 compares the in-situ TRT results with the numerical analysis values of the circulating fluid temperature with respect to time. The experimental values and numerical analysis predictions are in good agreement. Furthermore, after acquiring the pile wall temperature value at the steady-state condition through the numerical analysis, as shown in Fig. 11, Eq. (4) was used to calculate the borehole thermal resistance. The values were 0.067 m K/W and 0.077 m K/W for the vertical type GHE in Incheon and the energy pile in Suwon, respectively. Go et al. [19] introduced an empirical formula to derive borehole thermal resistance in energy pile. The borehole thermal resistance from the empirical formula for the energy pile in Suwon was 0.079 m K/W. Even though these results were not obtained from the experiments since temperature sensors were not installed on the borehole wall surface, the borehole thermal resistance value obtained through the numerical analysis using the borehole wall temperature might be demonstrated to be almost similar to the actual experimental results because measured values of the circulating water temperature were consistent with the numerical analysis values.

5.3. Estimation of ground thermal conductivity

The thermal conductivity was determined using the spiral coil source model of Eq. (3) which can appropriately describe the heat transfer behavior of a spiral coil type GHE. By combining the borehole thermal resistance formulas of Eq. (3) and Eq. (4), Eq. (7) can be derived.

$$T_f = R_b q_l + \frac{q_l}{(4\pi\alpha)^{3/2}\rho c}\int_0^t \frac{1}{(t-t')^{3/2}}\int_0^h e^{-\frac{F(x,y,z')}{4\alpha(t-t')}}\left(e^{-\frac{(z-z')^2}{4\alpha(t-t')}} - e^{-\frac{(z+z')^2}{4\alpha(t-t')}}\right)dz'dt' \tag{7}$$



(a) Temperature variation *vs* time (b) Temperature variation *vs* ln(time)

Fig. 9. Temperature variation of fluids for energy pile.

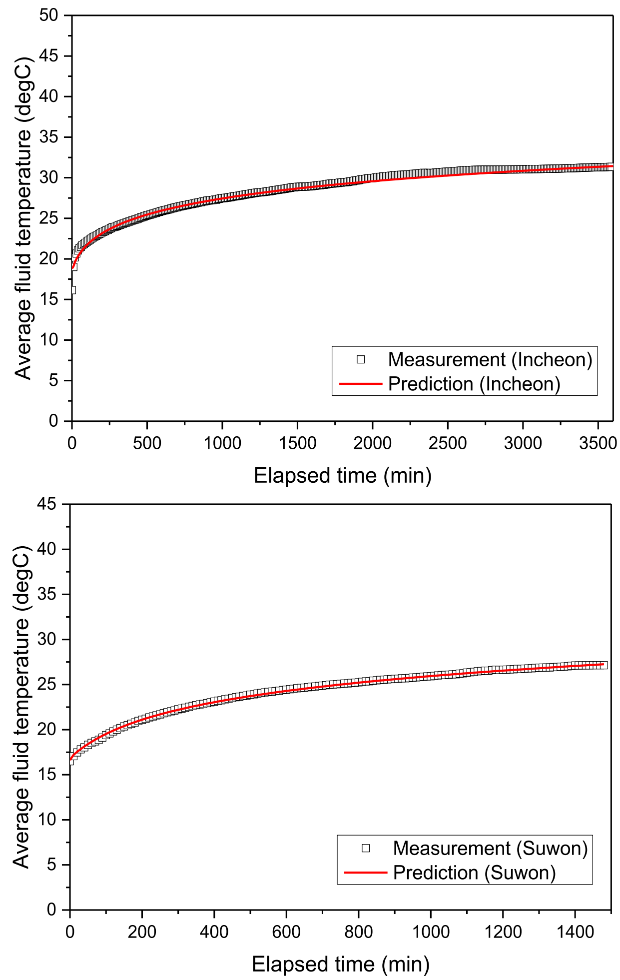


Fig. 10. Temperature variation of experimental results and numerical analysis.

The ground thermal conductivity was calculated by applying the least-squares error concept, as expressed in Eq. (8) with the temperature data from 22 to 65 h.

$$SSE = \sum_{i=1}^{n} \left(T_{f,av,i} - T_{f,i}\right)^2 \tag{8}$$

where $T_{f,av,i}$ are the mean fluid temperature values for the entrance and exit of the heat exchanger and $T_{f,i}$ is the result calculated using Eq. (7). Also, i refers to the measurement number and SSE is the sum of square error. The temperature value calculated from the spiral coil source model and the average circulating water temperature value obtained from the TRT after a quasi-steady state condition were compared to calculate the square error for the difference in the two temperatures. Here, the borehole thermal resistance was obtained by Eq. (4) with the simulation results, and weighted equivalent thermal properties from Tables 1 and 2 were used in using Eq. (7). Using the point at which the sum of the calculated square error is minimum as a basis, an inverse analysis for the ground thermal conductivity with Eq. (7) resulted in values of 2.06 W/(m K) and 2.25 W/(m K) for the vertical type borehole and energy pile, respectively. This was almost similar to the equivalent ground thermal conductivity. The actual equivalent ground thermal conductivity can be calculated using a weighted average method considering each ground layer condition [16].

5.4. Application of infinite line source model

As the spiral coil type GHE is not in a line form, there may be difficulties in applying the infinite line source model, which is the most widely used model for determining the ground thermal conductivity. However, according to Blackwell and Misener [27], the infinite line source model can be applied because the diameter has almost no effect when the L/D (L: length, D: diameter) or the ratio of the heat source length to the diameter is larger than 25–30. This signifies that the infinite line source model can be applied with a little difficulty even when the heat source length is finite and more than 30 times the diameter.

In this study, first, an in-situ TRT was conducted by installing a spiral coil type GHE on a vertical type borehole in Incheon. Since the diameter and vertical depth of the borehole were 30 cm and 30 m, respectively, the L/D was approximately 100; thus, the infinite line source model was used to determine the ground thermal conductivity. A spiral coil type GHE was also installed in the energy pile and an in-situ TRT

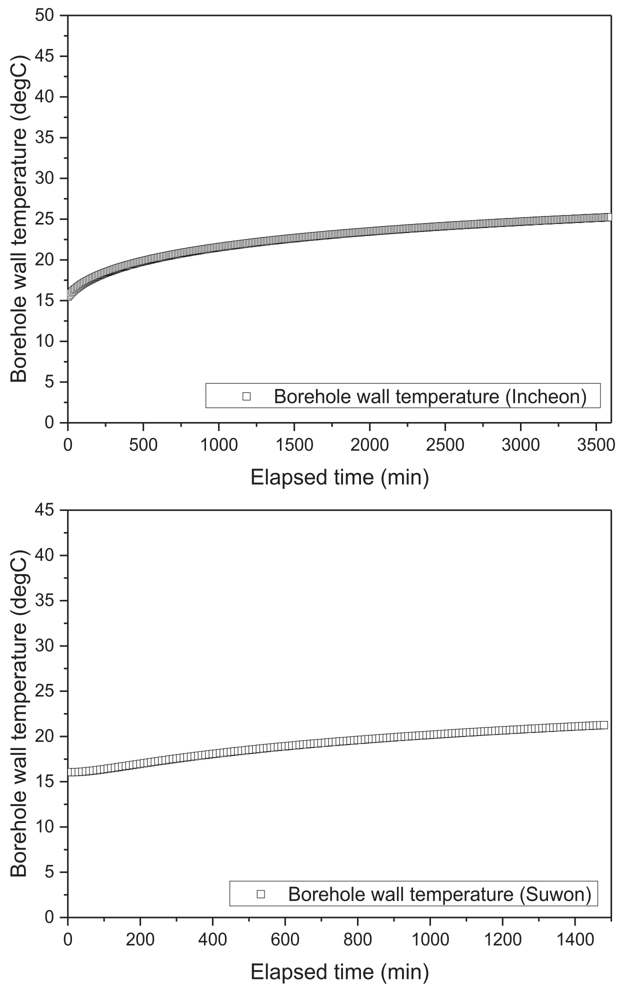


Fig. 11. Temperature variation at the borehole wall.

was conducted. The energy pile had also an L/D value greater than 30, as the borehole diameter and vertical depth were 40 cm and 12.8 m, respectively. In the beginning, the TRT was conducted for 48 h from Fig. 7. Taking a similar approach to the vertical type borehole, the ground thermal conductivity was calculated to be 1.86 W/(m K) by Eq. (6) with the TRT temperature data of Fig. 7(b), excluding the first 12 h of temperature data from the total of 48 h. However, the calculated value was quite different from the actual ground thermal conductivity value. However, with TRT results for 65 h until the steady state condition, the recalculated ground thermal conductivity using Eq. (6) with Fig. 8(b) was 2.18 W/(m K) and this was found to be similar to the actual equivalent thermal conductivity of the ground of 30 m depth. In case of energy pile, once again, Eq. (6) was used to calculate the ground thermal conductivity, which was 2.09 W/(m K). This was found to be similar to the actual equivalent thermal conductivity of the ground of 12.4 m depth. Table 3 shows the summary of ground thermal conductivity values obtained by analytical models.

When the condition considered in calculating the ground thermal conductivity for the spiral coil type GHE is used for the conventional vertical type GHE, a large amount of error occurs. Therefore, the TRT in the vertical type GHE has to be conducted for more than 65 h continuously, and the infinite line source model or spiral coil source model has to be applied after appropriately considering the time needed to reach a quasi-steady state and disregarding the initial portion of data in order to determine the ground thermal conductivity in a reasonable manner. However, since the infinite line source model can be simplified by Eq. (6), it was found that using this formula allows easier calculation of the ground thermal conductivity, which is much simpler than the complicated spiral coil source model.

Table 3
Summary of ground thermal conductivity values.

Ground thermal conductivity	[a]ILSM (W/(m K))	[b]SCSM (W/(m K))	Equivalent ground thermal conductivity (W/(m K))
Energy pile	2.09	2.25	2.11
Vertical GHE	2.18	2.06	2.08

[a] ILSM: infinite line source model.
[b] SCSM: spiral coil source model.

6. Conclusion

In this study, in-situ TRTs were conducted after installing a vertical type borehole and an energy pile with spiral coil type GHE. The TRT data were used to estimate the ground thermal conductivity using the spiral coil source model and the infinite line source model with borehole thermal resistance values obtained by numerical analysis model. The following conclusions have been obtained:

1. The spiral coil source model was used to derive a ground thermal conductivity in the case of vertical type borehole and energy pile with spiral coil type GHEs. First, in the case of vertical type borehole, the TRT was conducted for 48 h just as when a conventional vertical type borehole is used. However, unlike normal situation for vertical type borehole, it didn't reach the steady state condition in 48 h. Therefore, the TRT was conducted again for about 65 h until reaching the steady state. It is thought that the TRT should be conducted to the steady state condition, not just for 48 h if spiral coil type GHE is used. Second, the TRT was also conducted for the energy pile with a spiral coil type GHE. In comparison to the vertical type borehole, the energy pile is relatively shallow (12.4 m deep) and hence short time duration is regarded until a steady state is reached; consequently the thermal response testing was conducted for 30 h. In order to consider the borehole thermal resistance effect, the TRT results of vertical type borehole and energy pile were numerically modeled using FEM program with CFD module. As the experimental values and numerical analysis results were almost similar, borehole thermal resistance values were calculated with the numeral data. With the spiral coil source model and borehole thermal resistance value, the ground thermal conductivity was calculated as 2.06 W/(m K) and 2.25 W/(m K) for the vertical type borehole and energy pile, respectively. This was almost similar to the actual equivalent ground thermal conductivity.

2. Furthermore, in order to accurately verify the in-situ TRT results, the infinite line source model was applied. Even though the spiral coil type GHE is not in a line form, there may be difficulties in applying the infinite line source model. First, the ground thermal conductivity (1.86 W/(m K)), which was calculated in a similar manner to that for the conventional line type GHE (such as performing the TRT for 48 h and using the infinite line source theory with the initial 12 h of data disregarded), was different from the actual ground thermal conductivity value. As TRT results showed that even after 48 h the circulating water temperature did not reach a steady state and continued to rise continuously, the ground thermal conductivity for 48 h was not appropriate. In other words, in calculating the ground thermal conductivity for the spiral coil type GHE, using the same test conditions as that for the conventional line type heat exchanger would be inappropriate. Therefore, the ground thermal conductivity was recalculated considering longer data and disregarding the initial 25 h of data. The calculated ground thermal conductivity was 2.18 W/(m K), which is similar to the value obtained by the spiral coil source model, as the error is only less than 6%. Meanwhile, the ground thermal conductivity using the infinite line source model for the energy pile was 2.09 W/(m K), which is similar to the value obtained by the spiral coil source model, as the error is only less than 8%.

3. Therefore, the application of the infinite line source model with the spiral coil type GHE allowed accurate calculation of the ground thermal conductivity through in-situ TRT. However, since the time needed to reach a steady state may be different from that for the line type GHEs, the amount of data or time that should be disregarded and the total analysis time have to be closely investigated in applying the infinite line source model. Then, it might be much more convenient using the infinite line source model than the spiral coil source model in order to estimate the ground thermal conductivity for the spiral coil type GHE.

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