Energy 71 (2014) 547–555

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A numerical and experimental approach to the estimation of borehole thermal resistance in ground heat exchangers

Seok Yoon [1], Seung-Rae Lee*, Gyu-Hyun Go

Department of Civil and Environmental Engineering, KAIST, Daejeon 305-701, South Korea

ARTICLE INFO

Article history:
Received 12 February 2014
Received in revised form
22 March 2014
Accepted 27 April 2014
Available online 23 May 2014

Keywords:
Ground thermal conductivity
Borehole thermal resistance
Thermal response test
Thermal performance test
Multipole method

ABSTRACT

This paper presents a numerical and experimental study on the evaluation of borehole thermal resistance with TRT (thermal response test) and TPT (thermal performance test) results observed in closed-loop vertical type boreholes with U and W type GHEs (ground heat exchangers). Field TRTs were carried out for 48 h on a closed-loop vertical type borehole, and an equivalent ground thermal conductivity was estimated using the infinite line source model. Closed-loop vertical type boreholes with U and W type GHEs and field ground conditions were numerically modeled using a three dimensional finite element method to estimate borehole thermal resistance and the TRT results were compared. Field TPTs were also conducted for 100 h continuously to calculate the heat exchange rate and borehole thermal resistance. The borehole thermal resistance values were compared with various analytical solutions, and the multipole and EQD (equivalent diameter) method produced results closer to those of the experimental and numerical analysis than the SF (shape factor) method.

1. Introduction

Among various renewable energy resources, the use of geothermal energy has been regarded as energy efficient way of space heating and cooling [1–3]. Geothermal energy has a great potential as a directly usable type of energy, especially in connection with GSHP (ground source heat pump) systems. Hence, GSHP systems combined with various types of GHEs (ground heat exchangers) have been widely used since the early 20th century [4–6]. Geothermal energy is often called ubiquitous energy because it can be used anytime and anywhere.

The GSHP system is largely composed of a geothermal heat pump and a ground heat exchanger. The ground heat exchanger is a system that extracts or emits heat using a circulation fluid such as flowing water or an anti-freezing solution through the heat exchanger installed in the ground. The system uses the heat source of the ground, which maintains a relatively uniform temperature to release heat energy in the summer and absorb heat energy in the winter. The ground heat exchanger is an important element that determines the performance and initial installation fee of the entire system and generally 150–200 m depth closed-loop vertical types are used most widely. The closed-loop vertical type ground heat exchanger is composed of a heat exchange pipe, the ground and grout that fill the empty space between the pipes inside the borehole.

Considering the high initial construction cost, researchers are conducting numerous studies on closed-loop vertical type ground heat exchangers in order to obtain higher thermal efficiencies [7–11]. The heat transfer between the surrounding ground through the ground heat exchanger has a close relationship with the heat transfer between the fluid that circulates within the heat exchanger pipe and the complex medium (grout/ground) surrounding the pipe [12–14]. Therefore, the ground thermal conductivity and borehole thermal resistance are important design parameters that determine the heat performance of GSHP systems [15,16]. The ground thermal conductivity is almost accurately measured through an in-situ TRT and the obtained value is used as a design parameter in GSHP systems. However, there is no clear guideline on a method to determine the borehole thermal resistance and not many studies are being conducted in comparison with ground thermal conductivity measurement.

This paper presents a numerical and experimental study to derive the borehole thermal resistance. U type and W type GHEs were installed in a landfill area at Incheon International Airport in South Korea, and then in-situ TRTs and TPTs were conducted to verify the suitability of the borehole thermal resistance analytical models. Furthermore, the TRT test and on-site ground conditions

* 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.

http://dx.doi.org/10.1016/j.energy.2014.04.104

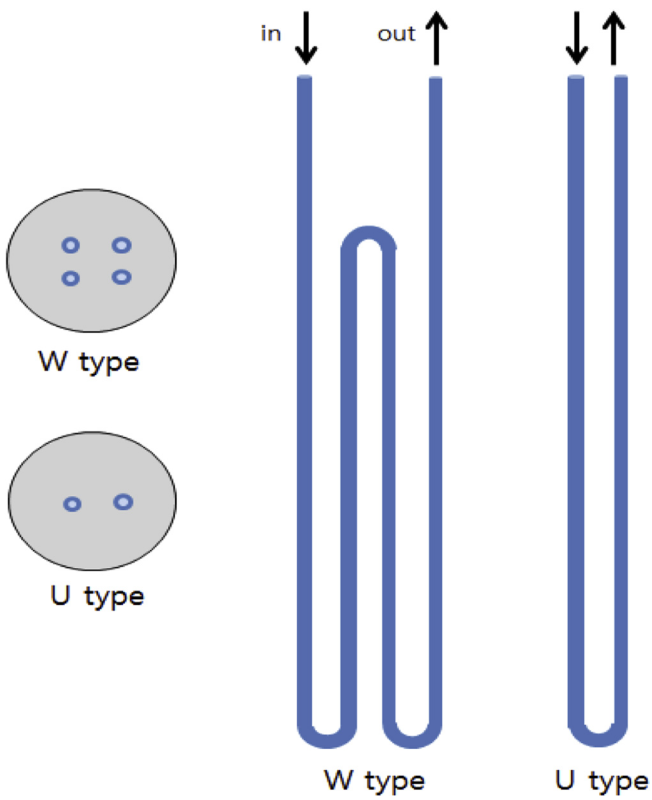


Fig. 1. Diagram of ground heat exchanger.

were numerically modeled using the finite element method coupled with a CFD (computational fluid dynamics) analysis. The borehole thermal resistance values were calculated by a numerical analysis of the TRT and TPT (thermal performance test) results and compared with analytical solutions.

2. Experimental setup

2.1. Setup of GHE

U and W type GHEs (Fig. 1) were installed in a partially saturated landfilled runway area of Incheon International Airport. The borehole depth was 50 m, and the diameter was 15 cm. The distance between each borehole was 6 m to avoid thermal inference. Polybutylene pipes (inner/outer diameter of pipe = 0.016/0.02 m) were used as GHEs, and bentonite grout was poured into the borehole. The total pipe length of U and W type GHE was 100 m and 200 m, respectively. Fig. 2 shows the construction process of the vertical GHEs.

The ground was composed of silt, clay, weathered granite soil and weathered rock. The ground water level was 3.5 m below the top of the embedded borehole, and no noticeable flow of ground water was observed. The SPT (Standard Penetration Test) N value was 9/30–33/30 in the partially saturated landfill ground, and weathered rock appeared 30 m below the ground level. The average void ratio was 0.95 and the water content was 30–35%.

2.2. Theory of TRT analysis

The heat transfer mechanism of the ground heat exchanger involves the process of absorbing and releasing heat to and from the grout material and the surrounding ground as the heat transfer fluid flows through the pipe within the borehole, whereas the heat transfer behavior between the ground heat exchanger and the surrounding ground involves a complex mechanism, and the heat transfer to the ground is through conduction [3]. The heat transfer governing equation from conduction in the ground is as follows:

$$-\lambda_i\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}+\frac{\partial^2 T}{\partial^2 z}\right)+\rho_i c_i\frac{\partial T}{\partial t}+q_{\text{internal}}=0 \tag{1}$$

where T is the temperature, λ is the thermal conductivity, ρ is the density, c is the specific heat capacity, q_{internal} is the internal heat generation. The subscript i denote each region of the GHE such that g and s indicate the grout and soil, respectively.

Heat transfer in the GHE involves pipe convection, pipe conduction, grout conduction in the borehole and ground conduction. In order to measure the ground thermal conductivity in the GHE system outside the borehole, some analytical equations such as line source, cylindrical source, and numerical analysis models have been used. Among these, the infinite line source model is the most widely employed to measure the ground thermal conductivity due to its simplicity and convenience in analysis, and the analytical solution for the heat transfer between the buried pipe and the ground can be obtained by the Kelvin theory. As shown in Fig. 3, the vertical closed-loop ground heat exchanger has a borehole radius (r_b) that is much smaller than the borehole length (L), and hence it can be assumed to be a line source, and the ground is regarded as an infinite and isotropic medium. When the heat transfer medium surrounding the line source is a different material, such as that of grout and soil, the following solution of the heat conduction equation can be obtained when considering the thermal resistance between the borehole and soil about the line source [17–19].

(a) Drilling of borehole (b) Installation of GHE (c) Bentonite grouting

Fig. 2. Construction process of GHE.

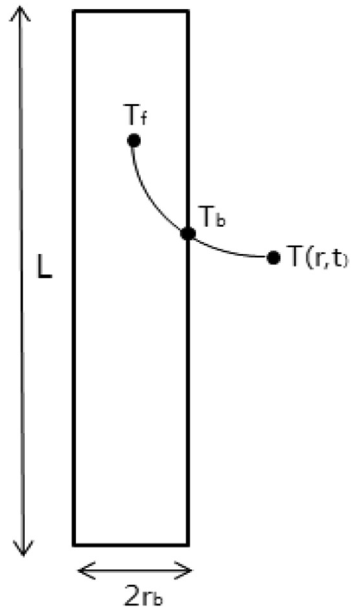


Fig. 3. Temperature variation around borehole.

$$T(r,t) - T_o = \frac{Q}{4\pi L\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du \tag{2}$$

Here, T_o is the initial ground temperature and α is the thermal diffusivity of the ground. In Eq. (2), ($r^2/4\alpha t$) is the integral variable, and the right side integral can be expressed as an infinite series as shown below using an exponential integral.

$$\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du = -\gamma - \ln\left(\frac{r^2}{4\alpha t}\right) + \frac{r^2}{4\alpha t} - \frac{1}{4}\left(\frac{r^2}{4\alpha t}\right)^2 \cdots \tag{3}$$

In Eq. (3), γ is the Euler constant with a value of 0.5772. When the integral variable ($r^2/4\alpha t$) in Eq. (3) is very small, Eq. (3) can be expressed in the following manner.

$$\Delta T(r,t) = \frac{Q}{4\pi\lambda L}\left\{\ln\left(\frac{r^2}{4\alpha t}\right) - \gamma + \frac{r^2}{4\alpha t}\left(1 - \frac{r^2}{16\alpha t}\right)\right\} \tag{4}$$

When the heat is transferred from the fluid temperature (T_f) of the circulating fluid to the ground, as shown in Fig. 3, Eq. (5) is applied, which is from the thermal resistance inside the borehole.

$$\frac{Q}{L} = \frac{T_f - T_b}{R_b} \tag{5}$$

Here, the circulating fluid temperature (T_f) is the average temperature of the circulating fluid inlet and outlet regions. The borehole wall surface temperature (T_b) is calculated as shown below by substituting $r = r_b$ into Eq. (4), which becomes $T_b = T(r_b, t)$.

$$T_b - T_o = \frac{Q}{4\pi\lambda L}\left\{\ln\left(\frac{r_b^2}{4\alpha t}\right) - \gamma + \frac{r_b^2}{4\alpha t}\left(1 - \frac{r_b^2}{16\alpha t}\right)\right\} \tag{6}$$

Combining Eqs. (5) and (6) and reorganizing about T_f gives Eq. (7).

$$T_f = \frac{Q}{4\pi\lambda L}\ln t + \frac{Q}{4\pi\lambda L}\left(\ln\frac{4\alpha}{r_b^2} - \gamma\right) + \frac{Q}{L}R_b + T_o \tag{7}$$

The fluid average temperature (T_f) in Eq. (7) can be expressed as a linear equation about ln$t$ as given in Eq. (8).

$$T_f = Ax + B \tag{8}$$

with $A = (Q/L)/4\pi\lambda$, $x = \ln t$, and $B = A((4\alpha t/r_b^2) - \gamma) + (Q/L)R_b + T_g$ Therefore, once A can be solved, the thermal conductivity (λ) can be obtained by

$$\lambda = \frac{Q/L}{4\pi A} \tag{9}$$

Therefore, as fluid temperatures at the inlet and outlet of GHEs can be measured with respect to time by the TRT, an effective thermal conductivity can be obtained with the value of the slope (A) from the T_f-ln$t$ relationship.

2.3. Principle of TPT

In-situ TPTs were conducted using U and W type GHEs. Prior to the TPT, in-situ TRTs were also conducted to measure the ground thermal conductivity. There is a difference between TRT and TPT. The TRT is used to measure the ground thermal conductivity where a pre-defined constant heat power is put into the water tank in the equipment. Then the ground thermal conductivity can be obtained by Eq. (9). On the other hand, the TPT evaluates the heat exchange rate of the borehole under the condition that the inlet temperature be kept constant. The heat exchange rate per length of borehole can be calculated using Eq. (10). T_{in} is the inlet temperature of the fluid, and T_{out} is the outlet temperature of the fluid, and m is the flow rate of the fluid

$$\frac{Q}{L} = \frac{mc(T_{\text{in}} - T_{\text{out}})}{L} \tag{10}$$

3. Numerical analysis

A finite element analysis program coupled with a CFD module in COMSOL Multiphysics [20] was used to simulate the TRTs conducted in a closed-loop vertical type borehole considering the configuration of U and W type GHEs. The governing equation of the numerical model based on the convection current and conduction is expressed by Eq. (11) [21].

$$\rho Ac\frac{\partial T}{\partial t} + \rho cAu\cdot\nabla T = \nabla\cdot A\lambda\nabla T + f_D\frac{\rho A}{2d_h}\left|u\right|^3 + Q + Q_{\text{wall}} \tag{11}$$

Here, Q refers to the regular heat injection and Q_{wall} represents the overlapped area of temperature between fluid convection and pipe conduction. Q_{wall} represents the overlapped area of temperature between fluid convection and pipe conduction. 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. Further, 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. (11)) 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. (12).

$$Q_{\text{wall}} = (hZ)_{\text{eff}}\left(T_p - T_f\right) \tag{12}$$

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. From Eq. (12), it can enable the exact heat

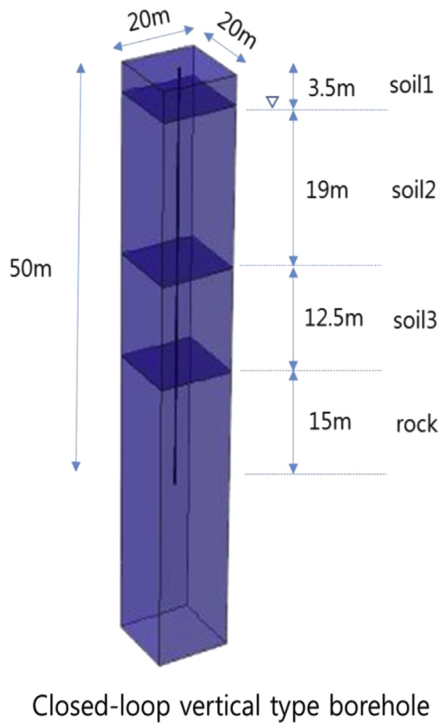


Fig. 4. Finite element model for the numerical simulation.

transfer with coupled analysis between fluid convection and pipe conduction. Further, $(hZ)_{\mathrm{eff}}$ is the effective value of the heat transfer coefficient, and Z is the wall perimeter of the pipe. For a circular tube, the effective hZ can be denoted as:

$$(hZ)_{\mathrm{eff}} = \frac{2\pi}{\frac{1}{r_0 h_{\mathrm{int}}} + \frac{1}{r_N h_{\mathrm{ext}}} + \sum_{n=1}^{N}\left(\frac{\ln\frac{r_n}{r_{n-1}}}{\lambda_n}\right)} \tag{13}$$

where λ_n is the thermal conductivity of wall n, r_n is the outer radius of wall n, and h_{int} and h_{ext} are the film heat transfer coefficients inside and outside of the tube. Fig. 4 represents the finite element model for the thermal response test simulation.

Table 1 shows the thermo-physical properties used in the numerical analysis. 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 temperature of the circulating water was derived using the function obtained from the TRT data (see Fig. 5). The thermal conductivity of the landfill soil was measured using TP-08 device (Hukseflux Thermal Sensors Inc.) based on a transient hot-wire method [22]. The soil was remolded to have the same void ratio and water content of the construction site. The thermal conductivity of the silt-clay in the landfill area below the ground water table was measured as 2.3 W/m K. Since the soil of every layer was not sampled, the thermal conductivity of the weathered granite soil was estimated at around 2.4 W/m K from the fitted model suggested by Park et al. [23] for deriving the thermal conductivity of Korean granite soil.

Table 1
Basic thermal properties of materials for numerical simulation.

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
Rock	2.50	879	2640
Bentonite grout	0.9	380	1580
Polybutylene pipe	0.38	525	955
Circulating water	0.57	4200	1000

4. Analytical solution

4.1. Series sum method

In the series-sum model, the borehole thermal resistance is estimated by summing the convective resistance of the fluid R_{fluid} (Eq. (15)), the conductive resistance between the pipe and the grout R_{pipe} (Eq. (16)), the thermal resistance of the grout R_{grout}, as depicted in Eq. (14).

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

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

$$R_{\mathrm{pipe}} = \frac{1}{2\pi\lambda_p}\ln\left(\frac{d_e}{d_e - (d_o - d_i)}\right), \quad d_e = \sqrt{n} d_o \tag{16}$$

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, λ_p is the thermal conductivity of the pipe, h_i is the convective heat transfer coefficient of the fluid circulating in the pipe, and n is the number of pipes (U type, $n = 2$; W type, $n = 4$). 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.

The thermal resistance of the grout is the largest factor in the overall borehole resistance, and an exact calculation of the grout resistance is very important for a reliable design of the GSHP system. For the calculation of the grout resistance, a few methods have been introduced, such as Eqs. (17) and (18).

$$R_{\mathrm{grout}} = \frac{1}{2\pi\lambda_g}\ln\frac{d_g}{d_o\sqrt{n}} \tag{17}$$

$$R_{\mathrm{grout}} = \frac{1}{\lambda_g \beta_0 (d_g/d_o)^{\beta_1}} \tag{18}$$

Here, d_g is the grout diameter and λ_g is the thermal conductivity of the grout. Eq. (17) is called an EQD (equivalent diameter method) when calculating the grout thermal resistance. It was proposed based on the concentricity assumption of steady-state operation. One of the pipe legs was assumed to be concentric with the grout region and the thermal influence from the other legs was estimated using the principle of superposition [24]. Further, Remund et al. [25] considered the shank distance between the pipe legs as an important factor for the estimation of the thermal resistance introduced in Eq. (18). They suggested shape factors β_0 and β_1 presented in Table 2, for which the borehole configurations corresponding to cases A, B, and C are shown in Fig. 6. A W type GHE was obtained by back analysis of the GLD (ground loop design) [26], a commercial design program. The GLD uses the shape factor method for calculating the grout resistance. Therefore, Eq. (18) is known as the SF (shape factor) method.

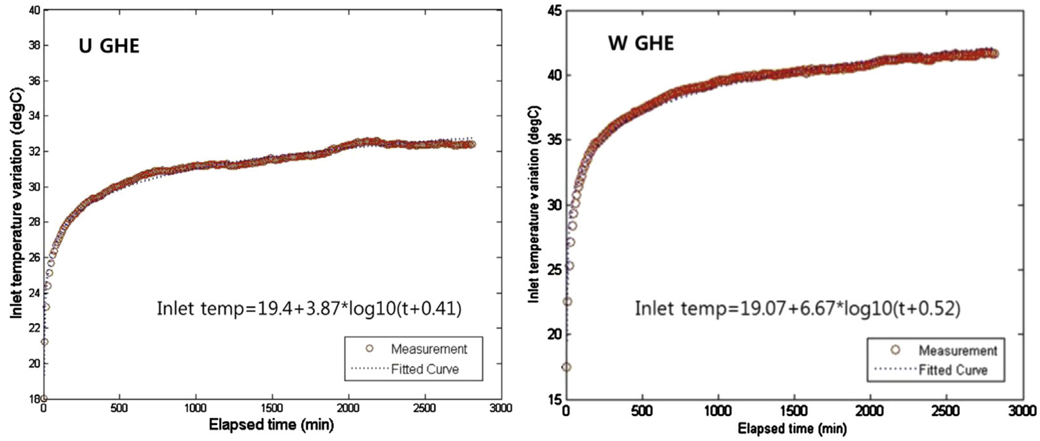


Fig. 5. Comparison between measured temperatures and predictions.

4.2. Multipole method

The multipole method [27,28] considers the conductive heat flow in and between pipes of different measurements of radius and asymmetrical location using a multipole algorithm. This model considers the steady state condition of the borehole. In this model, the tubes are placed in a circular homogeneous medium inside another infinite homogeneous medium. The solution of the multipole method was derived from the steady state two-dimensional heat conduction equation. The temperature rise of the ground is assumed to be caused by the heat sources (which are the tubes) and the heat sink at the mirror points (Fig. 7). The temperature rise at position (x, y), $\Delta T(x, y)$ is then calculated by Eq. (19).

$$\Delta T(x,y) = \frac{q}{2\pi\lambda_g}\mathrm{Re}(W_{n0}) \tag{19}$$

Here, q is the heat flux per unit length and $Re(W_{n0})$ is the real component of the zero-th order multipole (W_{n0}). For higher multipoles, derivations are taken of the W_{n0} (Eq. (20)).

$$W_{nj} = \frac{1}{(j-1)!}\cdot\frac{\partial^j}{\partial r_n^j}(W_{n0}) \tag{20}$$

where W_{nj} is the jth order multipole of the nth line source, W_{n0} is the 0th order multipole of the nth line source, j is the order of multipole and r_n is the location of the nth tube in the polar coordinate. The temperature rise of the borehole wall as compared to the undisturbed temperature of the ground soil is obtained by replacing $r_n = r_b$ (borehole radius). Among simulation models, this model is assessed as one of the most accurate method which exactly describes the real configuration of heat exchangers in a borehole, and it was used in the EED (Earth Energy Designer) [30] design program.

Table 2
Shape factors for U-type and Double-U type GHEs.

Configuration	U-type GHE		Double U-type GHE	
	β_0	β_1	β_0	β_1
A (Close together)	20.10	−0.9447	27.68	−0.9411
B (Average)	17.44	−0.6052	21.36	−0.6031
C (Along outer wall)	21.91	−0.3796	25.52	−0.3921

Eq. (21) represents the thermal resistance between the pipe and the borehole wall, while Eq. (23) was used to determine the thermal resistance between two pipes. Further, Eq. (23) is the sum of the thermal resistance of the pipe wall and the fluid boundary layer. Like the second formula in Eq. (24), 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.

$$\hat{R}^{o}{}_{m,m} = \frac{1}{2\pi\lambda_g}\left\{\beta_m + \ln\left(\frac{r_b}{r_{\mathrm{pm}}}\right) + \sigma\cdot\ln\left(\frac{r_b^2}{r_b^2 - r_m^2}\right)\right\} \quad m = 1,\ldots N \tag{21}$$

$$\sigma = \frac{\lambda_g - \lambda}{\lambda_g + \lambda} \tag{22}$$

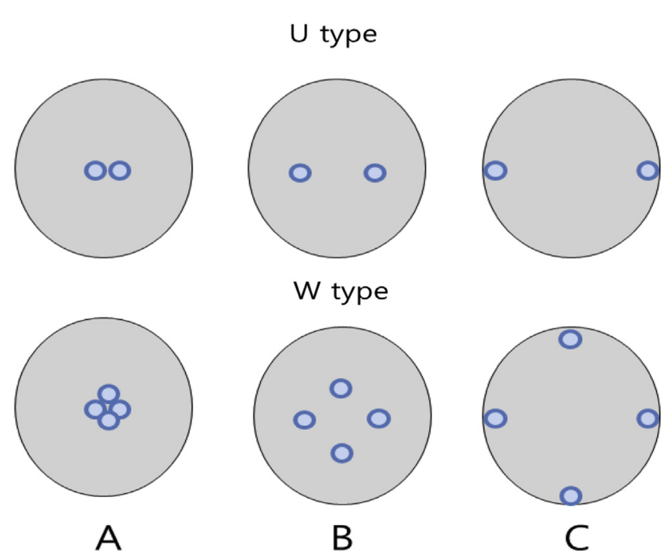


Fig. 6. Location of GHEs in boreholes.

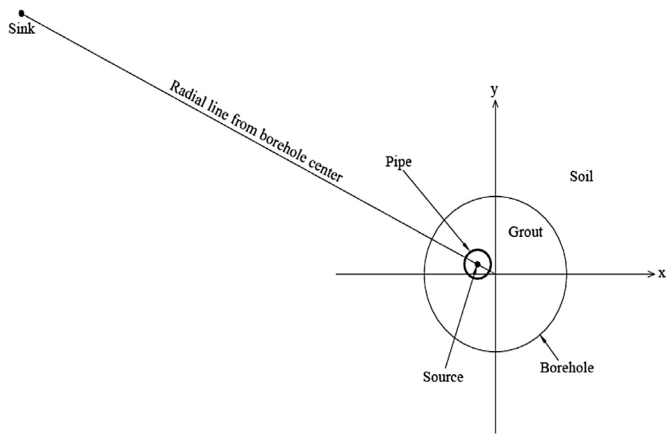


Fig. 7. Source and sink locations of a single pipe (Young, [29]).

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

$$m,n = 1,\ldots N \tag{23}$$

$$R_{pm} = \frac{1}{2\pi\lambda_p}\cdot\ln\left(\frac{r_{pm}}{r_{pm}-d_{pw}}\right) + \frac{1}{2r_{pm}\cdot h_p} \tag{24}$$

$$\beta_m = 2\pi\lambda_g R_{pm}$$

Here, σ is a dimensionless parameter for the two thermal conductivities, λ_g is the thermal conductivity of the grout and λ is the ground thermal conductivity. $\hat{R}^o{}_{m,m}$ 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. Further, h_p is the convective heat transfer coefficient by Rohsenhow et al. [31]. In contrast to the EQD and SF methods, the multipole method can consider the pipe configuration at any location and ground thermal conductivity.

4.3. Thermal resistance of soil and the heat exchange rate

Eq. (2) can be transformed as below [9].

$$T(r,t) - T_o = \frac{Q}{4\pi L\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du = \frac{Q}{2\pi L\lambda}\int_{\frac{r}{2\sqrt{\alpha t}}}^{\infty}\frac{e^{-u^2}}{u}du = \frac{Q}{2\pi L\lambda}I(\chi) \tag{25}$$

When $r = r_b$, the thermal resistance of soil is as follows:

$$R_s = \frac{T_b - T_o}{Q/L} = \frac{Q}{2\pi L\lambda}I\left(\frac{r_b}{2\sqrt{\alpha t}}\right) = \frac{Q}{2\pi L\lambda}I\left(\frac{1}{2\sqrt{F_o}}\right) \tag{26}$$

Here, when $0 < x \leq 1$, the I function can be calculated as in Eq. (27)

$$I(\chi) = 0.5\Big(-\ln\chi^2 - 0.57721566 + 0.99999193\chi^2 - 0.24991055\chi^4 + 0.05519968\chi^6 - 0.00976004\chi^8 + 0.00107857\chi^{10}\Big) \tag{27}$$

Moreover, when $x \geq 1$,

$$I(\chi) = \frac{1}{2\chi^2\exp(\chi^2)}\frac{A}{B} \tag{28}$$

Here, $A = i\chi^8 + 8.5733287\chi^6 + 18.059017\chi^4 + 8.637609\chi^2 + 0.2677737$, $B = \chi^8 + 9.5733233\chi^6 + 25.6329561\chi^4 + 21.0996531\chi^2 + 3.9684969$. The total resistance can be calculated by summing the borehole thermal resistance and the thermal resistance of soil as in Eq. (29).

$$\sum R = R_b + R_{soil} = R_{fluid} + R_{pipe} + R_{grout} + R_{soil} \tag{29}$$

The heat exchange rate is calculated as the temperature difference between the fluid average temperature and the initial ground temperature divided by the total thermal resistance followed by Eq. (30).

$$\frac{Q}{L} = \frac{(T_{in} + T_{out})/2 - T_o}{\sum R} \tag{30}$$

The outlet temperature can be obtained with Eqs. (10) and (30) after getting the total thermal resistance of Eq. (29), and heat exchange rate per depth can be calculated.

5. Results and discussion

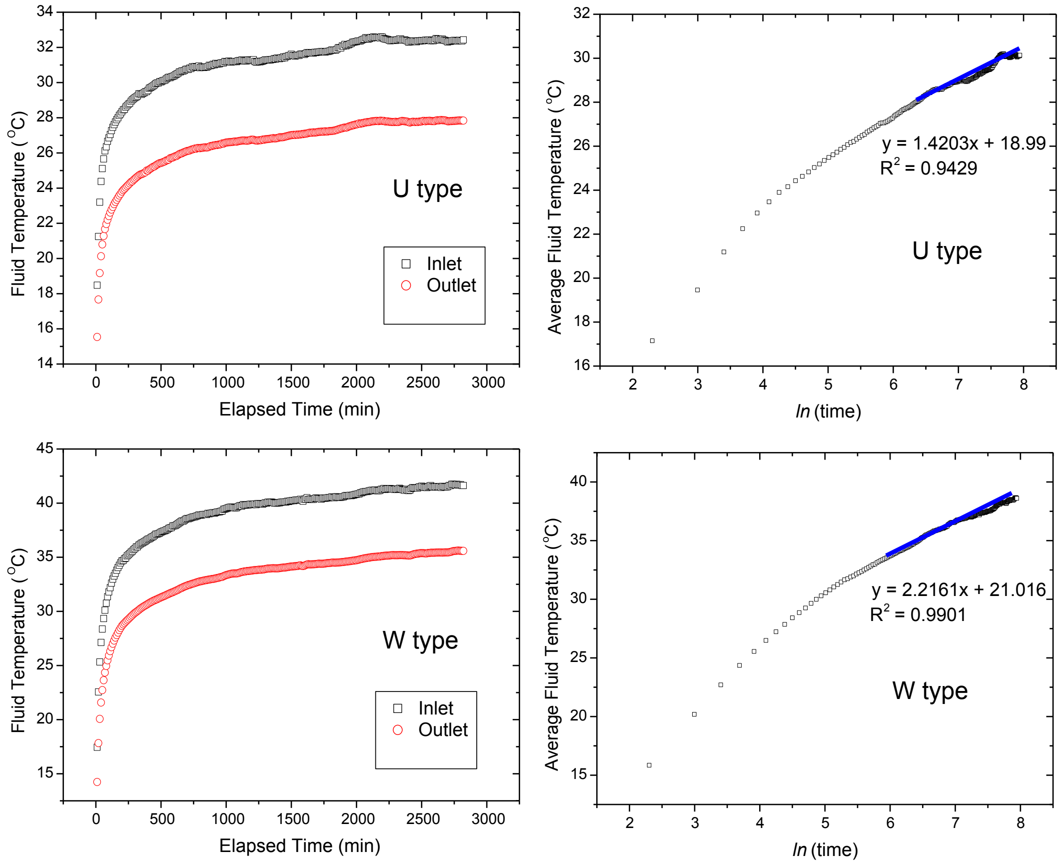
5.1. Experimental results

In this study, first, in-situ TRTs were conducted for 48 h until steady state conditions were achieved with U and W type GHEs to derive the ground thermal conductivity. Fig. 8 plots the temperature distribution at the inlet and the outlet of the GHE pipe, respectively. Heat-free water circulation was performed for 30 min to equalize soil and circulating fluid temperatures. The initial temperature of the soil from heat free water circulation was 16.44 °C for the U type GHE and 15.8 °C for the W type GHE. With the temperature value and the slope of ($\Delta T/\Delta \ln t$), the ground thermal conductivity from Eq. (9) was evaluated as 2.13 W/m K with the U type GHE and 2.15 W/m K with the W type GHE, respectively. The difference of the GHE type could lead to slightly different values of the ground thermal conductivity.

All the in-situ TPTs were conducted for 100 h under continuous operation conditions. Temperatures of the water at the inlet and the outlet were measured during the tests, and the flow rate was also measured at the outlet. The inlet temperature was 31 °C to consider the cooling operation, and the flow rate was 7–8 lpm. The heat exchange rates per length of U and W type GHEs were calculated with the temperature value at the inlet and outlet and the flow rate using Eq. (10). Fig. 9 shows the heat exchange rate with respect to time using U and W type GHEs. The average heat exchange rates for 100 h for U and W type GHEs were 35.71 W/m, 40.76 W/m, respectively. The W type GHE had a 10–15% higher heat exchange rate than the U type GHE. It can be thought that the W type GHEs had a relatively larger heat exchange area than the U type GHE.

5.2. Borehole thermal resistance

Fig. 10 shows the in-situ TRT results with the numerical analysis values of the fluid temperature with respect to time. The experimental values and numerical analysis results are in good agreement. Furthermore, after acquiring the borehole wall temperature value at the quasi-steady state condition through the numerical analysis shown in Fig. 11, Eq. (5) was used to calculate the borehole thermal resistance. The values were 0.233 m K/W and 0.209 m K/W for U and W type GHEs, respectively. Even though these results were not obtained from the experiments since temperature sensors were not installed on the borehole wall surface, the borehole



(a) Temperature distribution vs. time (b) Temperature distribution vs. lnt

Fig. 8. Fluid average temperature distribution during the TRT (Thermal response test).

thermal resistance value obtained through the numerical analysis using the borehole wall temperature would likely be similar to the actual experimental results. A U type GHE was installed like B case in Fig. 6, and pipe distance from center to center was about 6 ~ 7 cm. However, a W type GHE was installed between the A and B cases in Fig. 6, and pipe distance was about 5 cm. Thus, the coefficient of the shape factor in the W type GHE was calculated by interpolation between the values of A and B cases. Borehole thermal resistance values were also derived from the TPT results. As shown in Fig. 9, the temperature of the circulating fluid reached almost a steady state after 25 h. After calculating the soil resistance from Eq. (26), the average borehole thermal resistance was calculated from Eqs. (29) and (30) under the steady state condition.

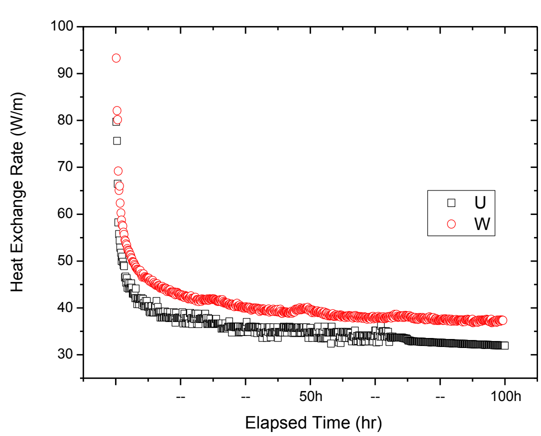


Fig. 9. Heat exchange rate for 100 h.

The analytically and experimentally determined borehole thermal resistance values from the TRT and TPT results are shown in Table 3. The borehole thermal resistance values from the TRT and TPT results had similar values. The borehole thermal resistance value, as well as the heat exchange rate, can be obtained from the TPT once the ground thermal conductivity is obtained. As there were some previous studies to derive the borehole thermal resistance using an infinite line source model as in Eq. (7) with the TRT results, the borehole resistance value was also calculated using Eq. (7). However, as the borehole thermal resistance varies greatly according to the arrangement and shape of GHEs, it is not adequate to use in the infinite line source model in calculating borehole thermal resistance because it is almost impossible to consider the GHE arrangement and shape exactly.

The comparison with analytical solution revealed that the SF method overestimates the borehole thermal resistance and that the EQD and multipole methods produce results similar to the numerical results. The multipole method gave more accurate results than the EQD, and hence it seems that the multipole method is better than the others in calculating the borehole thermal resistance because it considers the pipe configuration for any location and ground thermal properties. It is known that the borehole thermal resistance can be varied according to ground thermal conductivity [32].

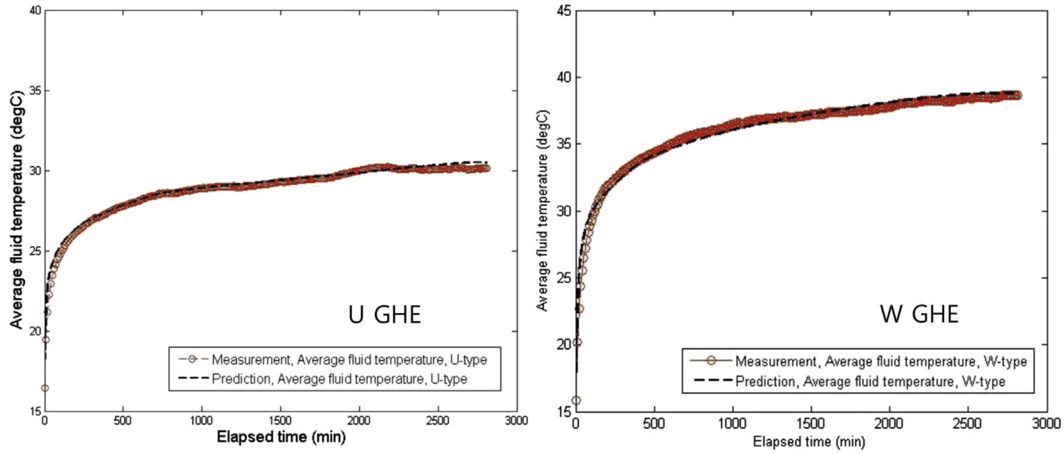


Fig. 10. Temperature variation of experimental results and numerical analysis.

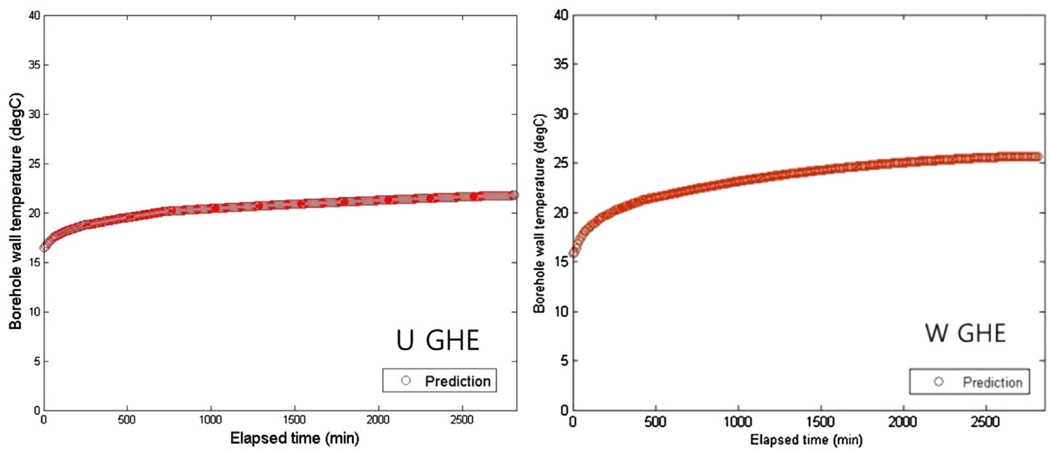


Fig. 11. Temperature variation at the borehole wall.

6. Conclusion

In this paper, U type and W type GHEs were installed in a landfill area. In-situ TRTs were conducted to measure the ground thermal conductivity and TPTs were conducted to measure heat exchange rates using U and W type GHEs. The borehole thermal resistance values were also calculated by a numerical analysis of the TRT, TPT results and line source theory with TRT data. Then, a comparative analysis with the analytical solution was then conducted, leading to the following conclusions.

1. The ground thermal conductivity calculated using the infinite line source model after conducting the in-situ thermal response test for a vertical closed-loop GSHP system with U type and W type heat exchangers was 2.13–2.15 W/m K. Generally, it is assumed that the ground thermal conductivity for the same ground will be the same, and we found here that the ground thermal conductivity was slightly greater when using the W type. This is probably the result of the difference of heat exchanger type shapes and the accuracy of temperature and power readings.
2. In-situ TPTs were also conducted for 100 h under continuous operation conditions. Heat exchange rates per length of U and W type GHEs were calculated under the cooling operation condition. The average heat exchange rates for 100 h for U and W type GHEs were 35.71 W/m, 40.76 W/m, respectively. The W type GHE had a 10–15% higher heat exchange rate than the U type GHE. The W type GHEs have a relatively larger heat exchange area than the U type GHE.
3. With regard to the GSHP system design, the ground thermal conductivity and borehole thermal resistance are very important factors, and hence the borehole thermal resistance value was calculated through a numerical analysis with the TRT results. In order to calculate the borehole thermal resistance based on the test in this study, numerous temperature sensors have to be installed on the borehole wall surface in the length and circumference directions. However, installing temperature sensors on the borehole wall surface was not possible due to the site and construction conditions. Therefore, the site and test conditions were modeled exactly through a numerical analysis to reproduce the site conditions, and the circulating fluid

Table 3
Summary of borehole thermal resistance values.

GHE type	FEM (based on TRT)	ILSM (TRT)	TPT	Multipole method	Series	
					SF	EQD
U type	0.233	0.215	0.230	0.233	0.282	0.227
W type	0.208	0.190	0.209	0.209	0.258	0.205

SF: Shape factor.
EQD: Equivalent diameter.
ILSM: Infinite line source model.

temperature measured through the thermal response test was found to be almost the same as the numerical analysis result. Based on this, the calculated borehole thermal resistance was 0.233 m K/W for the U type GHE and 0.209 m K/W for the W type GHE using the borehole wall surface temperature value obtained through the numerical analysis. Borehole thermal resistance values were also derived from the TPT results. With the heat exchange rate, soil resistance and average fluid temperature, the borehole thermal resistance value could be obtained under the steady state condition. Therefore, the borehole thermal resistance values from the TRT and TPT results had similar values. It can be concluded that the borehole thermal resistance value, as well as the heat exchange rate, can be obtained from the TPT once the ground thermal conductivity is obtained.

4. The borehole thermal resistance value from the TRT and TPT results was compared with various analytical solutions. The comparison results showed that the SF model overestimates the borehole thermal resistance while the EQD and multi-pole methods were in better agreement with the numerical analysis results. In addition, the borehole thermal resistance values calculated using the infinite line source model did not have significant differences from the test results. It has been reported that the borehole thermal resistance value varies greatly according to the arrangement and shape of the GHE, but because it is difficult to consider the heat exchange arrangement and shape with the infinite line source model, calculating the borehole thermal resistance using the infinite line source model is not desirable.
5. In conclusion, this study confirmed that the borehole thermal resistance value for the vertical closed-loop GSHP system design is accurate when using values obtained with the multi-pole method or the EQD method. However, unlike the SF and EQD methods, the multi-pole method can reflect the thermal conductivity of the ground, and as such further research on the effect that ground thermal conductivity has on the borehole thermal resistance is necessary for a more accurate analysis of the borehole thermal resistance analytical solution.

Acknowledgment

This research was supported by the basic research project by the National Research Foundation of Korea under the Ministry of Science, ICT and Future Planning, and by the 2011 Construction Technology Innovation Project (11 Technology Innovation E04) under the Korea Agency for Infrastructure Technology Advancement.

References

[1] Florides GA, Pouloupatis PD, Kalogirou S, Messaritis V, Panayides I, Zomeni Z. The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus. Energy 2011;36:5027–36.
[2] Johnston IW, Narsilio GA, Colls S. Emerging geothermal energy technologies. KSCE J Civ Engrs 2011;15(4):643–53.
[3] Li M, Lai ACK. New temperature response functions (G functions) for pile and borehole ground heat exchangers based on composite-medium line-source theory. Energy 2012;38:255–63.
[4] Man Y, Yang H, Diao N, Cji P, Liu L, Fang Z. Development of spiral heat source model for novel pile ground heat exchangers. HVAC R Res 2011;17(6):1075–88.
[5] International Energy Agency. Renewable energy essentials: geothermal; 2010.
[6] Choi JC, Lee SR, Lee DS. Numerical simulation of vertical ground heat exchangers: intermittent operation in unsaturated soil condition. Comput Geotech 2011;38:949–58.
[7] Beck M, Bayer P, Paly MC, Hecht-Mendez J, Zell A. Geometric arrangement and operation mode adjustment in low-enthalpy geothermal borehole fields for heating. Energy 2013;49:434–43.
[8] Gao J, Zhang X, Liu J, Li K, Yang J. Numerical and experimental assessment of thermal performance of vertical energy piles: an application. Appl Energy 2008;28:2295–304.
[9] Jun L, Xu Z, Jun G, Jie Y. Evaluation of heat exchange rate of GHE in geothermal heat pump systems. Renew Energy 2009;34:2898–904.
[10] Pahud D, Matthey B. Comparison of the thermal performance of double U-pipe borehole heat exchangers measured in situ. Energy Build 2001;33:503–7.
[11] Park H, Lee SR, Yoon S, Choi JC. Evaluation of thermal response and performance of PHC energy pile. Appl Energy 2013;103:12–24.
[12] Beier RA, Smith MD, Spitler JD. Reference data sets for vertical borehole ground heat exchanger models and thermal response test analysis. Geothermics 2011;40:79–85.
[13] Park H, Lee SR, Yoon S, Shin H, Lee DS. Case study of heat transfer behavior of helical ground heat exchanger. Energy Build 2012;53:137–44.
[14] Roth P, Georgiev A, Busso A, Barraza E. First in situ determination of ground and borehole thermal properties in Latin America. Renew Energy 2004;29(12):1947–63.
[15] Lee CH, Park MS, Kang SH, Sohn BH, Choi HS. Comparison of effective thermal conductivity in closed-loop vertical ground heat exchangers. Appl Therm Eng 2011;31:3669–76.
[16] Park S, Lee SR, Park H, Yoon S, Chung JH. Characteristics of an analytical solution for a spiral coil type ground heat exchanger. Comput Geotech 2013;49:18–24.
[17] Carslaw H, Jaeger J. Conduction of heat in solids. Oxford; 1947.
[18] Ingersoll LR, Adler FT, Plas HJ, Ingersoll AC. Theory of earth heat exchangers for the heat pump. ASHVE Trans 1950;56:167–88.
[19] Ingersoll L, Zobel O, Ingersoll A. Heat conduction with engineering geological and other applications. New York: McGraw-Hill; 1954.
[20] COMSOL. Multiphysics user's guide. COMSOL Multiphysics version 4.2a; 2011.
[21 Incropera FP, Burkhard S. Fundamentals of heat and mass transfer. 4th ed. John Wiley and Sons; 1996.
[22] Yun TS, Santamarina JC. Fundamental study of thermal conduction in dry soils. Granul Matter 2008;10:197–207.
[23] Park H, Park HS, Lee SR, Go GH. Estimation of thermal conductivity of weathered granite soils. J Korean Soc Civ Engrs 2012;32(2C):69–77 [in Korean].
[24] Shonder JA, Beck JV. Field test of a new method for determining soil formation thermal conductivity and borehole resistance. ASHARE Trans 1999;106:843–50.
[25] Remund CP. Borehole thermal resistance: laboratory and field studies. ASHARE Trans 1999;105:439–45.
[26] Gaia Geothermal. Ground loop design software. GLD2012.
[27] Bennet J, Claesson J, Hellstrom G. Multipole method to compute the conductive heat flows to and between pipes in a composite cylinder. Notes on heat transfer. Lund, Sweden: Lund University; 1987. p. 3.
[28] Hu P, Yu Z, Zhu N, Lei F, Yuan X. Performance study of a ground heat exchanger based on the multipole theory heat transfer model. Energy Build 2013;65:231–41.
[29] Young TR. Development, verification and design analysis of the borehole fluid thermal mass model for approximation short term borehole thermal response. Master Thesis, Oklahoma State University.
[30] Earth Energy Designer, Blocon. (www.buildphysics.com).
[31] Rohsenhow WM, Hartner JP, Ganic EN. Handbook of heat transfer fundamental. New York: McGraw-Hill; 1985.
[32] Go GH, Yoon S, Park DW, Lee SR. Thermal behavior of energy pile considering ground thermal conductivity and thermal interference between piles. J Korean Soc Civ Engrs 2013;33(6):2381–91 [in Korean].