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Thermal performance evaluation and parametric study of a horizontal ground heat exchanger

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ABSTRACT

A ground-source heat pump (GSHP) system uses a relatively constant ground temperature to emit heat in summer and to obtain heat during winter for heating and cooling energy. Among diverse GSHP systems, in designing a closed horizontal system, it is important to accurately estimate the thermal performance of the horizontal ground heat exchanger (GHE). Therefore, in this study, we investigated the performance of a horizontal GHE via experiments and numerical analyses. Thermal response tests (TRTs) were conducted to evaluate heat exchange rates by using horizontal slinky- and spiral-coil-type GHEs installed in a 5 m × 1 m × 1 m steel box filled with dried Joomunjin sand. Numerical analyses were conducted for verification with experimental results and a parametric study of affecting parameters on horizontal GHE. The results of the TRTs and the numerical analyses were well matched, and coil-type GHEs were found to perform better than the horizontal slinky-type GHEs. Our results show that, among horizontal GHE design parameters, GHE type and soil thermal conductivity are the main factors to determine the heat exchange rate of a GHE, whereas the pipe diameter does not have any effect on the GHE performance.

1. Introduction

As global have developed dramatically, the depletion of fossil fuels has increased the need for renewable energy sources. Accordingly, renewable energy has been widely used throughout the world as a substitute for fossil fuels due to its ecological advantages. Among various renewable energy resources, the use of geothermal energy has been regarded as the most efficient way of space heating and cooling (Johnston et al., 2011; Lee, 2011).

A ground-source heat pump (GSHP) system obtains heating and cooling energy through ground heat exchangers (GHEs) by absorbing or emitting heat from the ground, where the temperature is maintained as relatively constant regardless of the weather conditions. Such GSHP systems can be classified as either open-type system or closed-type. An open-type system uses the groundwater or surface water directly to obtain heating and cooling energy. A closed-type system uses circulating fluid flowing in the ground heat exchanger to exchange the heat between heat exchangers and the ground around them.

Closed-type systems can be used vertically or horizontally, depending on the installation method. A closed vertical system uses vertically installed GHEs in which circulating fluid flows under the ground to a depth of 150–200 m, and the empty space inside a borehole is filled with grout. Vertical systems can entail high initial construction costs, mainly due to creating deep boreholes, but they are widely used because of their high reliability. A closed horizontal system can be utilized as an alternative to the vertical system. Since GHEs in the horizontal system are installed at shallow depths of 1–3 m parallel to the ground surface, expensive boring costs are avoided. Thus, horizontal GHEs could be more useful than other types of GHEs in terms of cost efficiency. However, horizontal GHEs require a great deal of land space because of their installation orientation. Therefore, it is very important to minimize the land space requirements for the installation of horizontal GHEs by estimating accurately the performance of a given horizontal GHE to design the minimal horizontal trench length required. Prior studies have evaluated the performances of horizontal GHEs through experiments and numerical simulations (Mustafa and Hikmet, 2004; Florides et al., 2013). Meanwhile, among various types of horizontal GHEs, slinky- and coil-type GHEs can reduce horizontal trench length by arranging the pipe as a ring shape instead of a straight line that is

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used in the horizontal line configuration. A slinky-type GHE can be designed using a ground loop design (GLD), which is the only horizontal heat exchanger design program (Gaia Geothermal, 2012), and some studies evaluating slinky-type GHEs have been widely conducted (Chiew et al., 2013; Yupeng et al., 2010; Hikari et al., 2012). However, there is no other program or method to accurately design horizontal coil-type GHEs and researches considering horizontal coil-type GHEs are insufficient.

Therefore, more studies on horizontal coil-type GHEs are necessary to determine an efficient configuration of horizontal GHEs. As an example of such research, Congedo et al. (2012) carried out computer simulations of coil- and slinky-type horizontal GHEs considering soil thermal conductivity, installation depth, and fluid velocity. However, horizontal coil-type GHEs have never been thoroughly studied by experimental methods.

Thus, in this study, to examine how a specific GHE type affects the performance of GHE unit, a numerical analysis was performed, and the results were compared with the experimental data obtained from a thermal response test (TRT) using a steel-box mockup. Furthermore, using the same verified conditions in the numerical analysis, a thermal performance test (TPT) and a parametric study were performed to investigate in detail how horizontal GHE design parameters have effect on horizontal heat exchangers to establish the most significant design parameters.

2. Experiment

2.1. Description

The heat transfer process of a GHE is related to the repetition of absorbing and releasing heat to and from the borehole and the surrounding ground as heat transfer fluid flows through a pipe within the borehole. Meanwhile, heat transfer between the GHE and the surrounding ground consists of a complicated mechanism, but heat transfer to the ground mainly occurs by conduction (Park et al., 2013; Choi et al., 2011). The heat-transfer-governing equation used for conduction in the ground is as follows:

$$-\frac{d}{di}(\lambda\frac{dT}{di})+\rho c\frac{dT}{dt}+q_{\rm i}=0(i=x,y,z) \quad (1)$$

where T is the temperature, λ is the thermal conductivity, ρ is the density, c is the specific heat capacity, and $q_{\rm i}$ is the internal heat generation.

Various models for the heat transfer around a GHE, which are based on either analytical methodologies or numerical methods, are used to estimate the thermal conductivity of the ground (Yang et al., 2010). A TRT can be carried out to determine the ground thermal conductivity, using analytical models, by injecting constant heat to the equipment. On the other hand, a TPT is performed to evaluate the performance of a GHE by assessing the heat exchange rate of a GHE under the condition where the inlet temperature is kept constant (Yoon et al., 2014; Gao et al., 2008). The heat exchange rate can be calculated using Eq. (2).

$$Q=mc(T_{\rm in}-T_{\rm out}) \quad (2)$$

where $T_{\rm in}$ is the inlet temperature of the fluid, $T_{\rm out}$ is the outlet temperature of the fluid, and m is the flow rate of the fluid.

However, in the present study, a TPT could not be performed using the small-scale steel-box because the thermal conductivity of the sand was so low that the inlet temperature of the circulating water in the TPT could not be maintained constantly. Therefore, the TRTs were conducted with no heat injection, using only the power of the circulating pump, while the heat exchange rates were obtained using Eq. (2) in the same manner as when calculating the heat exchange rate in a TPT.

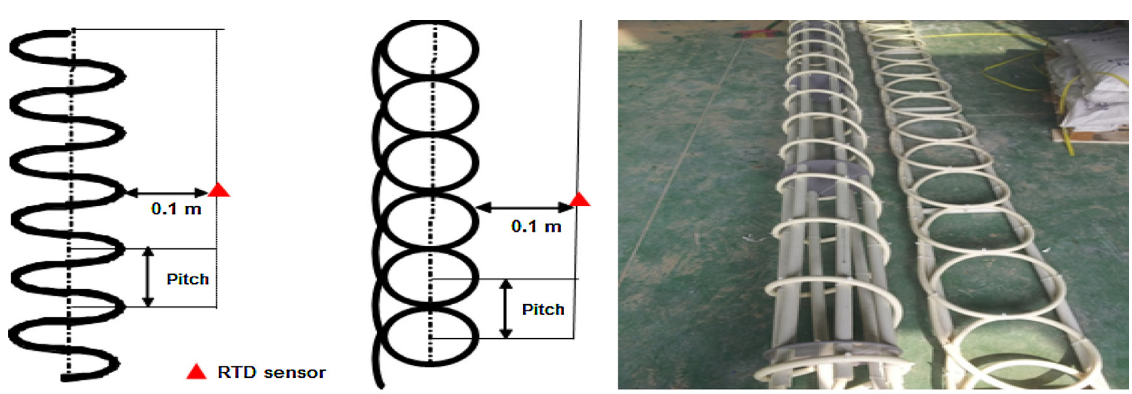
2.2. Experimental setup

In the experiment, a 5 m × 1 m × 1 m steel-box filled with dried Joomunjin standard sand was used to reflect the surrounding ground, while TPT equipment was installed to supply the circulating water and constant power to the inside of the heat exchanger buried in the ground. The horizontal GHEs were made of polybutylene (PB) pipe, which is commonly used in GHEs, and the outer and inner diameters of the pipe were 20 mm and 16 mm, respectively. The diameter of the ring in both the coil- and slinky-type heat exchangers was 30 cm, and the horizontal length of the GHEs was 4 m. To measure the temperature change of the surrounding soil, a resistance temperature detector (RTD) sensor was installed 10 cm away from the edge of the GHE, as shown in Fig. 1. The length of the coil-type heat exchanger can be calculated by Eq. (3) (Park et al., 2012), as follows:

$$L=\int_0^h\sqrt{\omega^2 r_o{}^2+1}dz=h\sqrt{\omega^2 r_o{}^2+1} \quad (3)$$

In Eq. (3), L is the total length of the coil-type GHE, h is the horizontal length of the heat exchanger, and r_0 is the radius of the coils. The wave number (ω), which is the number of complete ring cycles per unit length, can be calculated by a$2N\pi/h$and N is the number of the rings of the coil (Fig. 2). In addition, Eq. (4) is used to obtain the total length of the horizontal slinky-type GHE (Ministry of Commerce, Industry and Energy, 2006), as follows:

$$L=NL_l+2PN+\pi d/2+d \quad (4)$$



(a) Diagram of horizontal GHE (b) GHE in experiment

Fig. 1. Coil-type and slinky-type of horizontal GHE.

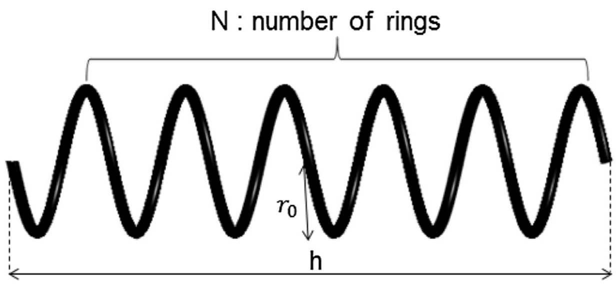


Fig. 2. Length of the coil-type GHE.

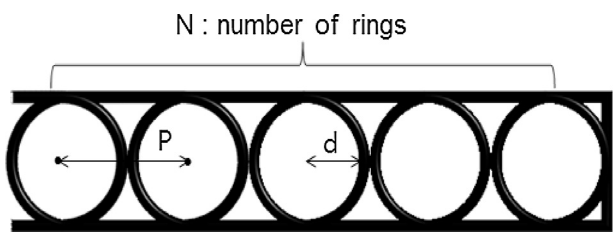


Fig. 3. Length of the slinky-type GHE.

Table 1
Specification of horizontal heat exchangers in the experiment.

GHE	Pitch (P)	Number of loop (N)	Total length (L)
Spiral coil	P = 30 cm	N = 15	L = 18 m
Horizontal slinky	P = 30 cm	N = 15	L = 24 m

Table 2
Properties of standard Joomunjin sand.

Properties	Value
Uniformity coefficient, c_u	2.06
Curvature coefficient, c_c	1.05
Specific gravity, G_s	2.65
Maximum dry density, $\gamma_{d\,\max}$ (kN/m^3)	16.17
Minimum dry density, $\gamma_{d\,\min}$ (kN/m^3)	13.49
Water content, w (%)	0

Here, N is the number of the rings of the slinky loops, L_l is the circumference of the slinky loops, P is the pitch of the slinky loops and d is the radius of the slinky loops (Fig. 3).

In this study, thermal response tests (TRTs) were conducted with respect to a case in which the pitch of both types of horizontal GHE were 30 cm, which is the same as the diameter of the rings. Table 1 shows the specifications of the GHEs calculated by using Eqs. (3) and (4), as used in the TRTs. To analyze the difference of the heat exchange rate according to the pipe shape, all specifications were set to be the same for both GHE types, except for total pipe length. Table 2 shows the properties of the standard Joomunjin sand contained within the steel box. Tests were conducted in dry conditions. The procedure of the experiment is shown in Fig. 4

2.3. Experimental results

The TRTs were conducted for 30 h continuously to measure the heat exchange rate for the two different types of the horizontal GHEs. The temperature of the circulating water reached a near steady state after 20 h from the beginning of the TRT (Fig. 5). The initial temperature of the Joomunjin sand was 17–18 °C and the average flow rate of the circulating water was 4–5.5 lpm. The heat exchange rate and the heat exchange rate per pipe length for the horizontal slinky- and coil-type GHEs, using a 30 cm pitch are shown in Fig. 6 and Table 3. The total average heat exchange

Table 3
Summary of the results.

GHE	Pitch (P)	Heat exchange rate (W)	Heat exchange rate per pipe length (W/m)
Spiral coil	P = 30 cm	260.2	14.45
Horizontal slinky	P = 30 cm	255.3	10.64

rates for the coil- and horizontal slinky-type GHEs were 260.2 W and 255.3 W, respectively. In addition, the average heat exchange rates per pipe length for the coil- and horizontal slinky-type GHEs were 14.45 W/m and 10.64 W/m, respectively, as shown in Fig. 7. The results indicated that the performance and efficiency per unit length of the coil-type GHE is better than those of the slinky-type GHE. In order to analyze the difference of performance of the two kinds of heat exchangers, independent-samples T test was conducted (Anthony, 2012). Table 4 shows the result of T-test. Significant probability was almost zero regardless of assumption of equal variance, and it is evident that there is a significant difference in heat exchange rates between the coil-type and slinky-type GHE (Yoon et al., 2015).

3. Numerical analysis

3.1. Description

The numerical analysis program used in this study was the Midas NFX which can analyze heat flow based on the finite element method (FEM) and computational fluid dynamics (CFD) (Midas IT, 2014). The governing equation of the numerical analysis based on fluid flow combined with heat flow is Navier–Stokes equation shown in Eq. (5).

$$\rho\left(\frac{\partial v}{\partial t}+(v\cdot\nabla)v\right)+\nabla p-\nabla\cdot(\mu\nabla v)=\rho f,\quad \nabla\cdot v=0 \tag{5}$$

Here, v refers to the velocity vector, p is the pressure field, ρ is the density, μ is the coefficient of viscosity and f is the volume acceleration.

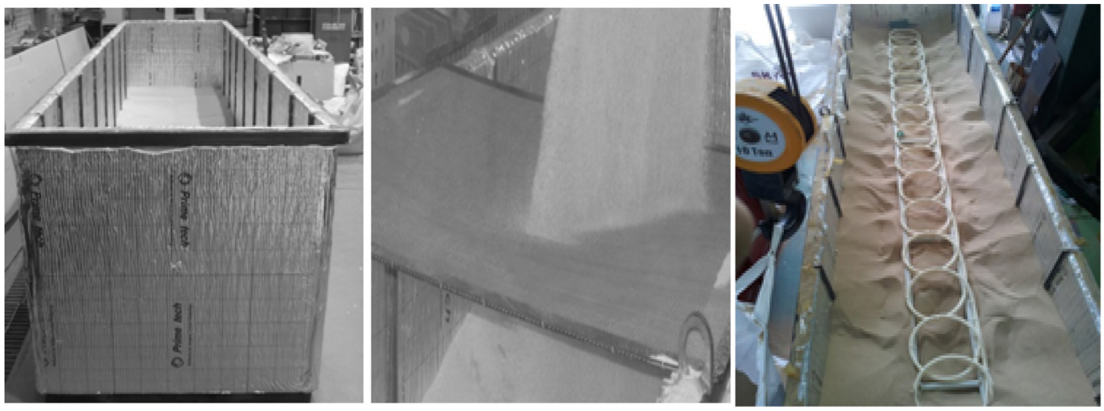
As the laws of conservation of mass and conservation of momentum are applied to the heat flow in Navier–Stokes, the equation can be used to perform heat flow and circulating fluid flow analyses simultaneously.

3.2. Verification

Prior to conducting a parametric study, to verify the suitability of the use of the numerical analysis program, results of numerical analysis using Midas NFX were compared with the experimental data. As in the experiment, TRTs in the numerical analysis program were carried out using a 5 m × 1 m × 1 m steel box filled with dried Joomunjin standard sand.

In order to compare the test results with those of the numerical analysis, identical material properties, including the boundary conditions of both tests, were applied in the program, and 3D numerical models with the surrounding ground in the steel box were developed, as shown in Table 5 and Fig. 8. The inlet temperature should have been constant in the TPT; however, in the test, the inlet temperature of the circulating fluid was increased due to the circulating pump power. Thus, in the numerical program, the inlet temperature of the circulating fluid was also set as equal to that in the test, in which the temperature increased due to the pump power (Fig. 9).

As shown in Table 6, the heat exchange rates of horizontal coil-type GHE were higher than those of slinky-type GHE in both cases. The values in the table were obtained by averaging the results at each time step. The ground temperature also showed a similar



(a) Steel box setting (b) Composition of sample (c) Installation of horizontal GHE

Fig. 4. Process of TRT.

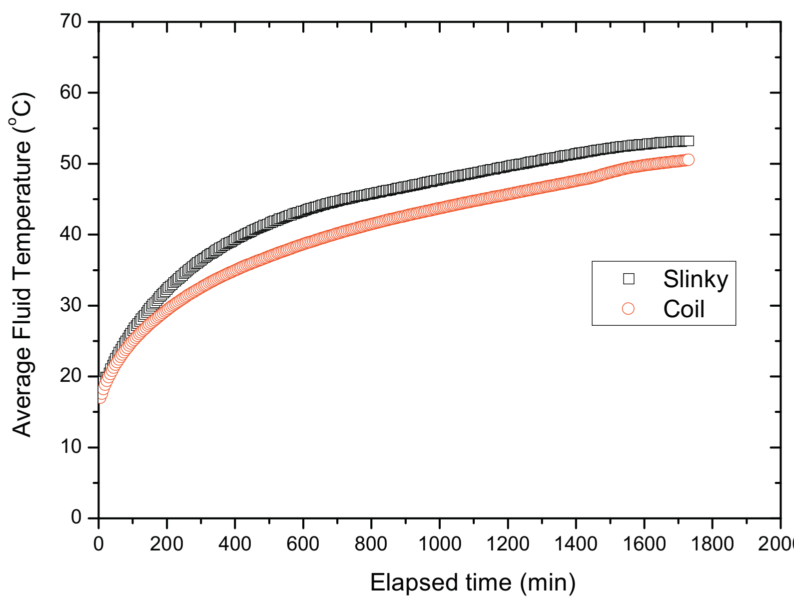


Fig. 5. Average fluid temperature.

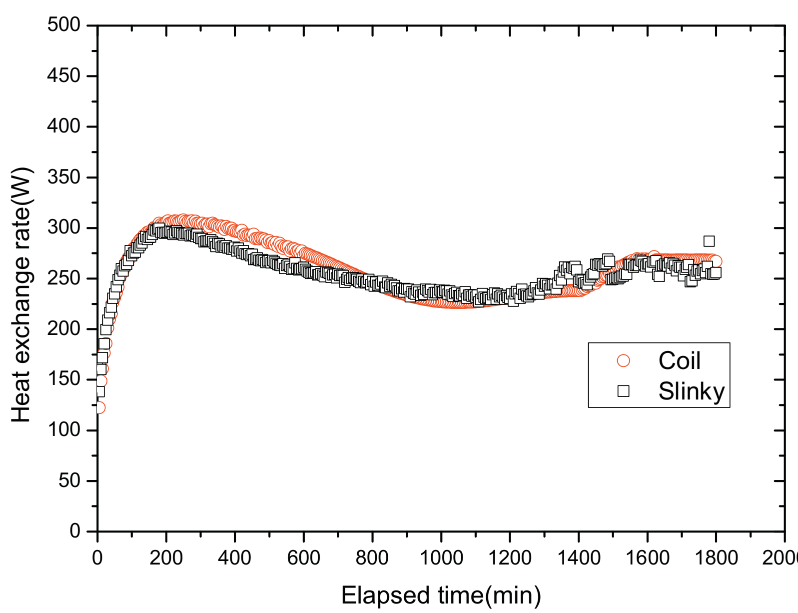


Fig. 6. Heat exchange rate.

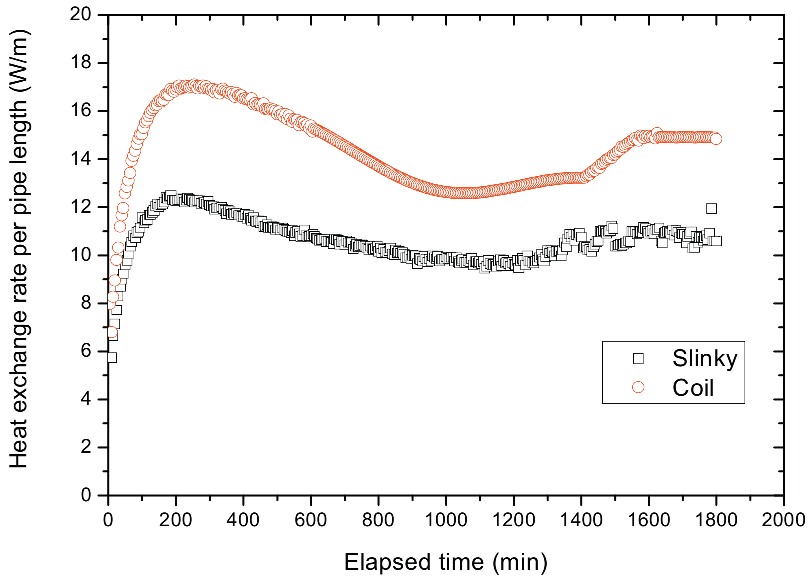
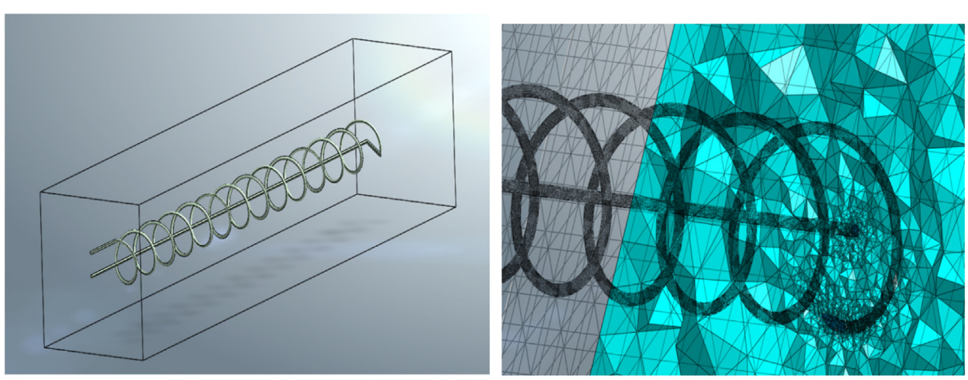


Fig. 7. Heat exchange rate per length.

Table 4
Result of independent-samples *T* test.

	F	Sig	t	df	Sig. (2-failed)	Mean difference	Std.error difference	95% Confidence interval of the difference	
								Lower	Upper
Equal variances assumed	120.798	.000	37.642	718	.000	3.73782	.09930	3.54287	3.93277
Equal variances not assumed			37.642	567.8	.000	3.73782	.09930	3.54278	3.93286



(a) Finite element model (b) Mesh formed in the program

Fig. 8. Finite element model for the numerical simulation.

Table 5
Specification of numerical analysis.

Type of GHE	Coil(20 mm)	Slinky(20 mm)
Diameter	30 cm	30 cm
Pitch	30 cm	30 cm
Rings	$N = 15$	$N = 15$
Flow rate	4.72 lpm	3.97 lpm
Velocity	0.251 m/s	0.211 m/s
Properties of the Joomunjin sand in the steel box	- Density: 1400 kg/m3 - Thermal conductivity: 0.26 W/mK - Specific heat: 807 J/kgK	

Table 6
Comparison of numerical-analysis results with experimental results.

	Results	Numerical analysis	Experiment
Coil- type GHE	Heat exchange rate	282.1 W	260.2 W
	Soil temperature	21.01 °C	21.11 °C
Slinky-type GHE	Heat exchange rate	280.9 W	255.3 W
	Soil temperature	24.05 °C	24.15 °C

tendency to the heat exchange rate. That is because heat exchangers exchange a large amount of heat with the soil when the heat exchange rate is high. Figs. 10 and 11show the heat exchange rate and the soil temperature variation for both types of GHE with elapsed time.

Small differences of approximately 8–10% between the tests and numerical analysis results were observed because of the various site conditions and experimental errors. According to the results,

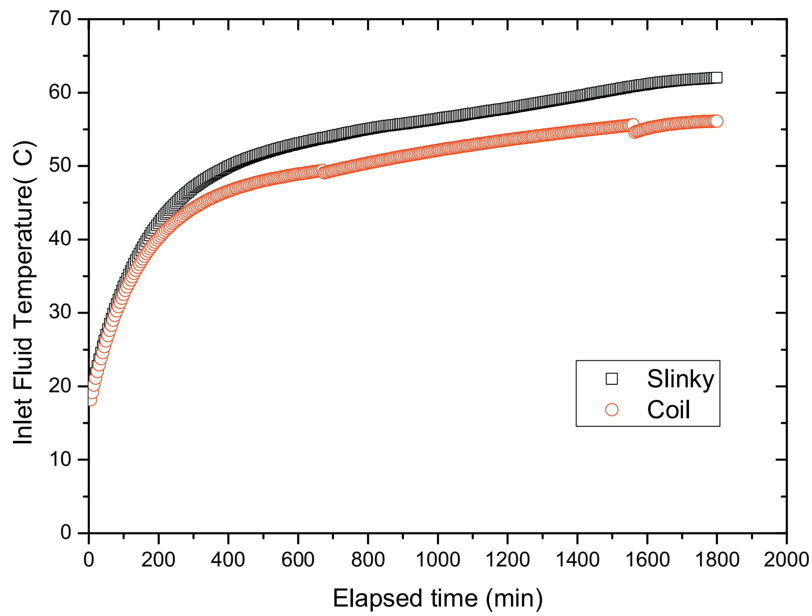


Fig. 9. Inlet fluid temperature of the experiments and numerical analysis.

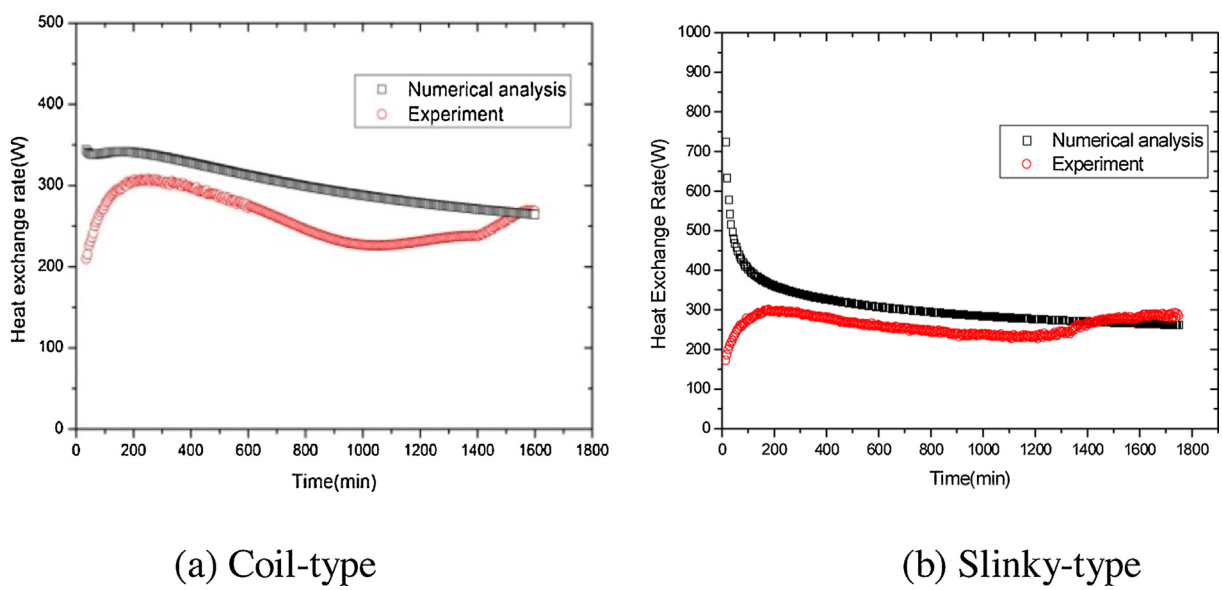


Fig. 10. Comparison of heat exchange rate between experiments and numerical analysis.

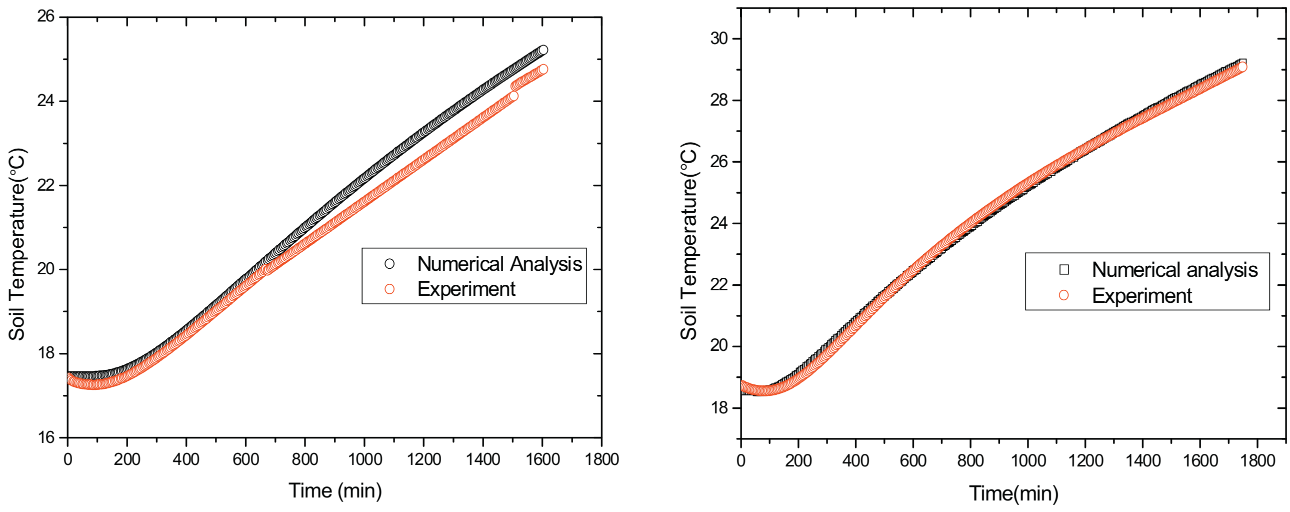
the heat exchange rates of the coil-type GHE and the surrounding soil temperature were higher than those observed for the slinky-type GHE. Thus, it can be concluded that the Midas NFX program can accurately predict results, and its results matches well with actual experimental results.

3.3. Parametric study

To compare the performance of horizontal coil-type and slinky-type GHEs more accurately, TPTs were conducted based on the numerical analysis using the Midas NFX. Furthermore, to analyze the effect of design parameters of horizontal GHEs, a parametric study based on the verified numerical analysis was performed. Among the many parameters affecting the performance of a horizontal GHE, type of horizontal GHE, surrounding soil thermal conductivity, and pipe diameter were chosen as critical parameters, considering the shallow installation depth of the horizontal GHE in this study.

The properties and boundary conditions in the parametric study were the same as those used in the verification analysis. However, instead of TRTs in the experiment and verification of numerical analysis, TPTs were conducted in a parametric study because the inlet temperature could be held constant in the numerical analysis, unlike in the experiment. Thus, the temperature of the circulating water was set at a constant value of 30 °C. Material properties and the boundary conditions used in the analysis are shown in Table 7.

The use of a small-scale steel box and the low soil thermal conductivity caused the differences of inlet and outlet circulating water temperature to converge quickly as the heat transfer between the GHE and the surrounding soil reached a steady state; therefore, the analysis was performed for only 10 h.



(a) Coil-type (b) Slinky-type

Fig. 11. Comparison of soil temperature between experiments and numerical analysis.

Table 7
Specification of the parametric study.

Analysis	Thermal performance test	
Type of GHE	Coil(20 mm)	Slinky(20 mm)
Flow rate	4.72 lpm	
Velocity	0.251 m/s	
Inlet temperature	30 °C	
Analysis time	36,000 sec	

Table 8
Results of thermal performance test for the parametric study.

Soil thermal conductivity (W/mK)	Type of GHE	Heat exchange rate(W)	Soil temperature(°C)
0.26	Coil-type	147.38	19.18
	Slinky-type	131.71	19.05
0.5	Coil-type	223.68	20.00
	Slinky-type	201.3	19.77
0.8	Coil-type	301.91	20.64
	Slinky-type	273.21	20.38
1.1	Coil-type	369.51	21.07
	Slinky-type	336.96	20.82

3.3.1. *Type of heat exchanger*

Horizontal-line-type GHEs have the advantage of a relatively simple shape and thermal mechanism compared to other types of GHEs. However, horizontal-line-type GHEs are inferior, in terms of performance, compared to horizontal coil- or slinky-type GHEs due to their straight configuration. Thus, in the present work, we examined only the performances of slinky- and coil-type GHEs.

The experimental data and numerical verification results showed that the coil-type GHE performs better than the slinky-type GHE when the soil thermal conductivity is 0.26W/mK. To obtain consistent results, each TPT was performed using the Midas NFX by varying the soil thermal conductivity values to 0.26 W/mK, 0.5 W/mK, 0.8 W/mK, and 1.1 W/mK. Each value was chosen by considering the relatively shallow installation depth of the horizontal heat exchangers. The analysis results of the thermal performance evaluation for each type of GHE are shown in Table 8.

The heat exchange rates of the coil-type GHE were always about 10% higher than those of the slinky-type for the considered soil thermal conductivity values. The results also show that horizontal coil-type GHEs had 10-11% higher heat exchange rates, compared to slinky-type GHEs, and higher surrounding soil temperatures. Therefore, it seems that the performance of coil-type GHEs is superior to that of slinky-type GHEs, regardless of the soil thermal conductivity. Fig. 12 shows an example heat exchange rate and ground temperature variation for the two different types of horizontal heat exchangers.

The results corresponded to the different configuration of GHEs. Horizontal slinky-type GHEs use a 2D-shaped pipe that is installed parallel to the ground, with rings of pipe overlapping pipe. On the other hand, horizontal coil-type GHEs have a 3D-spiral shaped pipe with rings of pipe that do not overlap each other. Since a coil-type GHE has a larger heat exchange ground volume with the ground than that of a slinky-type GHE, active heat exchange is more likely to occur in a coil-type GHE than in a slinky-type GHE.

3.3.2. *Soil thermal conductivity*

Soil thermal conductivity is significantly influenced by its saturation and dry density. Other factors that have a secondary effect upon soil thermal conductivity include mineral composition, temperature and time (Fireke et al., 1992; Penner et al., 1975; Brandon and Mitchell, 1989; Becker et al., 1992). Since a horizontal GHE is completely surrounded by the soil, the soil thermal conductivity has an effect on the heat transfer between the circulating fluid in the GHE and the surrounding soil, and this affects the performance of a horizontal GHE. Thus, this study investigated in detail how soil thermal conductivity affects the performance of horizontal GHE. The testing values of soil thermal conductivity and the analysis results of GHE performance were the same as those shown in Table 8. The heat exchange rates and the soil temperature obtained by TPTs with varying soil thermal conductivity in the numerical analysis are shown in Figs. 13 and 14, respectively.

The heat exchange rates of the tested GHEs were proportionally increased with respect to a heat exchange rate of 0.26 W/mK of soil thermal conductivity. With the coil-type GHE, soil thermal conductivity of 0.5W/mK, 0.8W/mK, and 1.1W/mK increased the GHE heat exchange rate by 52%, 104.9% and 150.7%, respectively. With the slinky-type GHE, soil conductivity of 0.5 W/mK, 0.8 W/mK, and 1.1W/mK increased the GHE heat exchange rate by 52.8%, 107.4% and 155.8%, respectively. The results showed that higher soil thermal conductivity corresponded to higher GHE heat exchange rates

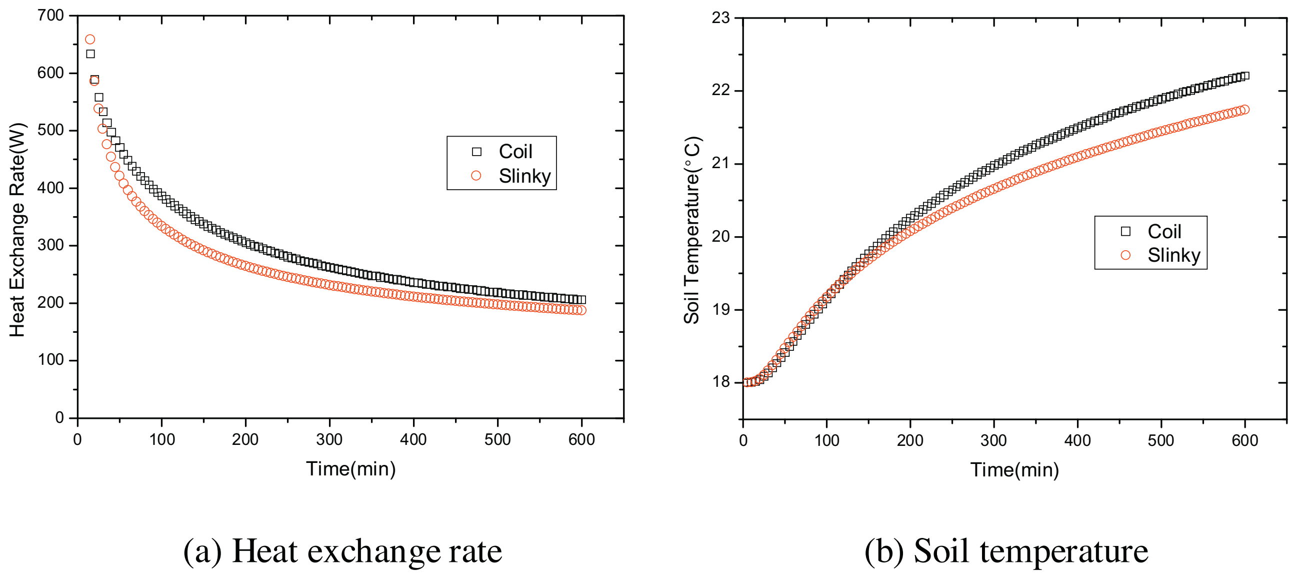


Fig. 12. Comparison of analysis results (type of horizontal GHE, λ = 0.8W/mK).

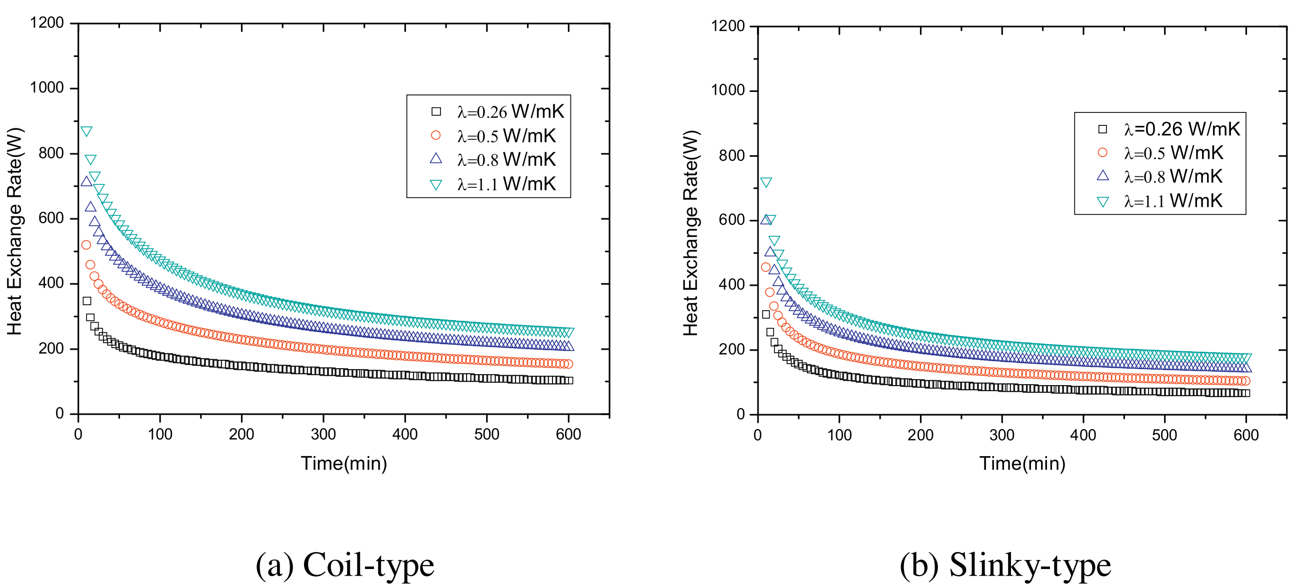


Fig. 13. Comparison of heat exchange rate (soil thermal conductivity).

along with higher soil temperatures. This is because the higher the soil thermal conductivity, the larger the amount of circulating fluid heat transferred from inside of the pipe to the surrounding soil. The changes in heat exchange rates with respect to soil thermal conductivity were quite similar for both types of horizontal GHE. Therefore, it is crucial to determine soil thermal conductivity accurately for proper GHE installation depth since the GHE heat exchange rate will vary with soil thermal conductivity, regardless of GHE type.

Table 9
Results of the thermal performance test according to pipe diameter.

	Pipe diameter(mm)	Heat exchange rate(W)	Soil temperature(°C)
Coil- type GHE	20	222.68	20.01
	25	208.64	20.07
	32	208.12	20.16
Slinky-type GHE	20	201.31	19.92
	25	208.43	20.11

3.3.3. Pipe diameter

The velocity and flow rate of the circulating fluid in the GHE can be affected by the cross-sectional area of the pipe, and this may influence the thermal performance of a horizontal GHE. Thus, by varying the diameters of a horizontal GHE pipe, various heat exchange rates were obtained to examine the effect of pipe diameter on the performance of a horizontal GHE. The diameters of GHE pipe used were 20 mm, 25 mm, and 32 mm for the spiral-coil-type GHE and 20 mm, and 25 mm for the slinky-type GHE. In the process, the velocity varied according to the diameters so that the flow rate, which is affected by the diameter and velocity, kept constant. The heat exchange rates obtained with each diameter are shown in Table 9 and Fig. 15.

Observed variations of the heat exchange rate due to the changes in pipe diameter were negligible. As the diameter of GHE pipe was increased, the differences between the inlet and outlet temperatures of the circulating fluid became higher, but the pipe's capacity,

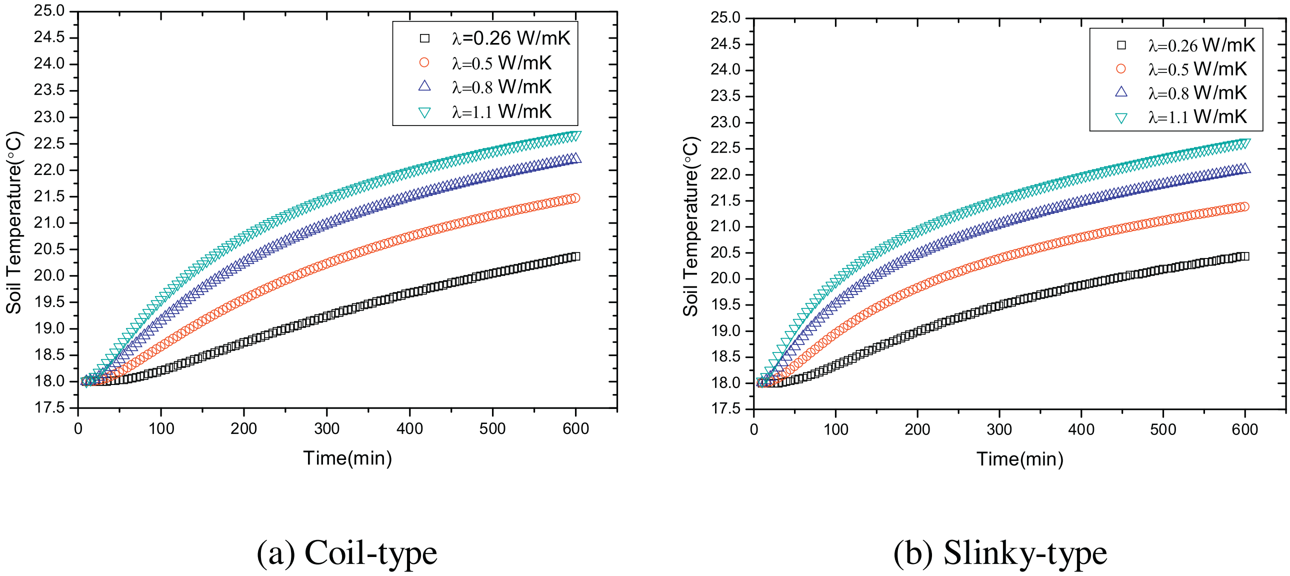


Fig. 14. Comparison of soil temperature (soil thermal conductivity).

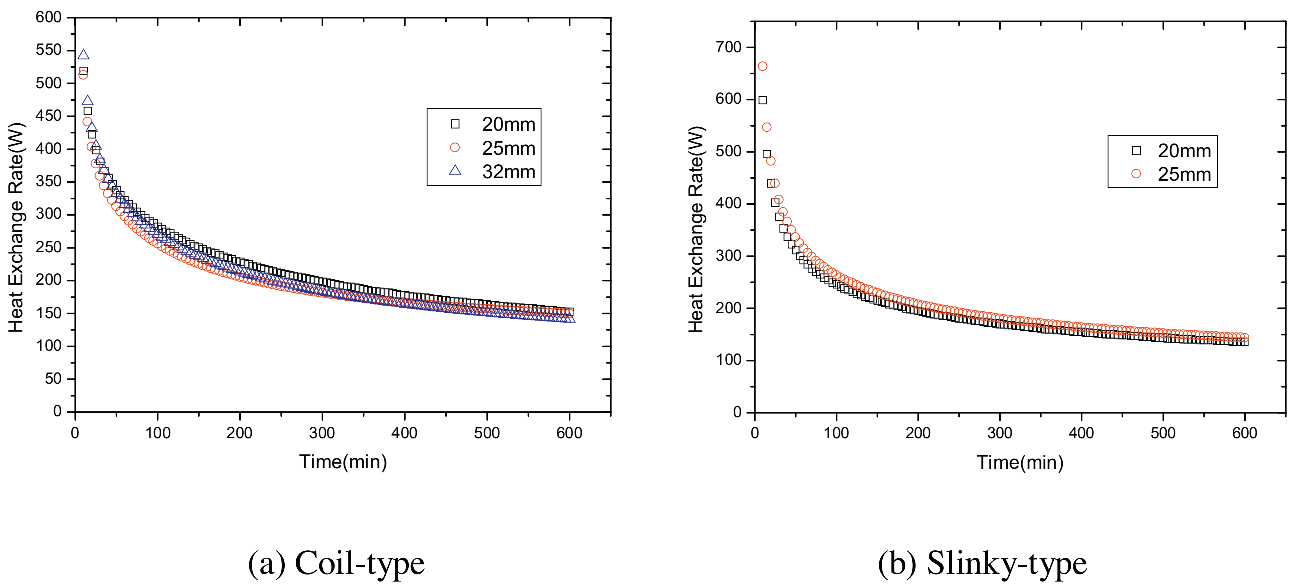


Fig. 15. Comparison of heat exchange rate (pipe diameter).

which can be expressed as the flow rate multiplied by the difference between the inlet and outlet temperatures, remained constant. Thus, our results show that pipe diameter does not significantly affect the performance of a horizontal GHE.

4. Conclusion

In the present study, we concluded an analysis to determine the factors influencing performance on horizontal GHEs. Firstly, to determine the best horizontal GHE configuration, in terms of performance, experiments were carried out. Then a numerical analysis was conducted, and the results were compared with the experimental data. Furthermore, a parametric study using a verified numerical model and conditions was conducted to establish the most significant parameters affecting the performance of a horizontal GHE. The conclusions of this work can be summarized as follows:

1. With horizontal slinky- and coil-type GHEs installed in a 5 m × 1m × 1 m steel box filled with dried Joomunjin sand, TRTs were conducted for 30 h to compare the heat exchange rates of each types of GHEs. The heat exchange rates of slinky- and coil-type GHE were 260.2 W and 255.3 W, respectively, which indicated that the horizontal coil-type GHE performed better than the slinky-type GHE.
2. A numerical analysis was performed for a parametric study and for its verification using a numerical program based on the finite element method. Heat exchange rates of slinky- and coil-type GHEs were obtained to compare with the results of the experiments, and the results of the TRTs and the numerical analysis were well matched. Therefore, the numerical model developed in this study can be useful in future parametric studies and further performance tests of horizontal GHEs.
3. Using the abovementioned numerical model, a parametric study was conducted that considered horizontal slinky- and coil-

type GHEs, ground conditions with varying thermal conductivity, and varying pipe diameters. The horizontal coil-type GHE showed a 10–11% higher heat exchange rate than the horizontal slinky-type GHE, regardless of soil conditions. As a result, it was concluded that among horizontal GHE design parameters, GHE type and soil thermal conductivity are the main factors determining the heat exchange rate of a GHE, whereas the pipe diameter does not have any effect on the GHE performance. Thus, in designing a horizontal GHE, it is important to choose the proper type of horizontal GHE, according to the constructability and purpose of use, and to accurately estimate the surrounding soil thermal conductivity.

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