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Life cycle cost analysis and smart operation mode of ground source heat pump system

Seok Yoon and Seung-Rae Lee*

Department of Civil and Environmental Engineering, Korean Advanced Institute for Science and Technology, 291Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

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Abstract. This paper presents an advanced life cycle cost (LCC) analysis of a ground source heat pump (GSHP) system and suggests a smart operation mode with a thermal performance test (TPT) and an energy pile system constructed on the site of the Incheon International Airport (IIA). First, an economic analysis of the GSHP system was conducted for the second passenger terminal of the IIA considering actual influencing factors such as government support and the residual value of the equipment. The analysis results showed that the economic efficiency of the GSHP system could be increased owing to several influential factors. Second, a multiple regression analysis was conducted using different independent variables in order to analyze the influence indices with regard to the LCC results. Every independent index, in this case the initial construction cost, lifespan of the equipment, discount rate and the amount of price inflation can affect the LCC results. Third, a GSHP system using an energy pile was installed on the site of the construction laboratory institute of the IIA. TPTs of W-shape and spiral-coil-type GHEs were conducted in continuous and intermittent operation modes, respectively, prior to system operation of the energy pile. A cooling GSHP system in the energy pile was operated in both the continuous and intermittent modes, and the LCC was calculated. Furthermore, the smart operation mode and LCC were analyzed considering the application of a thermal storage tank.

Keywords: life cycle cost; ground source heat pump; energy pile; smart operation mode

1. Introduction

Due to their economic benefits and environmentally friendly advantages, ground source heat pumps (GSHP) for efficient space cooling or heating are being applied in growing numbers (Johnston *et al.* 2011, Lee 2011, Loveridge and Powrie 2014, Park *et al*. 2012, Zhang *et al*. 2014). With geothermal cooling/heating systems, heat energy is fed into and withdrawn from the ground via GHEs (ground heat exchangers). The GHE is an important component that determines the performance of the GSHP system as well as the initial installation cost.

GSHP systems are available as both open and closed systems. The open system exchanges heat to/from aquifer water and the closed system exchanges heat to/from the ground by means of a fluid circulating in the GHEs. The closed system can be largely divided into vertical and horizontal types depending on the method by which the GHEs are installed. The horizontal system requires

*Corresponding author, Professor, E-mail: srlee@kaist.ac.kr

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the installation of a large number of GHEs parallel to the ground surface at a shallow depth; this type requires larger land space (Demir *et al*. 2009, Benazza *et al*. 2012, Chong *et al*. 2013). The vertical system, in which the GHEs are installed vertically into the ground to a depth of 150~200 m, is associated with high initial construction costs. The closed-loop vertical system is composed of the GHE, the ground, and grout to fill the space between the GHEs inside the borehole.

Considering the high initial construction cost of the vertical system, as an alternative, the usage of piles under a raft foundation as energy piles has recently become particularly attractive (Brandl 2006, Gao *et al*. 2008, Cui *et al.* 2011, Park *et al*. 2013). This approach has the advantage of a relatively lower initial construction cost and a lower spatial requirement. Compared to a conventional vertical system, the energy pile has a larger diameter and a shorter length. In Korea, most energy piles are shorter than 20m due to the shallow depth of the bedrock in many locations (Yoon *et al*. 2014a). Hence, spiral-coil-type GHEs in energy piles have been applied to increase the heat transfer area and to improve the flow pattern without air choking in the GHEs. A schematic diagram of the conventional vertical system and an energy pile with a spiral-coil-type GHE is shown in Fig. 1.

Many studies have undertaken economic analyses of GSHP systems (Tarnawski *et al*. 2009, Lee *et al*. 2012, Vu 2013). It is necessary to analyze the economic feasibility of these systems with respect to existing energy resources so as to evaluate the applicability of a GSHP system. In order to achieve this, a suitable economic analysis method for existing energy resources and ground heat exchanger systems using geothermal energy must be selected. For alternative energy savings systems such as geothermal energy systems, when determining energy savings and the scale of investment during the process of designing these structures, it is very useful to search for alternatives through a life cycle cost (LCC) analysis (Tarnawski *et al*. 2009). However, there are many assumptions with regard to different factors and government support elements. Hence, realistic life cycle analyses for these facilities have not yet been devised. Therefore, this research reflects actual impact factors such as the residual value and government subsidies pertaining to these systems in South Korea. In doing so, an LCC analysis of a GSHP system scheduled to be installed on the site of IIA passenger terminal 2 is conducted. A multiple regression analysis was also conducted to determine the correlations between independent and dependent variables.

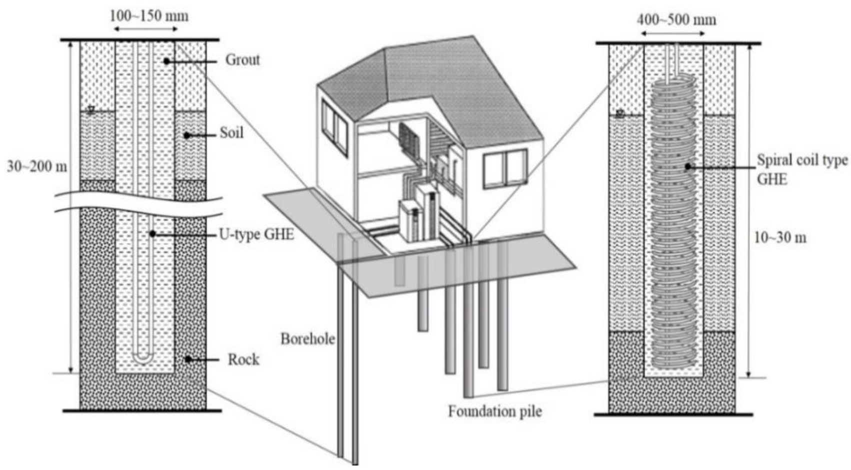


Fig. 1 Schematic diagram of vertical system and energy pile (Go *et al.* 2014)

Thermal performance tests on W-shape and spiral-coil-type GHEs were conducted in an effort to analyze the thermal efficiency according to operation mode. Additionally, an actual GSHP system using an energy pile was installed on site at the construction laboratory institute of the IIA. A cooling GSHP system in the energy pile was operated both continuous and intermittent mode, and the LCC was calculated. Furthermore, a smart operation mode is suggested, with an LCC analysis conducted considering the application of a thermal storage tank.

2. Economic analysis

2.1 Theory of economic analysis

In order to evaluate the validity of investment businesses, economic analyses hold considerable significance. An economic analysis measures benefits and costs in increments and evaluates whether the business overall will experience an increase or a decrease in net benefits. The key to economic analysis lies in the method by which it rationally estimates economic benefits. As applicable methods for estimating such economic benefits differ for individual businesses, it is not desirable to employ one particular method. In other words, it is necessary to select methods that take into consideration the concept of economic benefits for each particular business, and to use methods which are capable of more faithfully reflecting value. Therefore, it is necessary to review existing economic analysis models so as to select appropriate economic analysis methods.

The benefit-cost ratio (BCR) method uses the ratio of the total present value of the benefits divided by the total present value of the costs generated during the endurance period. The given discount rates are applied, and when the BCR is 1 or greater, the business is judged to have economic validity. The BCR method is used when, in a situation with the burden of the initial investment costs present, there are diverse investment alternatives. In such a case, the priority of each alternative is evaluated. The results of the evaluation of distinct investment alternatives are identical to those of the net present value (NPV) method. The general method for calculating the BCR is as follows

$$B/C = \sum_{t=0}^{n} \frac{B_t}{(1+r)^n} / \sum_{t=0}^{n} \frac{C_t}{(1+r)^n} \tag{1}$$

Here, $B_t$is benefits for year, $C_t$means costs for year$t$, r represent interest rates, and n = business analysis period.

The NPV signifies a certain amount out of future benefits excluding the costs discounted by the present value in consideration of interest rates, including inflation rates. This method for calculating the NPV is as follows

$$NPV = (B_o - C_o) + \frac{B_1 - C_1}{(1+r)} + ... + \frac{B_n - C_n}{(1+r)^n} \tag{2}$$

The analysis method using the NPV measures the value and the added value ensuing from the implementation of the business, and when the NPV has a positive value, the investment can be evaluated positively. The advantage of using the NPV is that it is possible to convert future cash flow into present value so as to enable direct comparisons by applying the concept of the time value of money (Yoon 2014b).

The internal rate of return (IRR) signifies the value of the discount factor where the NPV is 0. The calculation of the IRR can be achieved through a trial and error method or by plotting the NPV in terms of the IRR

$$C_o = \sum \frac{B_t}{(1+d)^t} \tag{3}$$

Here, C_o is the initial investment cost, B_t is the benefits from year t, and d represents the IRR. As an IRR analysis measures returns on investment, it is desirable to select businesses with the highest IRR values. Judgments can be made after a comparison with the current interest rate. For businesses to secure the desired level of validity, the IRR must be greater than the interest rate at the time of the analysis (Yoon 2014b).

The payback period (PBP) is the period during which the actual capital investment and the acquisition of financial capital at the initial stage become equal. After calculating the PBP for each alternative, an alternative with a short period is selected as optimal, and the PBP designates the period necessary for recovering the total investments with the profit or revenue obtained from the investments, and an alternative is selected by comparing the initial investment costs only. In addition, it is useful when the end users of facilities or building owners are interested in quickly recovering the funds invested. However, the life cycles of the facilities, maintenance, management costs, and interest rates are disregarded. The advantages of the PBP method are that it is simple and convenient. The disadvantage is that, in the case of businesses with the same PBP, they can be judged in the same way even when they have disparate cash flow characteristics

The LCC method is one in which economic feasibility is generally evaluated by totaling the costs generated at each stage, including construction, maintenance, operation and disposal. This method converts the total sum into an equivalent value within the scope of the economic life cycle. In other words, the LCC method can be used with comparative ease for calculating the total cost for each investment alternative and selecting the optimal plan (Fig. 2). It is known that energy-saving operations such as geothermal energy are good candidates when searching for alternatives through the LCC method so as to determine the amount of energy saved and the scale of the initial investment during the process of designing structures (An *et al*. 2005). Consequently, to understand the degree of actual energy reduction, research on economic analyses of new technology facilities and equipment is necessary, and an economic evaluation that uses the LCC method and takes facility life cycles into consideration is appropriate for the selection of initial alternatives. There are explanations of economic analyses in detail (Dhillon 2009, Yoon 2014b).

2.2 LCC analysis

In this study, an LCC analysis of a GSHP system scheduled to be installed on the site of IIA passenger terminal 2 is conducted while considering actual impact factors such as residual value and government subsidies in South Korea. Table 1 shows a summary of the building which is the subject of the LCC analysis. One hundred vertical-type GHEs of which the depth is 150 m are planned for installation. It is also assumed that half of the building load is covered by the operation of a water storage system. Table 2 also shows some items in the financial index of the LCC analysis. Most financial indices stem from the findings in previous LCC research on GSHP systems (Yoon 2014b).

The LCC analysis of the GSHP system in comparison with previous systems such as electricity and gas systems was conducted while considering actual impact factors. The initial construction cost of the GSHP system was twice as great, but the operation and maintenance costs were much lower than those of the previous systems. Furthermore, the economic efficiency of the GSHP system could be increased owing to government subsidies. The NPV was 1,228,460,015 Korean won, the IRR was 32%, and the B/C ratio was 4.55.

2.3 Analysis of influence index

In order to analyze the influence indices considering the LCC results, a multiple regression analysis was conducted using different independent variables, i.e., with changed values. Table 3 shows the results of the regression analysis. *B* means the coefficient of independent variables, and *t* can be defined as *B* value divided by standard error. From the *t* statistical analysis, p-value of coefficient in the all the independent variables were lower than 0.05, which means that every independent variable can be used significantly to estimate dependent variables. Every independent index can affect the NPV value in Table 3 because the P value of every independent variable was less than 0.05 (Anthony 2007). As financial factors such as the discount rate and the rate of price inflation cannot be controlled, it is necessary to reduce the initial construction cost and determine the optimum operation mode in order to reduce the total cost.

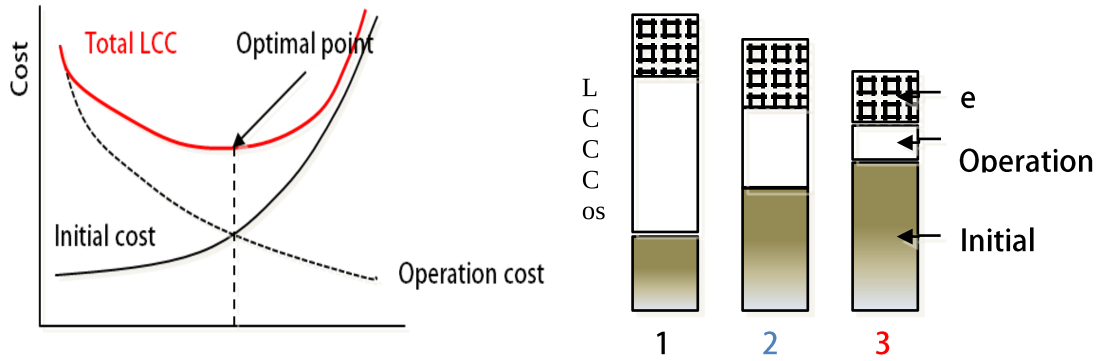


Fig. 2 Concept of LCC theory

Table 1 Building summary

Building	Total floor area	350,000 m^2
Size	Heating and cooling area	9,882 m^2
	Cooling load	1,512,000 kcal/hr
	Heating load	1,814,400 kcal/hr

Table 2 Financial index

Specification	Index
Discount rate	7.0%
Tax reduction	20%
Price inflation	3.14%
Lifespan	25 yr
Replacement period	15 yr
Residual value	a fixed rate

Table 3 Multiple regression analysis

	B	Standard error	*t*	P-value
Constant	3.283E+09	1.170E+08	2.810.E+01	1.030.E-13
X_1 (Initial construction cost)	-1.009E+00	6.421E-02	-1.572.E+01	2.740.E-10
X_2 (Lifespan of equipment)	-7.636E+06	2.374E+06	-3.217.E+00	6.206.E-03
X_3 (Discount rate)	-1.707E+08	7.936E+06	-2.150.E+01	4.010.E-12
X_4 (Price inflation)	2.052E+10	1.310E+09	1.563.E+01	2.950.E-10

Table 4 LCC results of storage tank application

	LCC (with storage tank)	LCC (without storage tank)
Initial construction cost	1,359,492,000	1,102,500,000
Operation cost	1,313,424,844	1,656,474,289
Residual value	-14,555,376	-11,803,896
Exchange value	156,695,633	127,074,624
Tax exclusion	-135,949,200	-110,250,000
NPV	1,228,460,015	1,143,572,899
LCC	2,679,107,901	2,763,995,018

Furthermore, in order to analyze the influence of the operation index, the LCC was calculated according to the existence of a thermal storage tank. Table 4 shows these LCC values, and NPV value is difference between LCC of GSHP system and LCC of electricity and gas system. It can be concluded that the LCC will decrease if a thermal storage tank is installed in the GSHP system because it can decrease the operation cost, though it does cause the increase in the initial construction cost. The GSHP system can be operated during the night, with storage into the thermal storage tank. As the heat pump is operated during the night, the cost of the electricity it uses at that time is approximately half that of the daytime electricity in Korea (Vu 2013).

3. Application of energy pile system

3.1 System setup

The GSHP system using a PHC (precast high-strength concrete) energy pile was installed on the site of the construction laboratory institute of the IIA. The length of the PHC pile (the inner/outer diameter ratio of the pile =0.34 m/0.5 m) was 15m, and six PHC piles were embedded. A polybutylene pipe (the inner/outer diameter ratio of the pipe = 0.016/0.02 m) as a spiral-type GHE was installed on the inside wall of the PHC pile using cement grout with a cement-to-water ratio of 0.5. The spacing of coil is 5 cm, and the coil diameter is 28 cm. Fig. 3 shows the pile arrangement and plan of the building. The total area for cooling and heating is 100 m^2.

The ground was composed of reclaimed soil, sedimentary soil, weathered granite soil and weathered rock based on a site investigation (Fig. 4). The ground water level was 1.0m below the top of the embedded pile, and no noticeable flow of ground water was observed. Ground thermal conductivity which is the most important factor in a GSHP system was 2.145 W/m·K according to the results of the thermal response test (TRT). The TRT was conducted over a period of 10 days until a steady-state condition was attained. The ground thermal conductivity can be obtained using infinite line source theory with TRT results (Florides and Kalogirou 2008, Roth *et al*. 2004). Fig. 5 shows the temperature variation of the fluids during the TRT.

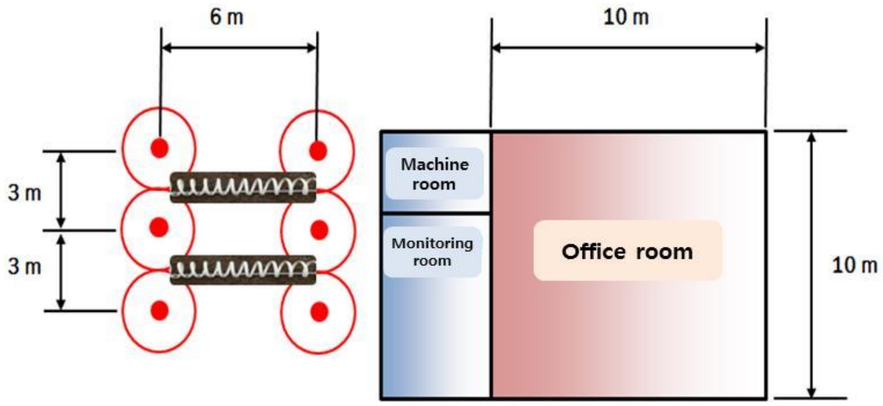
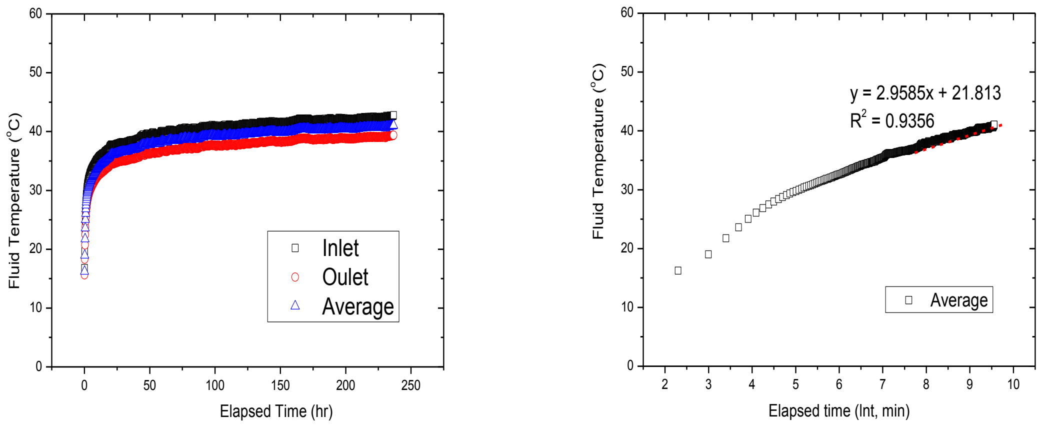


Fig. 3 Pile arrangement and plan of building

Depth (m)	Layer	Description	USCS⁺	SPT⁺⁺ blow count
1.0	Reclamation soil *Groundwater table* ▽	· Light brown color · Medium-texture sand · Medium dense	SP	11/30
8.8	Sedimentary soil	· Pinkish gray color · Silt clay · Saturated · Very weak	CL	13/30 5/30 1/30 4/30 8/30
15.0	Weathered granite soil	· Light brown color · Sand clay · Saturated · Medium hard	CL	10/30 11/30 15/30 42/30
	Weathered granite rock	· Light brown color · Intermediately weathered · Saturated		

⁺ Unified Soil Classification System
⁺⁺ Standard Penetration Test

Fig. 4 Drilling log of the test site



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

Fig. 5 Fluid average temperature distribution during the TRT

After the PHC pile construction and TRT, all of the pipes from the PHC piles were joined in a horizontal trench and connected to a circulating pump inside the building. The geothermal heat pump, circulating pump, buffer tank, expansion tank, and fan coil unit were then installed in the machine room and in an office room. Table 5 shows the specifications of the equipment installed as part of the GSHP system, and Fig. 6 shows the construction process. In addition, in order to measure the thermal efficiency of the GSHP system in the energy pile, a monitoring system was installed. The coefficient of performance (COP) of the heat pump, the temperature at the inlet and the outlet to the ground, a flowmeter for fluids, the thermal exchange rate, and the amount of electrical power consumed can be measured during the operation of the system.

3.2 Thermal performance test

A thermal performance test (TPT) can be applied to measure the heat exchange rate from the ground through the GHEs. There is a little difference between a TRT and a TPT. A TRT is used to measure the ground thermal conductivity, and a pre-defined level of constant heat power is put into the water tank in the TRT equipment. However, the TPT can be used to evaluate the heat exchange rate from the ground under the condition that the inlet temperature into the ground should be kept constant. The heat exchange rate (Q) according to the depth (L) of the vertical borehole or energy pile can be calculated by measuring the inlet and outlet temperatures of the fluid flow rate with Eq. (4).

Table 5 Specifications of equipment

	Capacity (kW)	COP	Heat source (ground)	Load source (building)	
			EWT (℃)	Flowmeter (lpm)	
Heat pump (cooling)	17.437	3.47	30	60	
Heat pump (heating)	16.441	3.81	5	60	
	Specification	Capacity (kW)	Power consumption (kW)	Flowmeter (lpm)	Head (m)
Circulation pump	Ground	2.2	2.2	60	26
	Storage tank	1.1	1.1	60	15
	Building	0.55	0.55	50	10
	Specification		Volume (l)	Material	
Buffer Tank	Closed type		600	STS 400	
Expansion Tank	Closed type		60	SS400	


(a) Pile driving

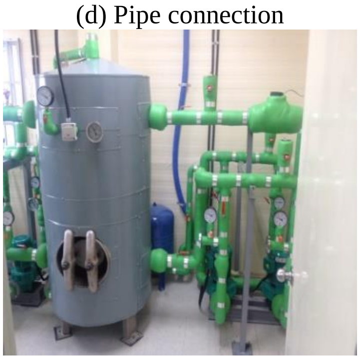

(b) Installation of GHEs into piles

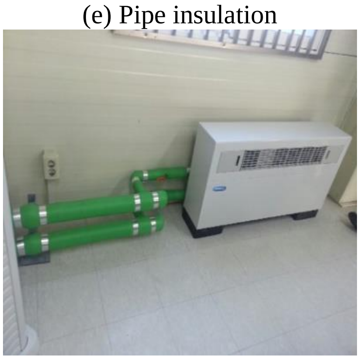

(c) Cement mortar grouting


(d) Pipe connection


(e) Pipe insulation


(f) Installation of heat pump


(g) Installation of buffer tank


(h) Installation of fan coil unit


(i) Completion

Fig. 6 Construction process of energy pile

$$\frac{Q}{L} = \frac{mc(T_i - T_o)}{L} \tag{4}$$

Here, T_i is the inlet temperature of the fluid, T_o is the outlet temperature of the fluid, and m is the flow rate of the fluid. The TRT and TPT are used with only one borehole or energy pile prior to the construction of heat pump and the machine room. Lee *et al*. (2013) developed equipment which has multiple functions for conducting TRTs and TPTs. In other words, the equipment is equipped with a heat controller as well as a temperature controller. Prior to the operation of the GSHP system of the energy pile, TPTs were conducted for W-shape and spiral-coil-type GHEs on a runway of the IIA (Fig. 7). Because the construction period of the energy pile system was restrained, the TPTs were conducted with two other vertical boreholes at a site close to the energy pile. As this site was in very close proximity to the construction site of the energy pile, the ground condition and basic properties were assumed to be similar. Table 6 shows the dimensions of each GHE used in the TPTs; the coil spacing and diameter were identical to those in the energy pile system.

First, TPTs were conducted for 100 hours under a continuous operation condition. The inlet water temperature on the ground was 31℃ for an effective cooling operation. The TPTs were then conducted for five days under an intermittent condition. This test lasted eight hours, with a 16-hour off period. The average heat exchange rates considering the lengths of the W-shape and the spiral-coil-type GHESs were calculated for both the continuous and the intermittent operation condition. Fig. 8 shows the heat exchange rates for the W-shape and the spiral-coil-type GHESs. The heat exchange rate of the spiral-coil-type GHE was nearly twice that of the W-shape GHE owing to larger contact area. Furthermore, the intermittent operation condition provided 30~40% superior thermal performance than the continuous operation condition. Table 7 presents a summary of the TPT results.

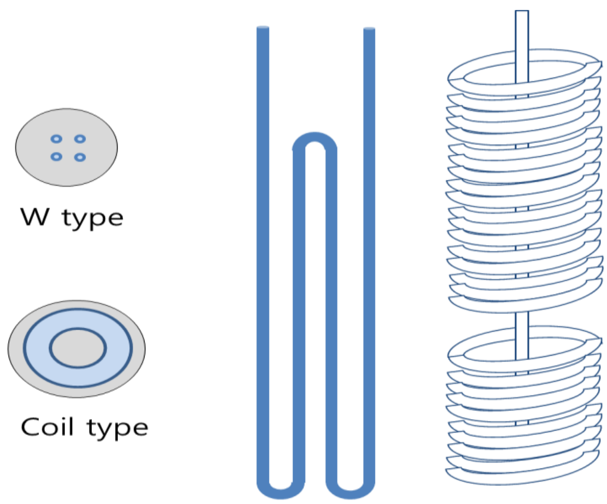
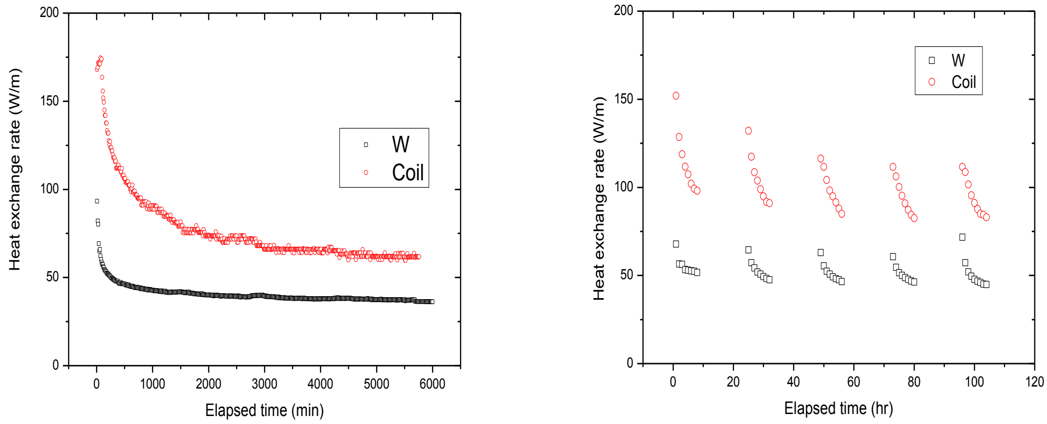


Fig. 7 Diagram of GHEs

Table 6 Dimension of GHE

Type of GHEs	W	Coil
Borehole Depth (m)	50	30
Diameter of borehole (mm)	150	300



(a) Continuous operation (b) Intermittent operation

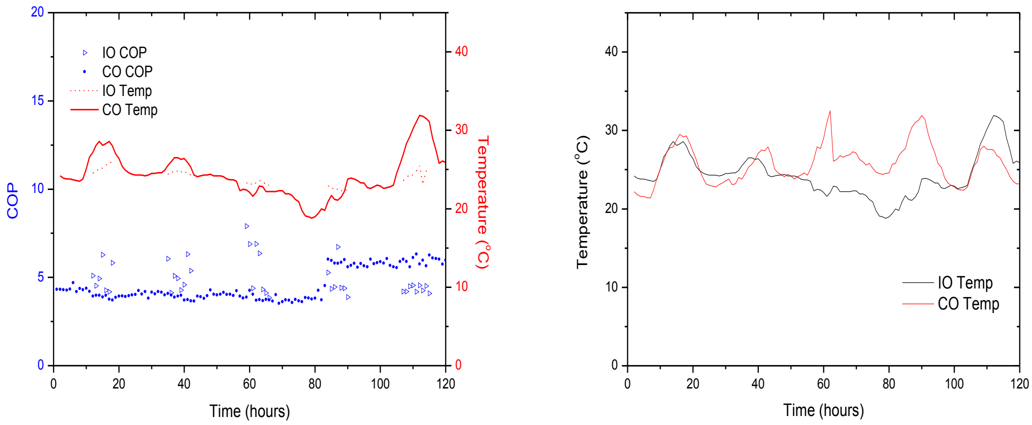
Fig. 8 Heat exchange rate per borehole depth

Table 7 Summary of TPT results

Type of GHEs	Heat exchange rate under the continuous operation (W/m)	Heat exchange rate under the intermittent operation (W/m)					
	100hr average	1day	2day	3day	4day	5day	5-day average
W	40.76	58.7	55.6	53.6	52.2	50.7	54.2
Coil	76.8	117.5	107.1	100.6	96.4	94	103.1

3.3 Smart operation of GSHP system

After the completion of the GSHP system in the PHC energy pile (Fig. 6), a test of the operation of the GSHP system was carried out. Given that a monitoring device was installed to measure the thermal efficiency of the GSHP system, the COP of the heat pump, the thermal exchange rate and the amount of electrical power consumed were measured in real time during the operation. In order to evaluate the smart operation mode, the continuous and intermittent operation modes of the GSHP system were applied each for five days. The on period was eight hours and the off period was 16 hours during the intermittent operation condition. The average outdoor temperatures were similar, between 21 and 32℃ during the test. Fig. 9 shows the outdoor temperature, the COP of the GSHP system and the indoor temperature for the five-day operation, and Table 8 presents the averages of the indoor and outdoor temperatures and the operation results including the total LCC. The desired indoor temperature is 26℃ in summer, and the GSHP system in the energy pile showed high thermal efficiency because the average indoor temperature was less than 26℃. The thermal efficiency during the use of the intermittent operation mode showed superior results compared to the continuous operation mode. The COP for the last (fifth) day in the intermittent operation mode was lower than that in the continuous operation mode; it is thought that a higher outdoor temperature during the intermittent operation caused the efficiency of the GSHP system to decrease (Lee *et al*. 2012). With the operation results, the total amount of electrical power consumed was measured and the LCC was calculated using electrical fee provided by KEPCO (Korea Electrical Power Corporation). The cost of the total LCC in the intermittent operation condition was approximately half that of the continuous operation condition.



(a) COP and indoor temperature (b) outdoor temperature

Fig. 9 Temperature and COP values during the GSHP operation

Table 8 Operation results of GSHP system

	Intermittent operation (09:00~17:00)	Continuous operation (24 hours)
Average COP	5.2	4.6
Cumulative consumption of electricity	268.3 kWh	584.7 kWh
Cumulative heat exchange rate from the ground	1,652 kWh	3,249 kWh
Total LCC	26 USD	57 USD
Average indoor temperature (Min ~ Max)	24℃ (22.3℃ ~ 26℃)	23℃ (20.7℃ ~ 25.8℃)
Average outdoor temperature (Min ~ Max)	25.9 ℃ (21.1℃ ~ 31.9℃)	25.7 ℃ (21.4℃ ~ 32.5℃)

Table 9 LCC results of storage tank application in energy pile

		Without storage tank	With storage tank
Consumption of electircity	Day time(09:00~17:00)	268.3 kWh	174.3 kWh
	Night time (23:00~09:00)	-	94.1 kWh
Operation LCC		26 USD	22 USD

In order to evaluate the smart operation mode, an LCC analysis was also conducted under the condition in which a thermal storage tank is used, though it was not installed in this GSHP system. With storage tank, HP can be operated during the day time for the heat storage in the tank using midnight power with the cheap electric rates, and it was assumed that about 40% of the total cooling-heating load could be covered with the thermal storage tank operation during the night (Incheon International Airport, 2010). In other words, the heat pump and the circulating pump of the ground and the thermal storage tank are operated during the night, and 40% of the total cooling-heating load can be stored in the thermal storage tank using electricity at night. Table 9 shows the LCC results with the thermal storage tank used in the energy pile. The LCC of the operation can be reduced by more than 20% if the thermal storage tank is installed.

It can be concluded that the intermittent operation mode can increase the COP of the GSHP system and reduce the operation cost by half in comparison with the continuous operation mode. Furthermore, the application of the thermal storage tank can reduce the operation cost by more than 20%. Therefore, it is considered that the intermittent operation mode and the use of a thermal storage tank are necessary to meet the requirements of the smart operation system based on a cost analysis.

4. Conclusions

This paper presents an advanced LCC analysis of a GSHP system and an influence analysis of each variable affecting the LCC results. A smart operation mode with a TPT using vertical-type GHE and a GSHP system using an energy pile underwent a cost analysis according to different operation conditions. The following conclusions can be drawn from this research.

1. First, an economic analysis of the GSHP system for the second passenger terminal of the IIA was conducted considering actual influencing factors such as government support and the residual value of the equipment.The economic efficiency of the GSHP system could be increased owing to government subsidies. The NPV was 1,228,460,015 Korean won, the IRR was 32%, and the B/C ratio was 4.55. In addition, a multiple regression analysis was conducted using different independent variables with different values in order to analyze the influence indices with regard to the LCC results. Every independent index was found to have the potential to affect the NPV value. As financial factors such as the discount rate and rate of price inflation cannot be controlled, it is necessary to reduce the initial construction cost and determine the optimum operation mode in order to reduce the total cost. Therefore, in order to analyze the influence of the operation index,

the LCC was calculated according to the existence of a thermal storage tank. The LCC was found to be lower if the thermal storage tank was installed in the GSHP system, as the use of such a tank can decrease the operation cost, even while increasing the initial construction cost.

2. TPTs of a vertical system using a W-shape and a spiral-coil-type GHES were conducted according to continuous and intermittent operation modes prior to the operation of the system in the energy pile. The inlet water temperature to the ground was 31°C to consider a proper cooling operation. After the TPTs were conducted for 100 hours under the continuous operation condition, TPTs were also conducted for five days under the intermittent condition (8 hrs on; 16 hrs off). The heat exchange rate of the spiral-coil-type GHE was nearly twice as efficient compared to the W-shape GHE owing to the larger contact area. Furthermore, the intermittent operation condition provided 30~40% superior thermal performance relative to that of the continuous operation.

3. A GSHP system using a PHC energy pile was installed on the site of the construction laboratory institute of the IIA. In order to evaluate the smart operation mode, continuous and intermittent operations of the GSHP system were applied for five days in each case. The COP of the GSHP system running in the intermittent operation mode showed results superior to those of the continuous operation mode. With the operation results, the total electrical power consumption amount was measured, and the total LCC under the intermittent operation condition was nearly half as expensive as that under the continuous operation condition. Moreover, an LCC analysis was also conducted under a condition in which a thermal storage tank was applied, though such a tank was not installed in this GSHP system. The LCC of the operation can be reduced by more than 20% if a thermal storage tank is installed. It can be concluded that the intermittent operation mode can increase the COP of the GSHP system and reduce the operation cost by half in comparison with the continuous operation mode. Furthermore, the application of a thermal storage tank can reduce the operation cost by more than 20%. Therefore, it is considered that the intermittent operation mode and the application of a thermal storage tank are necessary to meet all of the requirements of the smart operation system based on a cost analysis.

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