Comprehensive study on construction and design method for cast-in-place energy piles

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ABSTRACT: The Ground Source Heat Pump (GSHP) system has been regarded as the most effective heating and cooling system that uses geothermal energy to improve the thermal performance of heat pump and reduce energy consumption. For inducing heat exchange with ground, closed-loop vertical Ground Heat Exchangers (GHEXs) in the underground are generally coupled with heat pump units. Since conventional GHEXs are commonly constructed adjacent to the target buildings, they require additional borehole drilling and extra construction area, which causes a relatively high construction cost. Meanwhile, an energy pile can be an economical alternative to the conventional GHEXs, because it can significantly reduce initial construction costs by encasing heat exchange pipes inside existing pile foundations. In this paper, comprehensive study on the construction and design method for cast-in-place energy piles was carried out. First, six cast-in-place energy piles, which contain various configurations of heat exchange pipes, were constructed in a test bed. In order to investigate the thermal performance and thermo-mechanical behavior of cast-in-place energy piles, a series of in-situ tests (i.e., thermal response tests, thermal performance tests, and thermally-induced stress evaluation) were performed. From the results of in-situ tests, significant influence factors and overall procedure for designing and constructing cast-in-place energy piles were suggested. Finally, two-year heating and cooling operations for an office space were continually monitored to experimentally verify the applicability of cast-in-place energy piles. In addition, the economic feasibility of cast-in-place energy piles compared to the conventional GHEXs was evaluated.

Keywords:Cast-in-place energy pile, Ground heat exchanger, Thermal performance of energy pile, Thermal response test, Design of energy pile

1 INTRODUCTION

The ground source heat pump (GSHP) system is one of the most efficient heating and cooling systems because it utilizes the constant subsurface temperature regardless of the season to improve the thermal performance of heat pump and reduce energy consumption. In order to extract or release thermal energy from or to the ground formation, the GSHP system is coupled with the ground heat exchangers (GHEXs) where heat exchange occurs between the surrounding ground and a working fluid that circulate through the heat exchange pipe installed underground.

An energy pile contains a heat exchange pipe inside the pile and allows a fluid circulating through the pipe inducing heat exchange with the ground formation. By using existing structural foundation, the energy pile can reduce drilling cost, and requires no necessity to seek additional space for installing heat exchangers. Meanwhile, it has been reported that energy piles usually show relatively lower thermal performance than conventional vertical closed-loop GHEXs because the energy piles can utilize only a limited amount of geothermal source due to short installation length (Brandl 2006, Loveridge, 2012)

In this paper, comprehensive studies on cast-in-place energy piles were carried out depending on three key issues, i.e., thermal performance, thermo-mechanical behavior, and design method. The thermal performance of the cast-in-place energy pile was evaluated by an experimental approach. Full-scale energy piles were constructed in a test bed with various configurations of heat exchange pipe to experimentally provide the thermal performance and constructability depending on different pipe types. Then, two different field tests, in-situ thermal response test (TRT) and in-situ thermal performance test (TPT), were conducted to estimate the heat exchange capacities of constructed energy piles. In order to investigate the thermo-mechanical behavior of energy pile, a comprehensive measurement of temperature and thermal strain (stress) was carried out. The thermal strain (stress) in the longitudinal direction of the energy pile and temperature variation of ground formation was experimentally monitored during heating and cooling operation. Finally, a novel design algorithm for the cast-in-place energy pile system was provided. The developed design algorithm was verified by performing two-year heating and cooling operations for an office space, and the economic feasibility of cast-in-place energy piles compared to the conventional GHEXs was evaluated.

2 CONSTRUCTION OF ENERGY PILES

The systematical construction procedure for an energy pile is essential since energy pile should be constructed in accordance with the total construction procedures of building contrary to the conventional GHEXs installed separately from building construction. Utilizing the existing structure-foundation, the construction procedure of energy pile is involved in pile embedment step as organized in Figure 1.

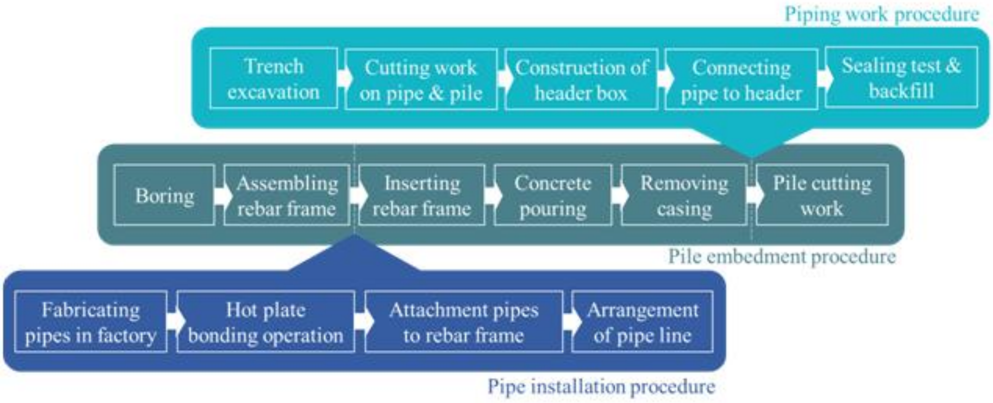


Figure 1. Construction procedure of energy pile involved in pile embedment procedure

The test bed for constructing the cast-in-place energy piles is located in Yongin city, South Korea. The bed rock composed of fresh gneiss appears at shallow depth (i.e., about 14 m). Therefore, cast-in-place concrete energy piles were designed to penetrate the ground into 14 m. The configurations of heat exchange pipe were determined to examine the relationship for available heat exchange area, constructability and thermal interference, which are three parallel U-type (5 pairs, 8 pairs, and 10 pairs), two coil-type (500 mm and 200 mm coil pitch) and one S-type. The external and internal diameters of heat exchange pipe were 27 mm and 21 mm, respectively. Considering strength, flexibility, corrosion resistance, and acid resistance, High-density polyethylene (HDPE) pipe was selected as the heat exchange pipe. The installed length of heat exchange pipes was summarized in Table 1.

Table 1. Configuration and total length of installed heat exchange pipe

Type	Parallel U-type			Coil-type		S-type
	5 pairs	8 pairs	10 pairs	Pitch 500 mm	Pitch 200 mm	
Length	130 m	208 m	260 m	101 m	240 m	160 m

3 EXPERIMENTAL STUDY ON THERMAL PERFORMANCE OF ENERGY PILE

Two different field tests, TRT and TPT, were conducted to study the thermal performance of constructed cast-in-place energy piles experimentally. From the results of field tests, the applicability of large-diameter cast-in-place energy pile was evaluated by comparing the results with those of the other types of GHEXs (e.g., conventional closed-loop vertical GHEXs, open-loop GHEXs, etc.) presented in references.

3.1 *Results of thermal response test*

In the in-situ TRT, the thermal response of GHEX is estimated by continuously monitoring the temperature changes of inlet and outlet fluid when a heat carrier fluid circulates through pipe with the constant rate of heat injection.

The TRT has been introduced as a method to estimate the in-situ value, the effective thermal conductivity of ground, in the field. The effective thermal conductivity is estimated by comparing the recorded temperature data of inlet and outlet fluid with an analytical model developed for simulating heat transfer mechanism (i.e., heat conduction and convection) around a buried heat source. The line heat source model (Carslaw and Jaeger 1959) available to simulate the thermal behavior of the line-shape of heat source is a typical model in practice due to its clarity and convenience for computation. However, because of much thicker in diameter but shorter in depth of energy pile, the line source model is not appropriate for analyzing TRT results with the line heat source model. Thus, in this study, the new term of relative heat exchange efficiency (*eff*) is used to compare the overall thermal performance of GHEXs indirectly. *eff* is defined by Eq. (1) being normalized with borehole length (L_{borehole}) and heat exchange pipe length (L_{pipe}).

$$eff_{borehole} = \frac{Q}{slope \times L_{borehole}}, eff_{pipe} = \frac{Q}{slope \times L_{pipe}} \tag{1}$$

where Q is the constant heat injection rate (W) and slope is the relationship between the average of the inlet and outlet temperatures and natural logarithm of time.

The efficiency of the heat exchanger can be compared to each other indirectly by obtaining the relationship between heating power and temperature increment due to the heating power. *eff*s of six cast-in-place energy piles with different configurations of heat exchange pipe are summarized in Table 2.

Table 2. Relative heat exchange efficiency (*eff*) of constructed cast-in-place energy piles

Type	Length of pipe / borehole	slope	$eff_{borehole}$		eff_{pipe}	
			Value	Ratio	Value	Ratio
5-pair-parallel U-type	130 m / 14.0 m	4.44	83.86	1.00	9.03	1.00
8-pair-parallel U-type	208 m / 14.0 m	6.22	100.49	1.20	6.76	0.74
10-pair-parallel U-type	260 m / 14.0 m	5.10	122.95	1.47	6.62	0.73
Coil-type pitch 500 mm	101 m / 12.5 m	4.95	81.11	0.97	10.20	1.12
Coil-type pitch 200 mm	240 m / 14.0 m	3.66	98.83	1.19	5.76	0.64
S-type	160 m / 14.0 m	7.29	87.05	1.04	7.62	0.84

In the results, the denser pipe volume is inserted in same borehole volume, the higher eff_{borehole} occurs due to the larger contact area for heat exchange. Usually, the degree of heat transfer in GHEX system is proportional to the contact area of adjacent media because the heat transfer between the pipe and composite medium (i.e., grout and ground) mainly occurs by heat conduction. However, eff_{borehole} is not directly proportional to the installed pipe length because the tight pitches of pipe lead to the thermal interference between each pipe loop. The thermal interference is also evident in comparing eff_{pipe}.

When comparing the results with the conventional closed-loop vertical GHEX, the cast-in-place energy piles have a relatively higher value of eff_{borehole} than conventional closed-loop vertical GHEXs, because the cast-in-place energy piles have a denser volume of heat exchange pipes in unit borehole length. On the other hand, eff_{pipe} is higher in the closed-loop vertical GHEXs, which represents the thermal interference between each pipe loop was minimized by encasing only single U-type or double U-type heat exchange pipe inside the borehole. The cast-in-place energy pile shows higher effectiveness in heat transfer in terms of the whole borehole of GHEX by increasing a total length of heat exchange pipe using the much larger diameter of the borehole, which increases the contact area for the heat exchange. Therefore, the drawback of heat exchange in energy pile, caused by relatively short borehole length, such as significant influence of air temperature and the low thermal conductivity of soil deposits in shallow depth of ground can be complemented by enlarging the heat exchange area with installing significantly longer heat exchange pipe in a diameter at least 10 times larger than that of the closed-loop vertical GHEX. However, since the thermal interference in the tight layout of pipes may reduce the effectiveness of heat exchange on GHEX, considering the optimum configuration of heat exchange pipe in the design stage is very important in the cast-in-place energy pile.

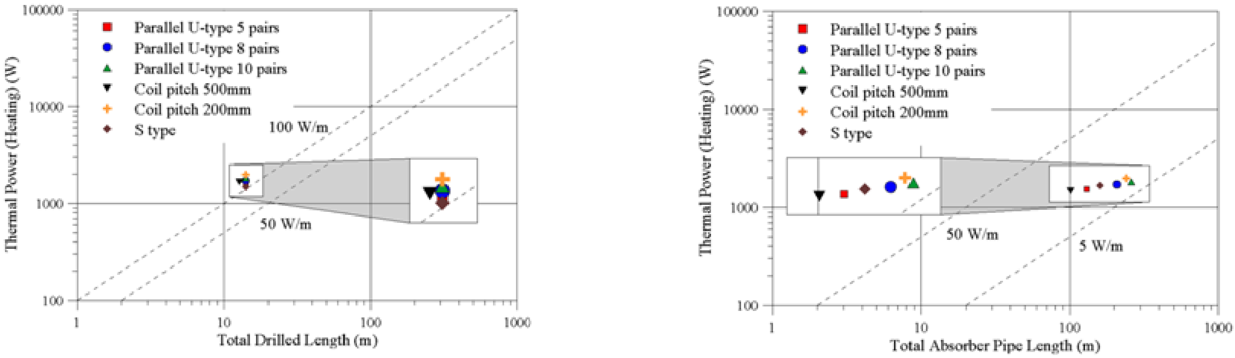
3.2 *Results of thermal performance test*

The in-situ TRT cannot provide actual heat exchanger rate (W/m) of GHEX in the real operating condition of GSHP system (Zhang et al. 2015). The TPT is performed with artificial heat load by maintaining the inlet fluid temperature constantly with the aid of a constant-temperature water bath. The in-situ TPT is the most suitable field test for evaluating the thermal performance of GHEX itself. In the TRT, the inlet fluid temperature is maintained at 30℃ for cooling operation and 5℃ for heating operation, and the flow rate was 14 L/min for cooling operation and 10 L/min for heating operation. The artificial load was intermittently applied by activating 8 hours and deactivating 16 hours to simulate heating and cooling operation of conventional commercial buildings.

Each heating and cooling test was performed for one week per each energy pile. In the result, the tendency of the heat exchange rate in accordance with the various configuration of heat exchange pipe is similar to the result of in-situ TRT. First of all, the larger pipe volume is inserted in same borehole volume, the higher heat exchange amount occurs due to the larger contact area for heat exchange. However, when inserting a large volume of pipes to improve the thermal performance of GHEX, the thermal interference in the tight layout of pipes reduced the effectiveness of heat exchange on GHEX. Therefore, the optimum configuration of heat exchange pipe is important design factor when constructing the cast-in-place energy pile. The optimum configuration of heat exchange pipe should be determined in consideration of not only heat exchange efficiency, but also a material cost and thermal interference effect when exceedingly longer heat exchange pipes are inserted.

To evaluate the applicability of the large-diameter cast-in-place energy pile, the results of field tests were compared with the other types of GHEXs presented in literature. Johnston et al. (2011) provided the upper and lower boundary of the heat exchange rate of various GHEXs obtained from preceding studies and concluded that the heat exchange amount per borehole length (i.e., $Q_{borehole}$) lies in the range of 50 W/m to 100 W/m and the heat exchange amount per pipe length (Q_{pipe}) lies in the range of 5 W/m to 50 W/m, respectively.

Figure 2 shows the heat exchange rate of the large-diameter cast-in-place energy piles in heating operation along with the general range proposed by Johnston et al. (2011). Figure 2 (a) indicates that the cast-in-place energy pile can reveal higher thermal performance per unit borehole length compared with other conventional types of GHEXs by increasing length of heat exchange pipe in a diameter at least 10 times larger than that of the closed-loop vertical GHEX. On the other hand, the Q_{pipe} of cast-in-place energy pile is located around the lower boundary of general range in Figure 2 (b), which means the cast-in-place energy pile shows the relatively lower effectiveness of heat exchange with respect to the unit pipe length due to the thermal interference.



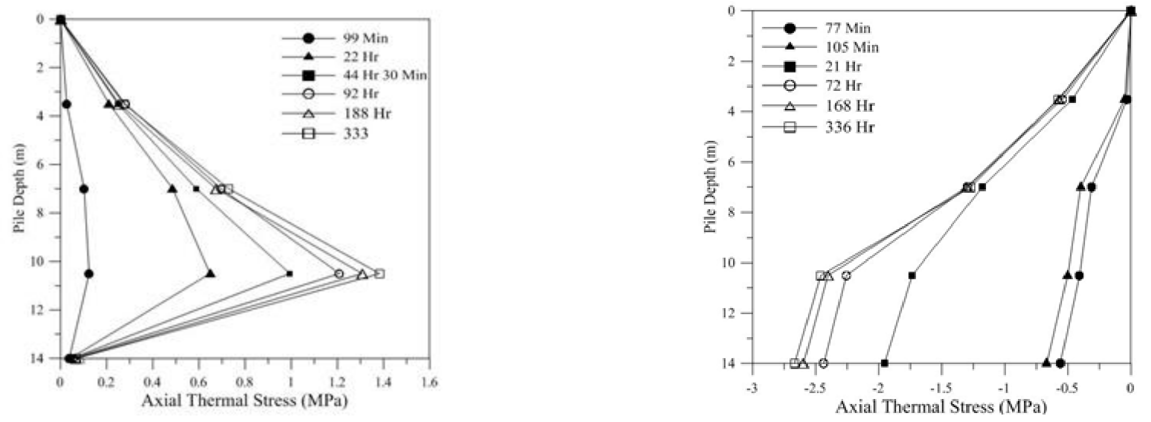
(a) Heat exchange rate per unit borehole length (b) Heat exchange rate per unit pipe length

Figure 2. Comparison of heat exchange rate of energy pile with various types of GHEX

4 THERMO-MECHANICAL BEHAVIOR OF ENERGY PILE

Even though the energy pile can be used for not only the supporting function of structure, but also a heat exchanger at the same time, however, the main purpose of it is supporting the structure. Considering that every material contract or expand according to its temperature change, the repetition of heating and cooling operation greatly affects to mechanical behavior and stress of energy pile, which can cause serious problems in supporting loads of the structure. Therefore, thorough consideration of thermo-mechanical behavior of energy pile should be conducted in design stage (Laloui et al. 2003, Bourne-Webb et al. 2009)

In order to investigate the thermo-mechanical behavior of cast-in-place energy pile, a comprehensive measurement of temperature and thermal strain (stress) was carried out for the 5-pair-parallel U-type energy pile. The thermal strain (stress) in the longitudinal direction of the energy pile was monitored during 15-day continuous operation. After the operation, another monitoring test was followed during 15 days with no application of heat exchange. The inlet fluid temperature was maintained as 6~9℃ for heating operation, and 29~30℃ for cooling operation.



(a) During heating operation (15 days) (b) During cooling operation (15 days)

Figure 3. Changes in thermal stress of energy pile surface along pile length

Figure 3 (a) shows the thermo-mechanical behavior of energy pile during the heating operation. Axial tensile stress was generated on the energy pile surface because the contraction of energy pile induced by the low-temperature working fluid was restrained by surrounding ground formation. On the other hand, during cooling operation, axial compressive stress was generated as the expansion of the energy pile due to the high temperature of fluid was restrained (Figure (b)).

According to the boring investigation of field test site, the bedrock appears at a depth of 8.5m and Young`s modulus, density, cohesion coefficient of ground formation also increase along the depth as indicated in N-value. Consequently, based on the geotechnical condition of ground formation, the axial stress shows increasing tendency along the pile depth. Because the bearing capacity between the pile and rock formation is especially large, this phenomenon appears obviously in the case of cooling operation test where expansion of the energy pile was restricted by hard material of the surrounding formation. End-bearing restraint at the pile base and restraining stress from surrounding ground formation that confines heat-induced strain of energy pile are both large, since the existence of bedrock at the bottom part of the energy pile. As a result, large axial stress is generated at the bottom part of energy pile during cooling operation as heat-induced expansion is restrained by bearing capacity as well as friction force. Generated axial stress during operation period gradually decreased with time and is at last completely eliminated as the energy pile and surrounding ground formation maintained heat equilibrium.

The general compressive strength of cast-in-place concrete is 28 MPa (Korean Standard Specification for Construction, 2013). In this study, the maximum thermal stress caused by 15-days energy pile operation field test is 1.4 MPa from heating test and 2.6 MPa from cooling test, which 5% and 10% of design criterion strength of cast-in-place concrete, respectively.

The result of the comprehensive in-situ test demonstrates that the thermal stress of the energy pile with bedrock formation at its bottom part has a considerable impact on the mechanical behavior of the energy pile as a structural foundation. Since the maximum thermal stress from the field test is about 10% of the compressive strength of cast-in-place concrete, it is concluded that additional safe factor of 10% should be applied to design strength of energy pile for supporting upper structure.

5 STUDY ON DESIGN METHOD FOR CAST-IN-PLACE ENERGY PILE

Commercial design programs for the GSHP system largely focus on a closed-loop vertical GHEX which is the most common type of GHEX. In addition, researches on design method for GHEX are also extremely biased towards a closed-loop vertical GHEX. Therefore, most commercial design programs cannot take into account the large volume of heat exchange pipes more than three pairs in the parallel U-type. Furthermore, they do not provide design tools for various heat exchange pipe configurations such as a coil-type or an S-type, which can be installed inside an energy pile with its large diameter.

Meanwhile, PILSIM2 is a simulation tool for the energy pile system developed from the well-known simulation program on the transient energy system, TRNSYS. The thermal performance of energy pile system, the heating and cooling potential of energy piles, and changes in fluid temperature during the operation period can be assessed with PILESIM2. Since PILSIM2 is a simulation program, it is inappropriate to use the program for design purpose directly. Therefore, in this paper, a novel design algorithm for a large-diameter energy pile system using the PILESIM2 program is provided. Figure 4 shows a design algorithm for large-diameter cast-in-place energy piles in order to determine the design load condition. When specifications of energy piles and ground conditions are given, affordable loads for heating and cooling a building space can be determined by this algorithm with satisfying the design EWT (Entering Water Temperature) range to achieve the maximum efficiency of the heat pump. The space area that can be covered by designed energy piles and ground conditions or the expected portion of energy demands on the considered area can be evaluated.

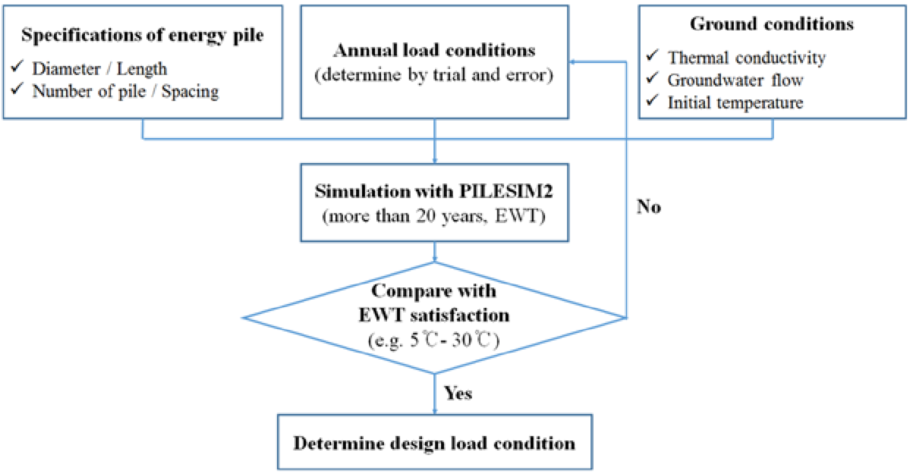


Figure 3. Design algorithm of energy pile system for determination of design load condition

However, since the PILESIM2 program can consider only parallel U-type pipes less than 5 pairs of pipes and the coaxial pipe, it is impracticable for the energy pile with large volume of heat exchange pipe more than 5 pairs (i.e. 8-pair- and 10-pair-parallel U-type pipe as considered in the test bed) and distinctive configurations such as the coil-type or S-type pipe. In order to overcome such a limitation, the design algorithm was modified by introducing an equivalent heat exchange coefficient with consideration of different configurations of heat exchange pipe, which is the ratio of exchangeable heat energy (Wh) to a standard configuration. Owing to the limitation of the PILESIM2 program, a 5-pair-parallel U-type energy pile can be the standard configuration. The exchangeable heat energy during the operation period can be estimated by field tests or numerical simulations. Then, the equivalent heat exchange coefficient of a considered pipe configuration is applied to the design results

In order to estimate the heating and cooling load amount (i.e., exchangeable heat energy (MWh)) that can be obtained from the energy piles constructed in the test bed, the design was carried out with the developed design algorithm. The specifications of energy piles applied in the design correspond to actual test bed conditions. Considering the design parameters, the variation of heat pump EWT for 20 years was simulated by PILESIM2 until the design EWT range of heat pump was satisfied. In the design result, the maximum heating and cooling loads were evaluated to be 5.59 RT for the cooling operation and 3.24 RT for the heating operation. Since about 1 RT is required for cooling an area of about 33 m^2, it is expected that six cast-in-place energy piles constructed in the test bed can cover the area of 185 m^2. Therefore, the GSHP system was constructed with six cast-in-place energy piles for heating and cooling the office space with the area of about 100 m^2 according to the design result.

6 VERIFICATION OF DESIGN METHOD FOR CAST-IN-PLACE ENERGY PILE

According to the design for the energy piles constructed in the test bed, the GSHP system was constructed using the six cast-in-place energy piles for heating and cooling office space with the area of 103.74m^2. A 5-RT-heat pump was constructed, and thermocouples were installed at inlets and outlets of the heat pump, in both the heat source (i.e., energy piles) direction and Fan Coil Unit (FCU) direction. Then, the exchangeable heat energy obtained from the energy piles and heating/cooling loads for the building were estimated from the measured temperature data along with the flow rate of working fluid. In addition, the electricity consumptions of the heat pump and circulating pumps were continuously measured with the aid of the data logger in order to evaluate the COP (Coefficient of Performance) of the GSHP system.

The heating and cooling of the office were made for two years in 2015 and 2016. During the operation, the average heating and cooling loads were evaluated to be 2.26 RT and 3.54 RT, respectively, while the maximum heating and cooling loads were estimated to be 4.20 RT and 4.31 RT, respectively. Consequently, the total energy averagely obtained per one year is 11.18 MWh for the cooling operation and 23.92 MWh for the heating operation. In other word, the actual heating and cooling loads are higher than the results of the design, which means more loads were used for heating and cooling the office than expected by design. When excessively large heating and cooling loads are required from the heat pump, overloads more than their own thermal capacities are imposed to the GHEXs, and eventually more dramatic changes in the geothermal environment can be expected. Consequently, overloads may affect the EWT variation of GHEX, which results in the degradation of the thermal performance of GSHP system. The COP and SPF (Seasonal Performance Factor) of the GSHP were summarized in the Table 3.

Table 3. Thermal performance of heat pump and GSHP system

Performance index	Operation condition	
	Heating	Cooling
COP of the heat pump	3.12	3.29
COP of the GSHP system	2.77	3.00
SPF	2.68	2.85

Considering that the COP of a GSHP system is usually more than 3.0, the COP and SPF of the GSHP system showed slightly poor performance than general GSHP system as expected. However, considering that the COP of conventional heating, ventilating, and air conditioning (HVAC) systems is usually around 1.0, the GSHP system constructed in the test bed is expected to save considerable operation costs, and heating and cooling energies.

In order to evaluate the burden of the overloads imposed to the energy piles, the LWT and EWT variation of energy piles during one year was presented in Figure 4. The LWT and EWT variations are dependent variables of heating and cooling loads for the considered building. Since the GSHP system was designed based on the design EWT range of heat pump (i.e., 5℃ in heating operation and 30℃ in cooling operation), Figure 4 should satisfy it.

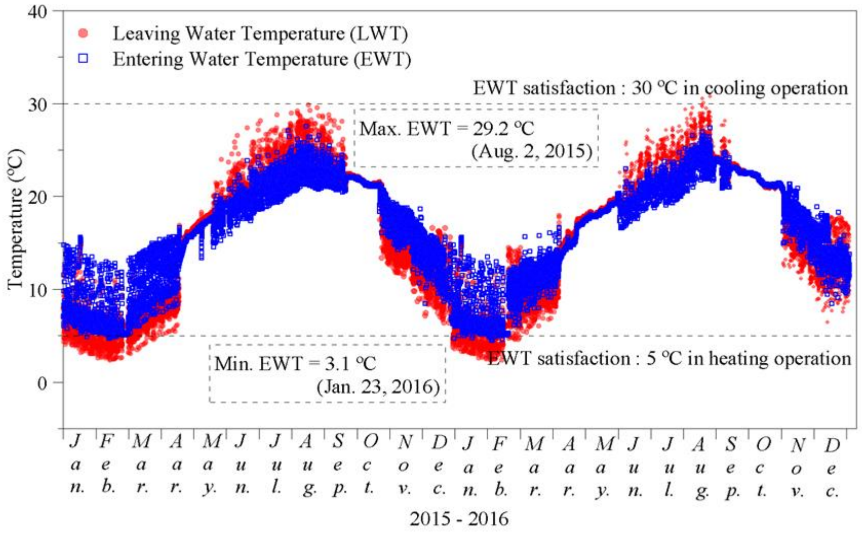


Figure 4. LWT and EWT variation of GSHP system

The minimum EWT during heating operation and the maximum EWT during cooling operation were measured as 3.1℃ and 29.2℃, respectively. The minimum EWT excessed the EWT satisfaction while the maximum EWT satisfied the design EWT ranges. In other words, the overloads were imposed to the energy piles during heating operation. The excess of design EWT range means that considered energy piles have insufficient capacity for dealing with the heating and cooling load of the building. The excess of design EWT range may cause the degradation of the thermal performance of GSHP system, which can lead to less economic efficiency. In addition, since the overloads were applied to the ground only during heating operation while the stable loads were imposed during cooling operation, the ground temperature will annually decrease due to the unbalance of heating and cooling loads. In order to prevent the overloads during heating operation, additional radiators should be installed to lessen the required heating loads of the office.

7 CONCLUSION

(1) First, full-scale energy piles were constructed in the test bed with various configurations of heat exchange pipe to experimentally evaluate the thermal performance and constructability depending on different pipe types. And, the standard construction method for large-diameter cast-in-place energy pile was provided by organizing the construction processes.

(2) Two different field tests were conducted to estimate the heat exchange capacities of constructed energy piles. In the results, the cast-in-place energy pile can reveal higher thermal performance per unit borehole length compared to the other conventional types of GHEXs by increasing heat exchange pipe length in large diameter. However, when inserting a large volume of pipes to improve the thermal performance of GHEX, the thermal interfere in the tight layout of pipes reduced the effectiveness of heat exchange. This result indicates the importance of determination on optimum pipe configuration in the design of cast-in-place energy pile.

(3) The maximum thermal stress caused by the 15-days continuous operation on cast-in-place energy pile was 10% of design criterion strength of cast-in-place concrete. Therefore, it is concluded that additional safety factor of 10% should be applied to design strength of energy pile for supporting upper structure. The stress during operation period gradually decreased with time and was at last completely eliminated as the energy pile and surrounding ground formation maintained heat equilibrium.

(4) A novel design algorithm for a cast-in-place energy pile system was provided using the PILESIM2 program and verified by monitoring the thermal performance of the GSHP system during two years. In the results, the total energy obtained from the heat pump was higher than the results of the design and the minimum EWT excessed the EWT satisfaction. This discrepancy was attributed to the different inlet fluid temperature condition, the low flow rate in the heat exchanger, and the trench from energy piles to the building with shallow depth.

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