DEVELOPMENT OF PERFORMANCE PREDCTION TOOL FOR THE GROUND SOURE HEAT PUMP SYSTEM CONSIDERING EFFECT OF GROUND SURFACE

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Abstract: The authors developed performance prediction tool for the GSHP system considering the influence of the ground surface. In this paper, the outlines of calculation method are firstly explained. Next, the TRT was carried out to validate the precision of the performance prediction tool. As the result, good agreement with the measured outlet temperature of the GHEX and the calculated one was observed. Additionally, performance of the GSHP systems using foundation pile with length of 6 m installed to the residential house is predicted. The minimum outlet temperature and maximum temperature of GHEX are less than 10 ^{o}C and more than 35 ^{o}C respectively when 15 piles are used as the GHEXs. Therefore, more than 20 piles are required for the GSHP system used for heating and cooling in the residential house. The heating SCOPs are approximately 4.0 and the cooling SCOPs are approximately 5.0. The results indicate that the GSHP system using foundation piles can operate with high efficiency.

Key Words: ***Ground Source Heat Pump, Performance Prediction Tool, Effect of Ground Surface, Foundation Pile***

1 INTRODUCTION

The Ground Source Heat Pump (GSHP) system is gradually gaining attention in Japan. The point view of cost reduction, it is effective to use the ground heat exchangers (GHEXs) buried in the shallow layer like the energy pile system for the residential buildings. However, the shallow layer in the ground is affected by air temperature and solar radiation.
The authors developed a performance prediction tool for the GSHP system considering effect of ground surface by combining two calculation methods. The first one is the calculation method for temperature variation in the ground affected by the heat extraction or injection via the GHEX (Katsura et al., 2008). The method is used for the conventional performance prediction tool for the GSHP system (Katsura et al., 2009, Nagano et al., 2006). The other is the calculation method for underground temperature distribution.
In this paper, the authors firstly explain the outlines of calculation method. Next, the result of the thermal response test (TRT) in order to validate the accuracy of the calculation is introduced. In addition, the authors assume introduction of the GSHP system using the foundation piles with the length of 6m to the residential house and predict the performance of GSHP systems.

2 PERFORMANCE PREDICTION COSIDERING EFFECT OF GROUND SURFACE

2.1 Overview of Calculation Method for Ground Temperature

Soil is treated as infinite isotopic constant solid and the ground surface is considered as the flattened solid surface without water evaporating and condensing. Then the heat transfer in the ground is treated as the unsteady heat conduction in the three dimensional cylindrical coordinate system. The heat transfer is expressed as Equation (1).

$$c_{ps}\rho_s \frac{\partial T_s}{\partial t} = \lambda_s \left(\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} + \frac{\partial^2 T_s}{\partial z^2} \right) \tag{1}$$

The temperature variation in the ground affected by the heat extraction or injection via the GHEX and the temperature variation in the ground caused by the ground surface can be calculated by resolving the solution into the following Equation (2).

$$T_s(r,z,t) = T_{s0} + \Delta T_{s1}(r,z,t) + \Delta T_{s2}(z,t) \tag{2}$$

Here, the first term in the right side is the initial ground temperature. The second term is the temperature variation affected by the heat extraction or injection via the GHEX. The third term is the temperature variation caused by the ground surface. The temperature variation caused by the ground surface is calculated with Equation (3)

$$T_{s2}(z,t_c) = T_T(z,t_c) + T_I(z,t_c) + T_J(z,t_c) \tag{3}$$

Where z is the underground depth and t_c is the elapsed time from July 1st.
The underground temperature distribution T_T is formed by the air temperature. The underground temperature distribution T_I and T_J are built by the solar radiation and the effective radiation to the ambient air, respectively. The temperature distribution T_{s2} is calculated by the approximate equations of T_T, T_I and T_J. These approximate equations are found by using a nonlinear least squares method (Marquardt method) and inputting hourly weather data such as the air temperature, solar radiation, etc., at the arbitrary area. Figure 1 compares the calculated underground temperature distributions with the measured one.

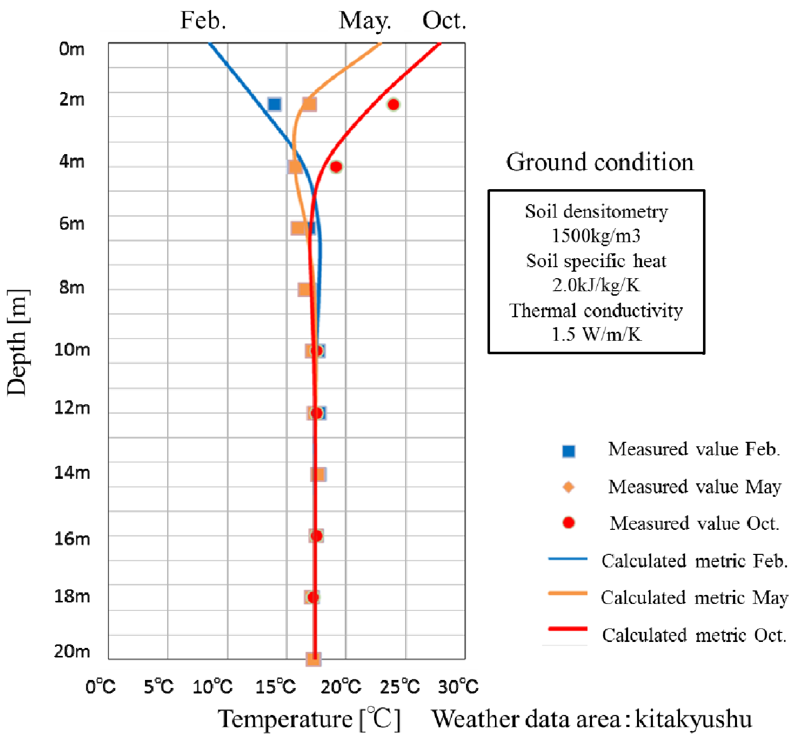

Figure 1 Comparison of underground temperature distribution

2.2 Performance Prediction Considering Effect of Ground Surface

Combining the above calculation method of the underground temperature distribution and the calculation method of temperature variation in the ground affected by the heat extraction or injection via the GHEX, the authors developed the performance prediction too for the GHEX considering effect of ground surface. The average temperature on the surface of the GHEX (borehole or pile) can be calculated by using Equation (4).

$$\frac{1}{L}\int_0^L T_s(r,z,t)dZ = T_{s0} + \frac{1}{L}\int_0^L \Delta T_{s1}(r,z,t)dZ + \frac{1}{L}\int_0^L \Delta T_{s2}(z,t)dZ \qquad (4)$$

Here, the first term in the right side is the initial ground temperature. The second term is the temperature variation affected by the heat extraction or injection via the GHEX. In this term, the boundary condition at $z = 0$ is set as $T_s = T_{s0}$. The details of calculation are described in the previous papers (Katsura et al., 2009, Katsura et al., 2008, Nagano et al., 2006). The third term is the temperature variation caused by the ground surface and the variation can be calculated with Equation (3).

3 THERMAL RESPONSE TEST TO VALIDATE CALCULATION RESULT

3.1 Outline of Thermal Response Test

The thermal response test shown in Figure 2 was carried out in order to validate the accuracy of the performance prediction tool. The water was circulated through the GHEX from March 11 to 13th with the conditions of constant flow rate and constant heating (Average 2kW). Then the inlet and outlet temperatures of GEHX, underground temperatures and flow rate were measured as shown in Figure 2.

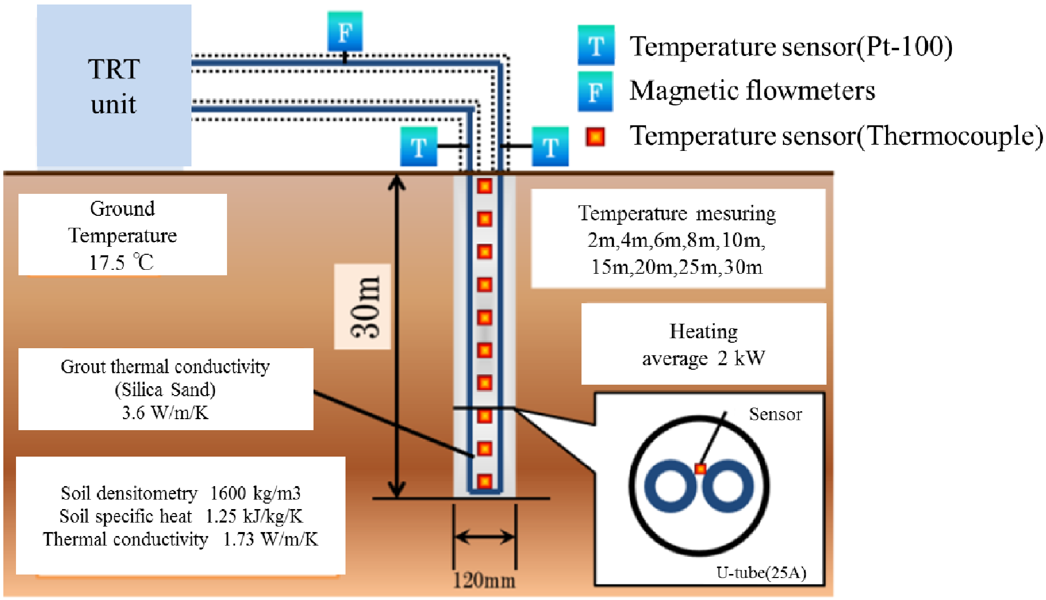

Figure 2: Diagram of thermal response test

3.2 CALCULATION CONDITIONS

Table 1 shows the calculation condition. The conditions of GHEX and soil are the same as the TRT. The density and specific heat of the soil is estimated basis on the geological formation. The measured ground temperature of 17.5 °C is given. The effective thermal conductivity is set as 1.73 W/m/K, which is obtained by the TRT previously conducted. The measurement values of hourly inlet temperature of the GHEX and flow rate are given. Then, the hourly outlet temperature and surface temperature of the GHEX according to depth are calculated. The surface temperatures of U-tube are calculated by using Equation (5) and giving the calculated borehole surface temperature because the measurement points are the surface of U-tube in the TRT.

$$T_{U-out} = T_s(r_{p-out}, t) - Q_p / (K_{p-out} A_{p-out}) \quad (5)$$

Here, Q_p is hourly heat injection rate. The values of K_{p-out} and A_{p-out} are the borehole overall heat transfer coefficient and the borehole surface area, respectively. The value of K_{p-out} is calculated by the boundary element method (Nagano et al., 2006)

Table 1 Calculation condition

GHEX	Specification	Single u-tube
	Boundary condition of ground surface	Temperature boundary condition
	U-tube interval	0.03 m
	GHEX length	30 m
	Diameter of borehole	0.12 m
	U-tube outside diameter	0.032 m
	U-tube inside diameter	0.026 m
	Grout thermal conductivity	3.6 W/m/K
Soil	Density of soil	1600 kg/m^3
	Undisturbed temperature	17.5 ℃
	Specific heat of soil	1.25 kJ/(kgK)
	Soil heat conductivity	1.73 W/(mK)

3.3 Result and Discussion

Figure 3 compares the measured outlet temperature with the one calculated by using the performance prediction tool. Good agreement with the measured outlet temperature and the calculated one is observed. Furthermore, the comparison between the measured underground temperature and the calculated underground temperature according to depth is shown in Figure 4. The error between measured and calculated temperatures is hardly observed at 2 m depth. The calculation values during the TRT are 1~2 ^{o}C lower than the measured values at 6m and 10 m. However, amply sufficient precision to be used as the tool is confirmed. The thermal conductivity of silica sand used as grouting material is usually 1.8 W/m/K. But a good agreement was observed when thermal conductivity of grouting material is given as 3.6 W/m/K. The parameters that mainly affect the temperature variation in the TRT are pointed to the effective thermal conductivity of the ground, undisturbed temperature in the ground, and effective thermal conductivity of the grouting material. The effective thermal conductivity of the ground and undisturbed temperature in the ground are obtained by the TRT previously conducted. Thus, it would appear that the convection in the silica sand is generated and the apparent effective thermal conductivity of grouting material increases.

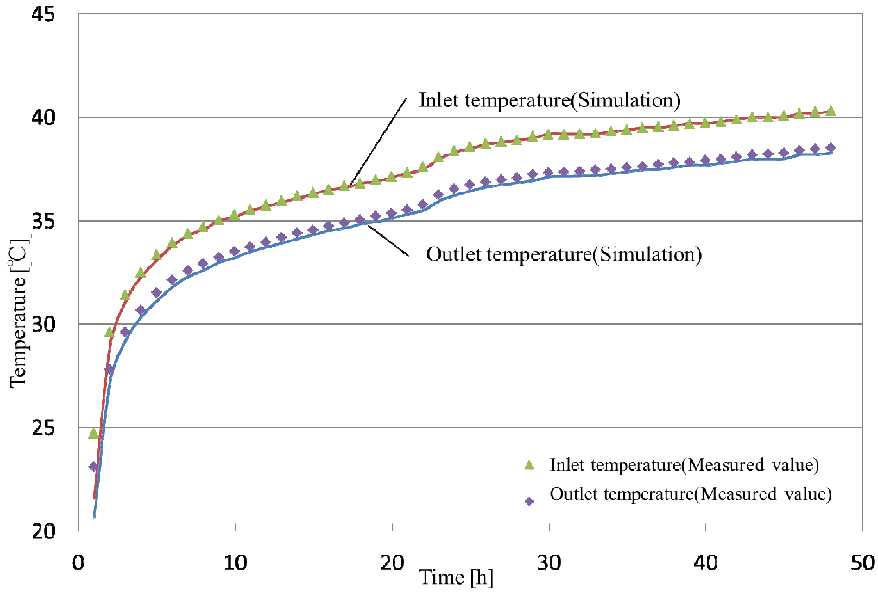

Figure 3: Comparison of inlet and outlet temperature of GHEX

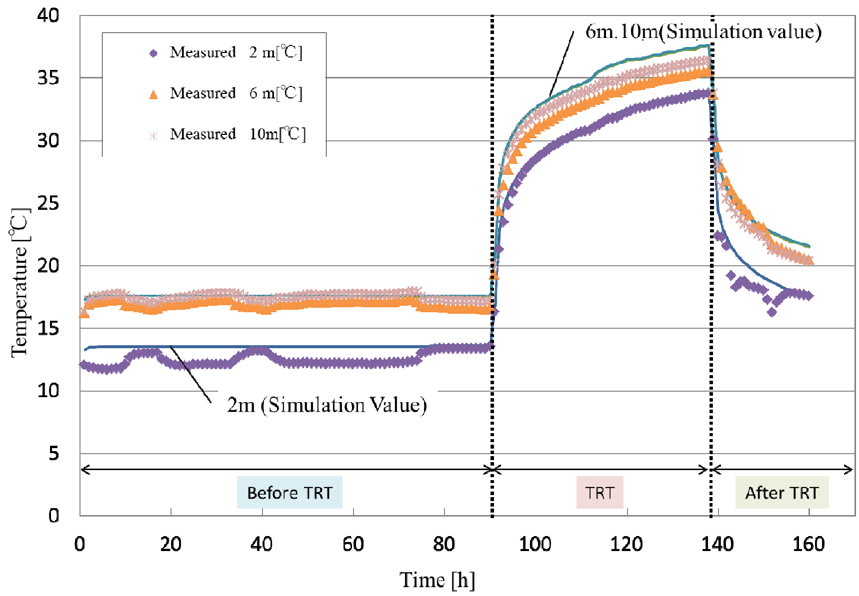

Figure 4 Comparison of surface temperature of U-tube

4 INVESTIGATION ON INSTALLATION OF GSHP SYSTEM USING FOUNDATION PILE

4.1 Calculation Conditions

The authors predict the performance of the GSHP systems using foundation pile with short length installed to the residential house. Table 2 shows the calculation conditions. The heat pump unit is a water-cooled variant refrigerant flow (VRF) air conditioning system. Figure 5 shows the arrangement of GHEXs (Foundation piles). The longitudinal and lateral intervals of foundation piles are 2 m, respectively. Five foundation piles are connected in series as shown in Figure 5. The number of foundation piles is given as 15, 20 and 25. Therefore, the GSHP system has 3~5 parallel circuits. Hourly heating and cooling load on the basis of the measured value is given. Figure 6 shows the hourly heating and cooling load. The length of the GHEX is 6m all. Single U-tube is used for the one foundation pile. The authors measured underfloor temperature in the model house because the foundation piles are buried in the ground under the floor. Then, the measured underfloor temperature is given as the air temperature on ground surface for calculation of underground temperature distribution. Figure 7 shows the relationship between the outside temperature and the temperature under the floor. It is assumed that there is no influence of solar radiation. Two year's operation of the GSHP system is simulated by using the performance prediction tool. The inlet and outlet temperature of the GHEXs, the power consumption of the GSHP system (Compressor and circulation pump) and SCOP of the GSHP are calculated by changing the number of GHEXs (Foundation piles).

Table 2 Calculation condition for GSHP system performance prediction

Building	Residential house	
City	Yahata(Kitakyushu) JAPAN	
Heat pump	Water-cooled multi-heat pump	
	Heating load	12.5 kW
	Heating power consumption	3.2 kW
	Cooling load	11.2 kW
	Cooling power consumption	3.1 kW
	Pump flow rate	12 L/min
	Pump power consumption	0.02 kW
GHEX	Specification	Single u-tube
	Ground surface Condition	Temperature boundary condition
	U-tube interval	0.03 m
	GHEX length	6.0 m
	Diameter of borehole	0.12 m
	U-tube outside diameter	0.032 m
	U-tube inside diameter	0.026 m
	Grout thermal conductivity	1.8 W/(m・K)
Soil	Density of soil	1600 kg/m^3
	Underground temperature	17.8 ℃
	Specific heat of soil	1.25 kJ/(kgK)
	Soil heat conductivity	1.0 W/(m・K)

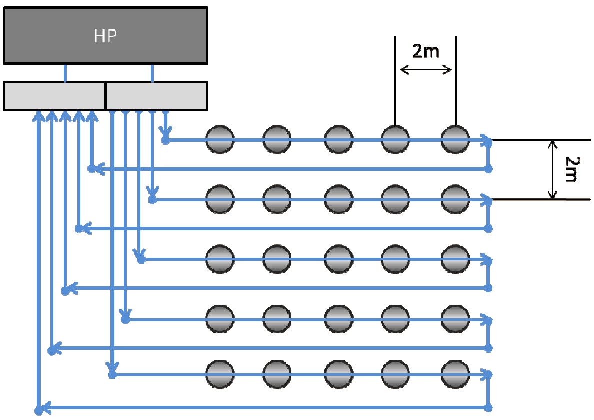

Figure 5 Arrangement of the GHEX

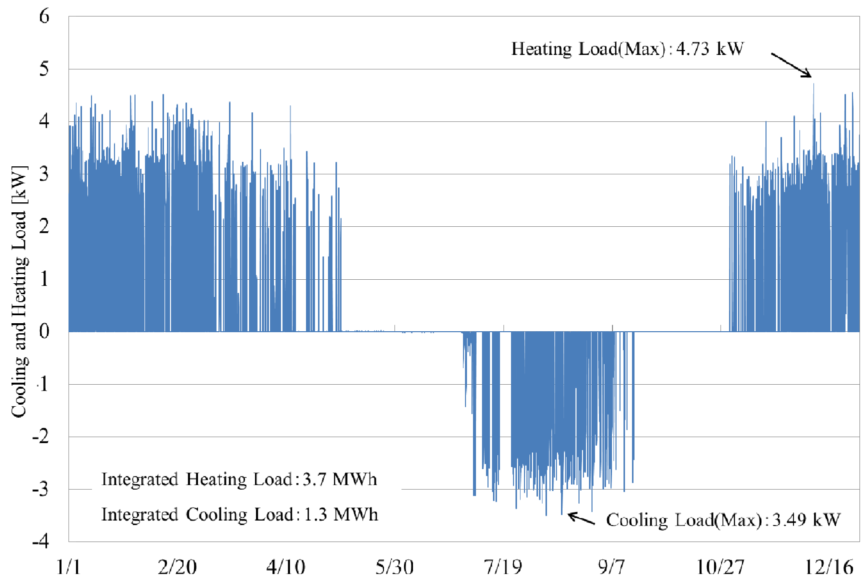

Figure 6 Hourly cooling and heating load

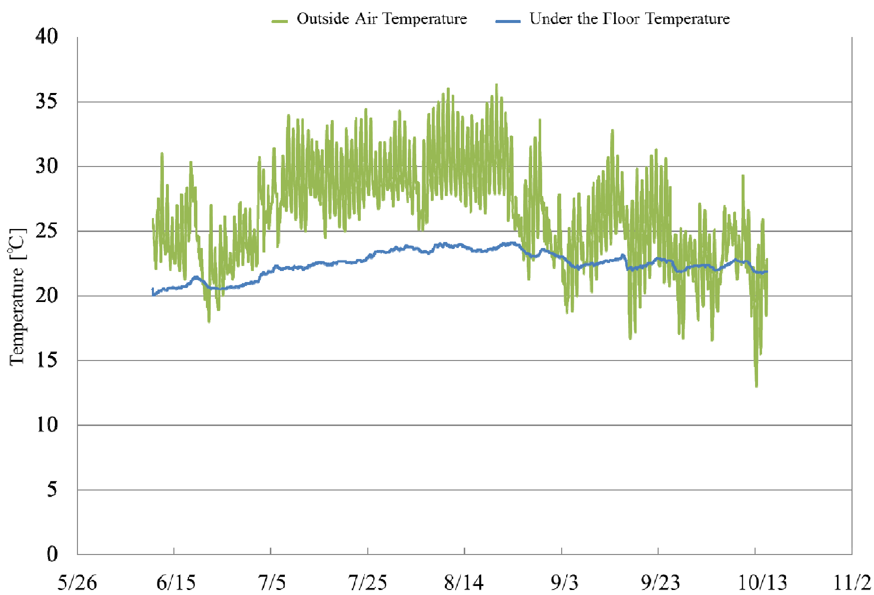

Figure 7 Outside air temperature and underfloor temperature

4.2 Result and Discussion

Monthly variations of the average surface temperature of GHEXs according to the number of GHEXs are shown in Figure 8. When the number of GHEXs is larger, the temperature variation becomes smaller. Hourly variations of the outlet temperature of GHEXs are shown in Figure 9. The minimum outlet temperature in the case of 15 piles becomes 6.5 °C. This result indicates that the minimum inlet temperature decreases about 1.5 °C. There is the risk of thermal medium's freezing, when the water is used as thermal medium. Therefore, assuming that water is used, more than 20 piles are required. In addition, there is a possibility that the maximum temperature during cooling period is more than 35 °C in the case of 15 piles and the cooling output from heat pump unit declines. It is thought that more than 20 piles are required.
Figure 10 shows the electric power consumption and SCOP of the GSHP system according to pile number. The heating SCOPs for every condition are approximately 4.0 and the cooling

SCOPs for every condition are approximately 5.0. The results indicate that the GSHP system using foundation piles can operate with high efficiency.

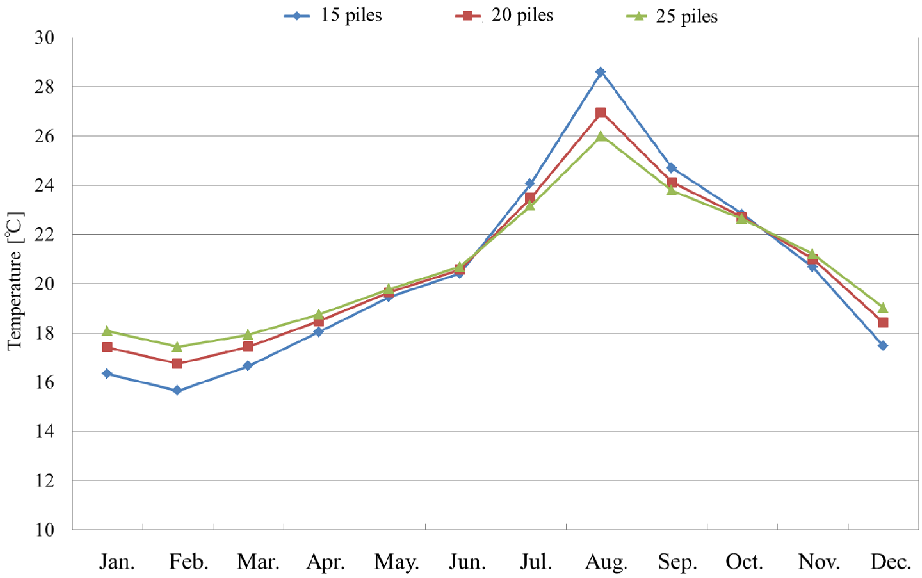

Figure 8 Monthly variations of average surface temperature of GHEX (Foundation pile)

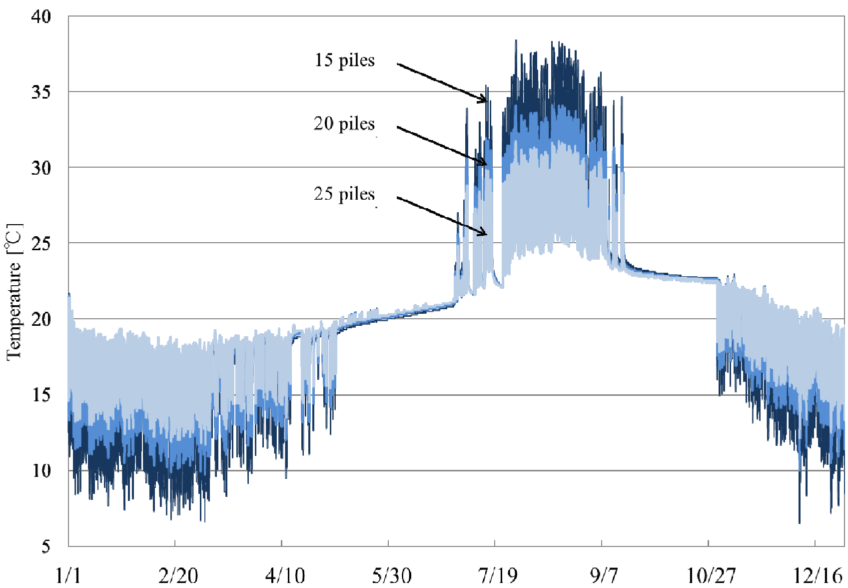

Figure 9 Hourly variations of outlet temperature of GHEXs

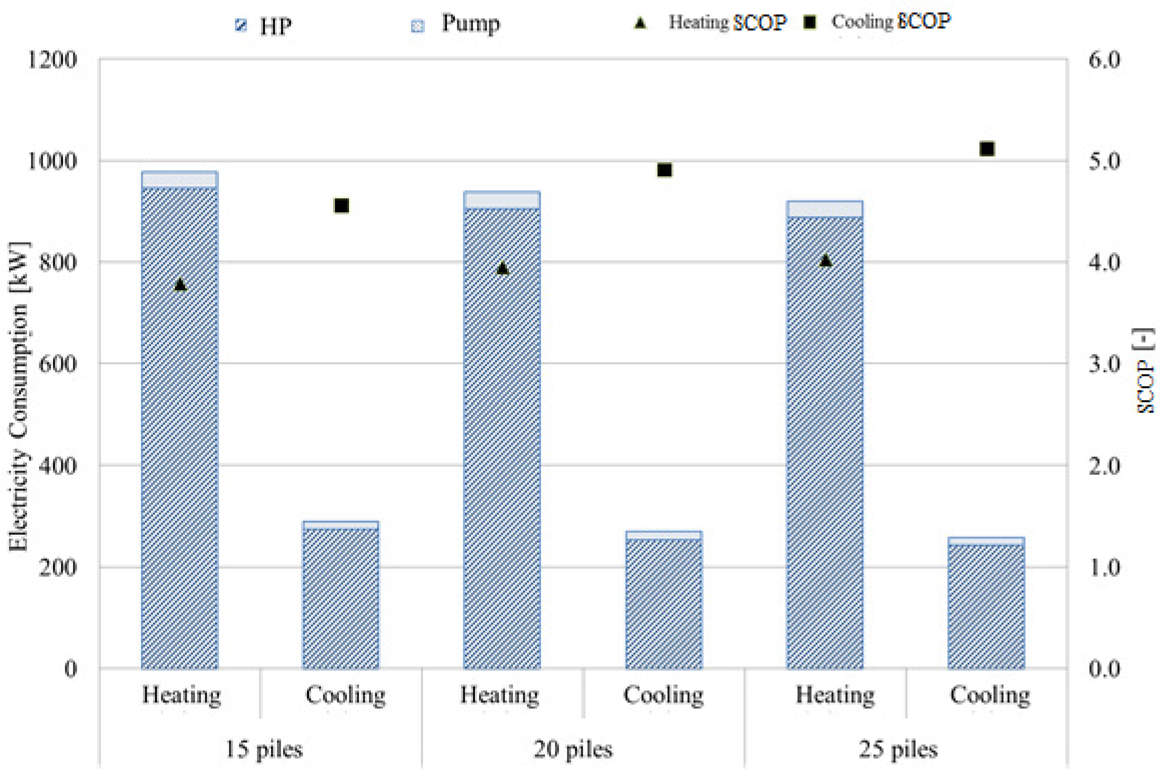

Figure 10 Electric power consumption and SCOP of GSHP system according to pile number

5 SUMMARIES

1) Combining the calculation method of the underground temperature distribution and the calculation method of temperature variation in the ground affected by the heat extraction or injection via the GHEX, the authors developed performance prediction tool for the GSHP system that considers the influence of the ground surface. The outlines of calculation method were explained.
2) The TRT was carried out to validate the precision of the performance prediction tool. As the result, good agreement with the measured outlet temperature of the GHEX and the calculated one was observed.
3) Performance of the GSHP systems using foundation pile with short length installed to the residential house is predicted. The minimum outlet temperature and maximum temperature of GHEX are less than 10 °C and more than 35 °C respectively when 15 piles are used as the GHEXs. Therefore, more than 20 piles are required for the GSHP system used for heating and cooling in the residential house.
4) The heating SCOPs are approximately 4.0 and the cooling SCOPs are approximately 5.0. The results indicate that the GSHP system using foundation piles can operate with high efficiency.

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NOMENCRATURE

A: Surface area [m^2], c_p: Specific thermal capacity [kJ/kg/K], *K*: Overall heat transfer coefficient [W/m^2/K],, *L*: Length [m], *Q*: Amount of heat [W], *r*: Radius [m], *T*: Temperature [^{o}C], *t*: Time [h], t_c: Elapsed time from July 1st [h], *z*:Distance for z axis [m], ρ: Density [kg/m^3]

Subscript

p: Ground heat exchanger, *p-out*: Ground heat exchangers’ surface, *s*: soil, *system*: system, *SP*: Solar panel, *ST*: Storage tank, *WHP*: Water source heat pump, *1in*: Inlet in the primary side, *1out*: Outlet in the primary side