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Development and application of a new calculation method for double spiral ground heat exchangers

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Abstract

This study provides a new calculation method for double spiral ground heat exchangers (GHEs) and involves the combination of the analytical infinite line source (ILS), and infinite cylindrical source (ICS) models with the capacity resistance model (CaRM). Method adopts the concept of fin efficiency, enabling it to calculate underground temperature change easily and accurately, followed by integration into a simulation tool for ground source heat pump (GSHP) systems. Verification was done by comparing the simulation results with actual operating data, measured from a zero-energy building (ZEB) in Sapporo, Japan. Under conditions of instantaneous large heat injection, significant differences were observed between the simulation the actual measurements during initial 50 h. the number of temperature nodes in the network was increased to effectively reduce the error between simulations and measurements.

Keywords: ground source heat pump system, double spiral ground heat exchangers, capacity resistence model, energy pile,simulation;

1. Introduction

More than 140 countries have pledged to achieve net-zero emissions at the COP 26 meeting held in UK, 2021 [1], this has reaffirmed that climate change is the greatest threat to all of us. Building energy consumption accounts for 40% of the total global energy consumption, to substantially reduce greenhouse gas emissions, energy supplies for space cooling/heating must be shifted from fossil fuels to renewable energy sources [2].

Ground source heat pump (GSHP) systems are gaining popularity in residential and commercial buildings due to their high energy efficiency, environmental friendliness, and ease of integration with other energy systems. However, the biggest obstacle to promoting GSHP systems is the large amount of land required and the high cost of drilling for ground heat exchangers (GHEs).

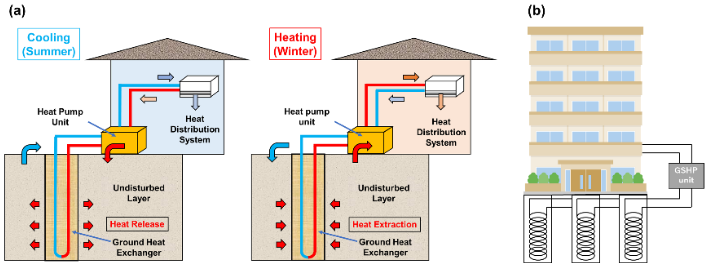

Fig. 1. (a) Operation of GSHP system with borehole U-tube GHE; (b) Buildings with GSHP system using thermal piles

Thermal piles have been adopted in recent years to tackle these problems. Thermal pile is a type of energy structure that incorporates the GHEs of GSHP systems through the foundation elements of the building.

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Thermal piles can not only support the structure of the building but also serve as GHEs [3]. In this paper, a new simulation tool is developed by combining this calculation method (for temperature change inside the thermal pile) with a ground temperature simulation program for GSHP systems (for temperature change outside the thermal pile) for temperature simulations of thermal piles with double spiral pipe GHEs.

2. Development of the new calculation method for double spiral pipes

In the previous study, several methods were used to calculate the heat transfer inside the spiral tube. Cui et al. [4] proposed a ring-coil heat source model but did not provide exact solutions for the spiral coil source. Zhang et al. [5] made improvements by considering the arrangement and pitch of spiral pipe and simplified the calculation. This new model, however, cannot be applied if the grouting material differs from that of the surrounding soil. Park et al. [6] created an efficient spiral coil source model along with its analytical solution, but its long-term operational efficiency is yet to be verified.

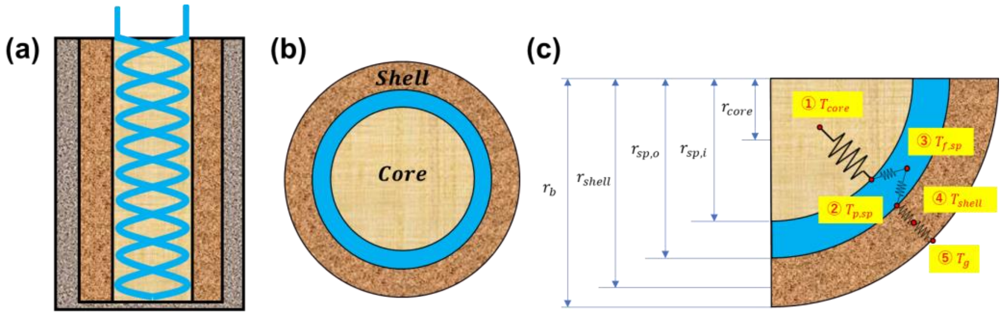

Fig. 2. (a) Sectional view of thermal pile, (b) Top view of thermal pile, and (c) Partial detail of thermal pile

The larger diameters of the thermal pile than the common value of the borehole make it essential to consider the heat capacity of the grouting material when studying the thermal performance of double spiral pipe GHE. Previous works [7] presented a numerical model, CaRM-He, to solve this problem and analyzed the thermal behavior of a short-length spiral pipe GHE.

This study also employed the capacity and resistance model (CaRM) to account for the thermal capacitance of grouting material, temperature nodes were arranged in the radial direction to reduce the amount of calculation while obtaining acceptable calculation accuracy. The volume of the thermal pile is divided into three parts (Fig. 2):

- “core” part: grouting material
- double spiral tube
- “shell” part: thermal pile material between spiral tube and borehole boundary

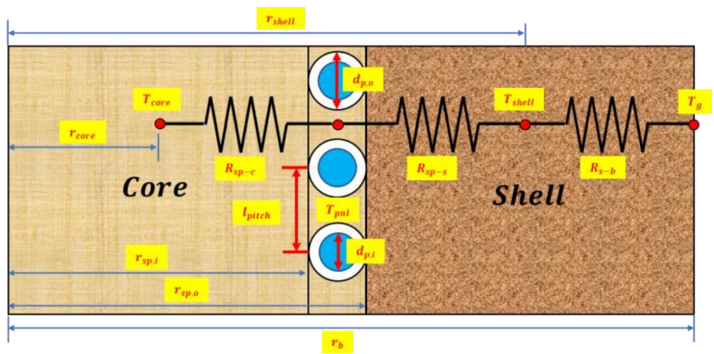

Fig. 3. Sectional drawing of the thermal pile

The heat transfer processes inside thermal pile consist of three parts [7] [8]:

- heat conduction in the “core” part
- heat convection between flowing circulating fluid and pipe surface
- heat conduction in the “shell” part

As the outer diameter of the pipe $d_{p,o}$ is much smaller than the borehole diameter, the double spiral pipe was considered as a line that injects/absorbs heat into/from the ground in summers/winters [8]. Assuming this, the thermal resistances between "core" part and double spiral pipe, double spiral pipe and "shell" part, and "shell" part and surrounding soil can be respectively expressed in form of equations (Fig. 3):

$$R_{sp-c} = \frac{1}{2\pi \cdot l_b \cdot \lambda_{core}} \cdot ln\left(\frac{r_{sp,i}}{r_{core}}\right) \tag{1}$$

$$R_{sp-s} = \frac{1}{2\pi \cdot l_b \cdot \lambda_{shell}} \cdot ln\left(\frac{r_{shell}}{r_{sp,o}}\right) \tag{2}$$

$$R_{s-b} = \frac{1}{2\pi \cdot l_b \cdot \lambda_{shell}} \cdot ln\left(\frac{r_b}{r_{shell}}\right) \tag{3}$$

However, the temperature of the layer between "core" and "shell", which contains double spiral pipe and grout, is difficult to calculate. We have found a calculation method adopting fin efficiency to solve this problem.

Previous studies proposed a calculation method, Kollmar-Liese method, for the thermal emission of flat floor heating panels with a cylindrical heat source [10]. In a hot-water floor heating system, as shown in Fig. 4 (a), it is assumed that a virtual fin with a width (d) equal to the outer diameter ($d_{p,o}$) of the pipe is attached to the pipe. Fig. 4 (b) depicts a combination of a virtual fin and a pipe, fin efficiency η of the virtual fin can be calculated:

$$m = \sqrt{\frac{2\alpha}{\lambda \cdot d}}; h = \frac{l_{pitch} - d_{p,o}}{2}; \eta = \frac{tanh(m \cdot h)}{m \cdot h} \tag{4}$$

Assuming that the surface temperature of the pipe is T_H and the ambient temperature is T_L, the mean temperature T_m of the virtual fin can be calculated using the Kollmar-Liese method [10]:

$$T_m = T_L + \eta \cdot (T_H - T_L) \tag{5}$$

The vertical section of the double spiral pipe GHE resembles a "vertical" floor heating panel (Fig. 4 (c)). The convective thermal resistance between circulating fluid and pipe surface can be expressed as:

$$R_{sp-f} = \frac{1}{2\pi \cdot r_{p,i} \cdot l_{sp} \cdot \alpha_f} + \frac{1}{2\pi \cdot \lambda_p \cdot l_{sp}} \cdot ln\left(\frac{r_{sp,o}}{r_{sp,i}}\right) \tag{6}$$

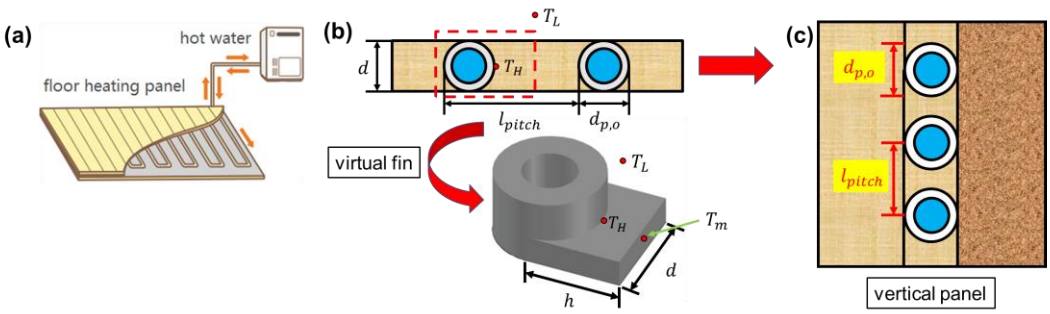

Fig. 4. (a) A typical radiant floor heating system (b) Principle of Kollmar-Liese method (c) Similarity between floor heating panel and double spiral pipe GHE

According to Kollmar-Liese method, heat transfer coefficient between spiral tube and "core" grout, spiral tube and "shell" grout can be calculated [9]:

$$K_{fcore} = \frac{1}{2\pi \cdot r_{core} \cdot l_b \cdot R_{sp-c}} \tag{7}$$

$$K_{fshell} = \frac{1}{2\pi \cdot r_{shell} \cdot l_b \cdot R_{sp-s}} \tag{8}$$

$$Z_{core} = \frac{l_{pitch} - d_{p,o}}{2} \cdot \sqrt{\frac{2 \cdot K_{fcore}}{\lambda_p \cdot d_{p,o}}} \tag{9}$$

$$Z_{shell} = \frac{l_{pitch} - d_{p,o}}{2} \cdot \sqrt{\frac{2 \cdot K_{fshell}}{\lambda_p \cdot d_{p,o}}} \tag{10}$$

$$\eta_{fshell} = \frac{tanh(Z_{shell})}{Z_{shell}} \tag{11}$$

$$\eta_{fcore} = \frac{tanh(Z_{core})}{Z_{core}} \tag{12}$$

Using Kollmar-Liese method, the average temperature of the “vertical” panel T_{pnl} can be expressed as:

$$T_{pnl} = \frac{1}{2}\left[\left(T_{sp} - T_{core}\right) \cdot \eta_{fcore} + T_{core}\right] + \frac{1}{2}\left[\left(T_{sp} - T_{shell}\right) \cdot \eta_{fshell} + T_{shell}\right] \tag{13}$$

Using T_{pnl}, the heat balance equation in each part can be expressed:

- Circulating fluid in double spiral pipe:

$$c_f \cdot \rho_f \cdot \pi \cdot r_{p,i}^2 \cdot l_{sp} \cdot \frac{dT_f}{dt} = c_f \cdot \rho_f \cdot v_f \cdot \left(T_{f,in} - T_{f,out}\right) - \frac{T_{f,sp} - T_{p,sp}}{R_{sp-f}} \tag{14}$$

- The “core” part:

$$c_{core} \cdot \rho_{core} \cdot \pi \cdot r_{sp,i}^2 \cdot l_b \cdot \frac{dT_{core}}{dt} = \frac{T_{pnl} - T_{core}}{R_{sp-c}} \tag{15}$$

- The “shell” part:

$$c_{shell} \cdot \rho_{shell} \cdot \pi \cdot (r_b^2 - r_{sp,o}^2) \cdot l_b \cdot \frac{dT_{shell}}{dt} = \frac{T_{pnl} - T_{shell}}{R_{sp-s}} - \frac{T_{shell} - T_s}{R_{s-b}} \tag{16}$$

Our laboratory has developed a high-speed simulation program for GSHP systems in previous research. It is based on the analytical model of Infinite Line Source (ILS) and Infinite Cylindrical Source (ICS) models [10]. In this research, the new calculation method for double spiral GHEs was integrated into the simulation program in MATLAB R2020b, and the calculation flow is illustrated in Fig. 5.

For one time step $dt = 60s$, the calculation procedures are under:

- Electricity consumption E_{hp} of the heat pump unit and fluid temperature $T_{1,out}$ flowing out of the heat pump unit are calculated using the building load Q_2 (secondary side), heat extraction/injection from/into the ground Q_1 (primary side). $T_{1,out}$ is equal to the inflow temperature of the circulating fluid $T_{p,in}$.
- The heat transfer processes inside the thermal pile and inflow temperature of the circulating fluid $T_{p,out}$ have been calculated using the new calculation method proposed. $T_{p,out}$ is equal to the fluid temperature $T_{1,in}$ flowing into the heat pump unit, which will be used for the next time step.
- The surrounding soil temperature T_s (outside the thermal pile) is calculated in GroundClub, T_s is equal to the thermal pile boundary temperature T_b, which will also be used for the next time step.

The simulation results of the GHSP system for long-term operations can be obtained by performing continuous step-by-step simulations of temperature changes in pipe inlet $T_{p,in}$, outlet $T_{p,out}$, and ground T_s.

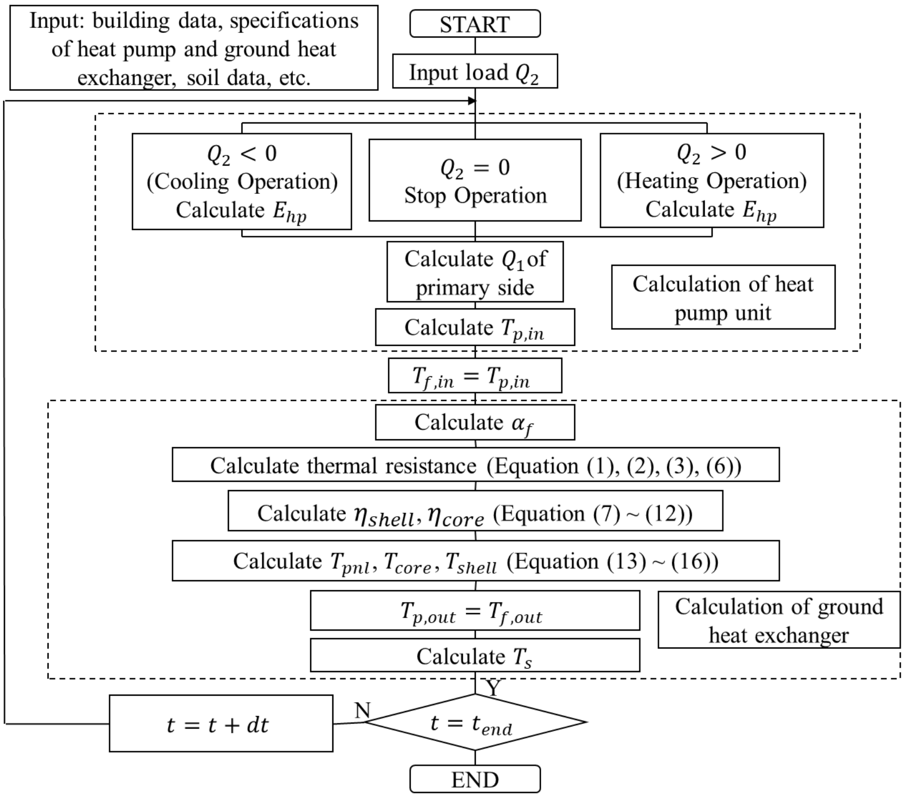

Fig. 5. Calculation flowchart for the GSHP system with double spiral pipe GHEs

3. Results and analyses

The verification work was carried out in a 3-story house in Sapporo, Japan. Table 1 lists the basic information about the house. Energy efficient technologies used in this house include a photovoltaic panel system for electricity supply, heat recovery ventilation system, and GHSP system, FCU (fan coil unit), and radiant air conditioning system. The house has been in operation since 2021/7 and was verified as a nearly-ZEB (zero energy building).

There are 3 GSHP units (rated power 10 kW) and 24 thermal piles installed on each floor of the house to provide space heating and cooling and snowmelt in winter. Figure 14 illustrates the system diagram of each floor. The thermal pile configuration for each floor is as follows: 4 (2 series × 2 parallel) for 1st floor (stores), 6 (2 series × 3 parallel) for 2nd floor (office rooms), 4 (1 + 1 + 2) for 3rd floor (office rooms and meeting rooms) and 10 for snowmelt (Fig. 6 (c)).

Each GSHP unit has temperature sensors and electromagnetic flow meters that collect real time measurements of pipe inlet temperature $T_{p,in}$, outlet temperature $T_{p,out}$, circulating fluid flow v_f, and power consumption of heat pump unit E_{hp}. Data was collected over a period of one year and was used for the purpose of verification.

Table 1. Basic information of the house

Building	**Energy saving technologies**
Location: Sapporo, Japan	Heat recovery ventilation system
Floor area: 650.85 m^2	High thermal insulation
Number of floors: 3	PV system
Operation time: 2021/7 ~ now	Radiant air conditioning system
Structure: Wooden	GSHP system

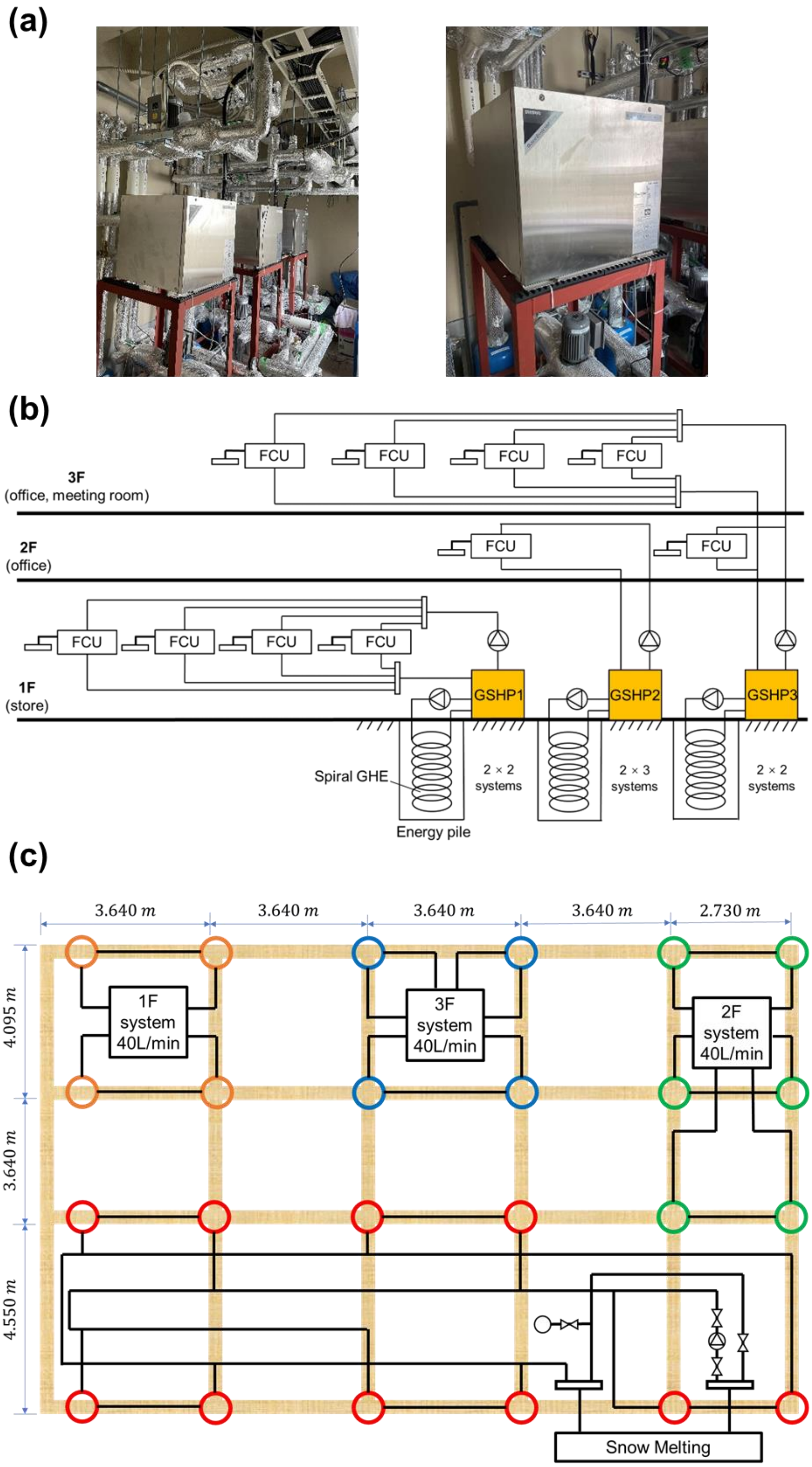

Fig. 6. (a) Heat pump units on the first floor, (b) Schematic diagram of the 3-story house, (c) Layout diagram of thermal piles installed in the house

Table 2. GSHP system specifications

Description	Unit	Value
Thermal pile		
Depth l_b	*m*	20
Outer radius r_b	*m*	0.3
Inner radius $r_{sp,o}$	*m*	0.2
"Core" part (cement & soil)		
Thermal conductivity λ_{core}	*W/m·K*	0.6
Specific heat capacity c_{core}	*kJ/kg·K*	0.9
Density ρ_{core}	*kg/m³*	2100
"Shell" part (concrete)		
Thermal conductivity λ_{shell}	*W/m·K*	2.0
Specific heat capacity c_{shell}	*kJ/kg·K*	0.95
Density ρ_{shell}	*kg/m³*	2500
Double spiral GHE		
Pipe outer diameter $d_{p,o}$	*m*	0.032
Pipe inner diameter $d_{p,\mathrm{i}}$	*m*	0.026
Spiral distance l_{pitch}	*m*	0.25
Thermal conductivity of pipe material λ_p	*W/m·K*	0.38
Length of spiral pipe l_{sp}	*m*	94.63
Soil		
Specific heat capacity λ_s	*kJ/kg·K*	2
Density ρ_s	*kg/m³*	1500
Initial temperature T_s	*℃*	12
Circulating fluid: 40% ethylene glycol solution		

Table 2 gives the specifications of the GSHP system. In October 2021, an in-site thermal response test (TRT) was performed to determine the thermal conductivity of the ground soil. The data were analyzed using the Kelvin Line Theorem, and the effective thermal conductivity of soil was calculated to be λ_s=1.846 (W/m·K). By applying this value to the simulation, the verification work was performed by comparing the measured and simulated data and simulation under two cases discussed below:

3.1. Space cooling in summer

During the space cooling period, the indoor room temperatures were set to 26 ℃. As majority of the rooms on the first floor are occupied, GSHP unit 1 ran the longest. As such we chose this unit for data analyses. The heat injection from the house into ground can be calculated using the hourly recorded pipe inlet/outlet temperature and the flowrate data of the circulating fluid during the space cooling period (Fig. 7 (a)):

$$Q_{injection} = \rho_f \cdot c_f \cdot v_f \cdot (T_{p,in} - T_{p,out}) \tag{16}$$

Then heat injection during this period was used as the primary side load Q_1 for subsequent simulations. Except for the preparation time, the verification period was set as 2021/8/1–2021/8/31. Fig. 7 (b) shows the comparative hourly changes of the pipe inlet temperature $T_{p,in}$ for both, measured and simulated data.

The RMSE (Root Mean Squared Error) value between measurement and simulation data from 8/1 to 8/31 was reported to be 0.73, indicating the accuracy of the simulation tool. The simulated and measured average temperatures were reported to be 19.71 ℃ and 19.77 ℃, respectively. Changes in both temperatures display similar trends, with minor differences when the temperatures change rapidly.

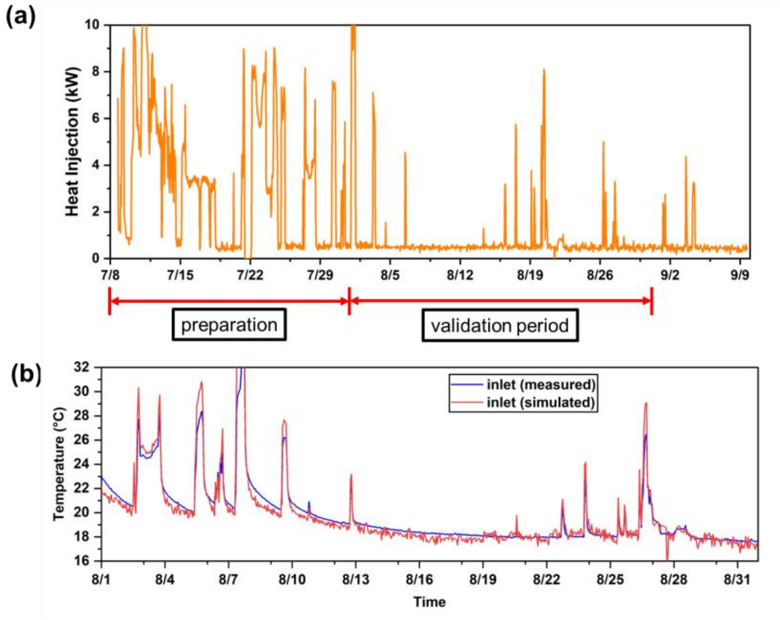

Fig. 7. (a) Heat injection into the ground during space cooling period (b) Pipe inlet temperature during space cooling period

3.2. Space heating in winter

All GSHP units were set to provide 45 °C hot water during the space heating period, while the indoor room temperatures were set to 22 °C. The recorded data was used to calculate the heat extracted from the ground, the results for which are shown in Fig. 8 (a):

$$Q_{extraction} = \rho_f \cdot c_f \cdot v_f \cdot (T_{p,out} - T_{p,in}) \quad (17)$$

Fig. 8 (b) plots the comparison between measured and simulated data for pipe inlet temperature. Excluding maintenance and holiday time, the verification period was selected from 1/7 to 2/7, which is the coldest period in Sapporo, when space heating is most needed. The results show that the temperatures between measurement and simulation are well matched with an RMSE value of 1.06. This value is acceptable and demonstrates the effectiveness of this simulation tool.

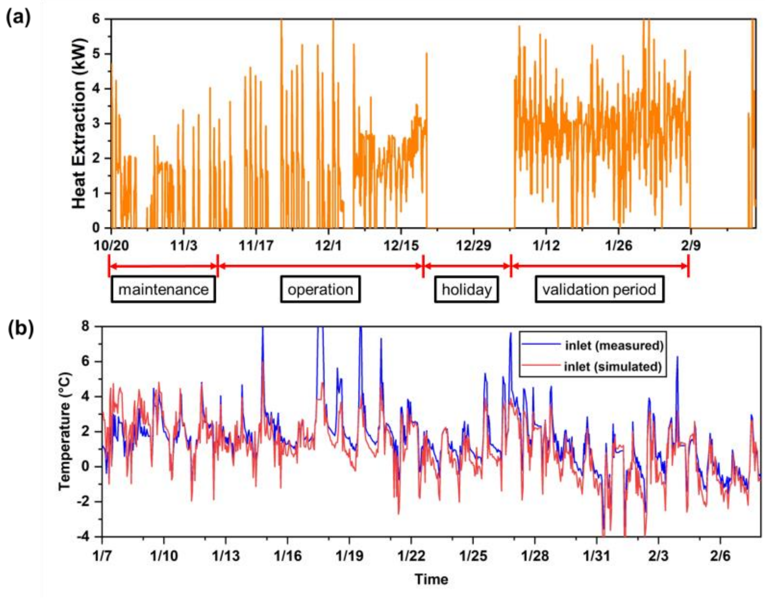

Fig. 8. (a) Heat extraction from the ground during space heating period (b) Pipe inlet temperature during space heating period

This simulation tool has been designed to generate high accuracy performance assessment results to make sound estimates supporting the early-stage decision-making. The summer and winter verifications show that this simulation tool for performance prediction can be applied in the preliminary design phase of future GSHP systems using thermal piles and double spiral pipe GHEs.

4. Discussion

The measurement results of the TRT test were compared with the simulation results during the verification works, as shown in Fig. 9. Although the two sets of data agree well after a period of 100 h, there are significant errors in both pipe inlet and outlet temperatures during initial 50 h. This means that, when applying the CaRM model, there will be a significant difference in the simulated and calculated temperature changes over a short period of time in case of large instantaneous heat injections.

This is mainly because the CaRM or lumped thermal capacity model assumes that the temperature of each solid is spatially independent (uniform) and can be represented by the same temperature. If the volume of the solids corresponding to the temperature nodes is too large, the represented temperatures may deviate from the actual temperatures.

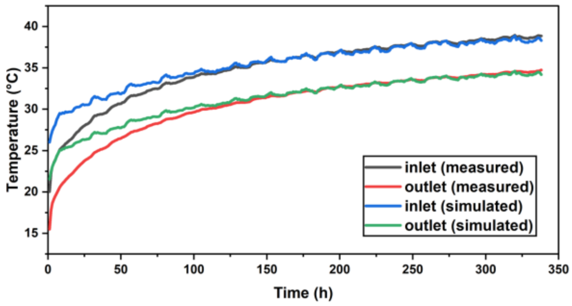

Fig. 9. Comparison of pipe inlet & outlet temperature between simulation and measurement

To solve this problem, the size of solid can be reduced so that the network of interconnected thermal resistances and capacities has a finer mesh. The “core” and “shell” part are divided into n regions (Fig. 10 (a)), corresponding to n temperature nodes. With this, the heat load and circulating fluid flow in the initial 50 h of TRT can be used as an input for the simulation, Fig. 10 (b) shows that the deviation between the simulation results and the actual measured data reduces with increase in temperature nodes during the initial 30 h. This thus proves that the simulation tool can also be used for short-term operation predictions.

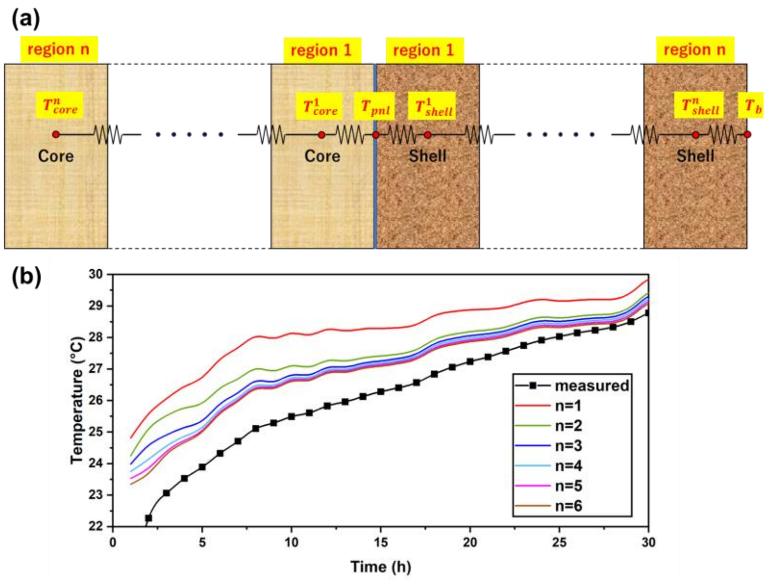

Fig. 10. (a) Concept of dividing “core” and “shell” part into n annual regions (b) Comparison of pipe inlet temperature in initial 30 h

5. Conclusion

The proposed new calculation method based on the CaRM model is an improvement over the previous ones as it adopts the concept of fin efficiency and integrates a simulation program for GSHP system. The main findings of this paper are:

- Different from the traditional U-shaped pipe GHE, the double spiral pipe GHE adopts shorter underground borehole, but has a larger area for heat exchange between the ground and circulating fluid without additional drilling work, which saves the initial costs of the GSHP system and promotes its use in the future.
- By replacing the spiral pipe with a "vertical" heat generating/absorbing panel, the temperature changes in each part of the thermal pile can be easily obtained without a huge amount of calculation.
- Verification work carried out in an energy-efficient house proved that the simulation tool produces reliable and high-precision simulation results for the long-term operation of GSHP systems, both in summers and winters. This would assist in the preliminary designing phase of future GSHP systems.
- For short-term simulations of less than 50 h, the simulated results can still agree well with the measured results by adding more temperature nodes to the thermal network.

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Nomenclature

Symbols		**Subscripts**	
l	length/depth, m	b	borehole of thermal pile
η	fin efficiency	sp	spiral pipe
T	temperature, °C	s	ground soil
R	heat resistance, K/W	f	circulating fluid
r	radius, m	in	inlet
d	diameter, m	out	pipe outlet
α	heat transfer coefficient, $W/m^2{\cdot}K$	o	outer
λ	thermal conductivity, $W/m{\cdot}K$	i	inner
v	flow rate, m^3/s	$core$	"core" part
Q	thermal load, kW	$shell$	"shell" part
ρ	density, kg/m^3	pnl	"vertical" panel
c	specific heat capacity, J/kg·K	p	GHE pipe
E	electricity consumption, kW	hp	heat pump

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