



Development of a Simulation Tool for Ground Source Heat Pump Systems Using Horizontal Ground Heat Exchangers

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Presentation outlines



1. Introduction
 - Background and issue of ground temperature calculation-
2. Regression model of temperature response function using ANN
3. Simulation tool for GSHP system using horizontal spiral GHE applying temperature response
4. Application –Case studies to determine the required GHE length-

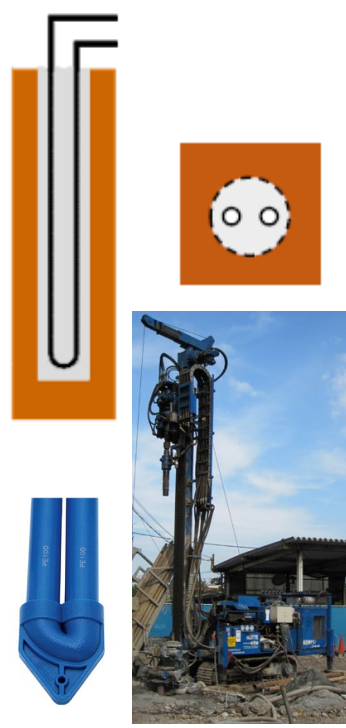


Introduction -Background-

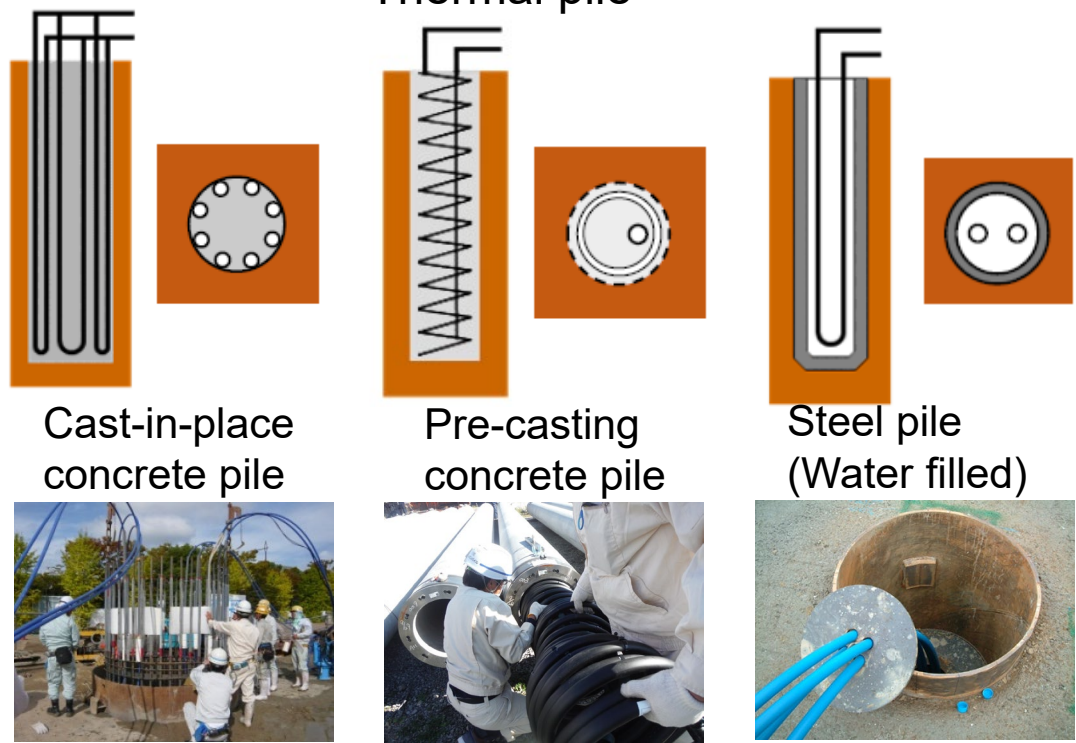


Examples of ground heat exchangers (GHEs)

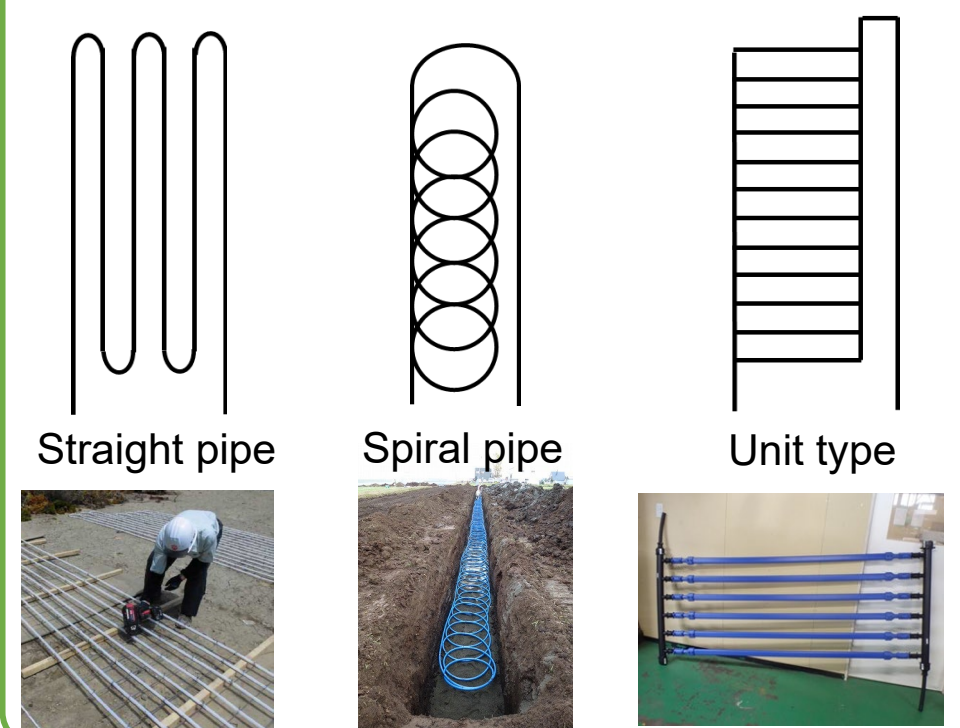
Borehole



Thermal pile



Horizontal



Design and simulation tool for GSHP systems with various GHEs has been required



Introduction -Background-

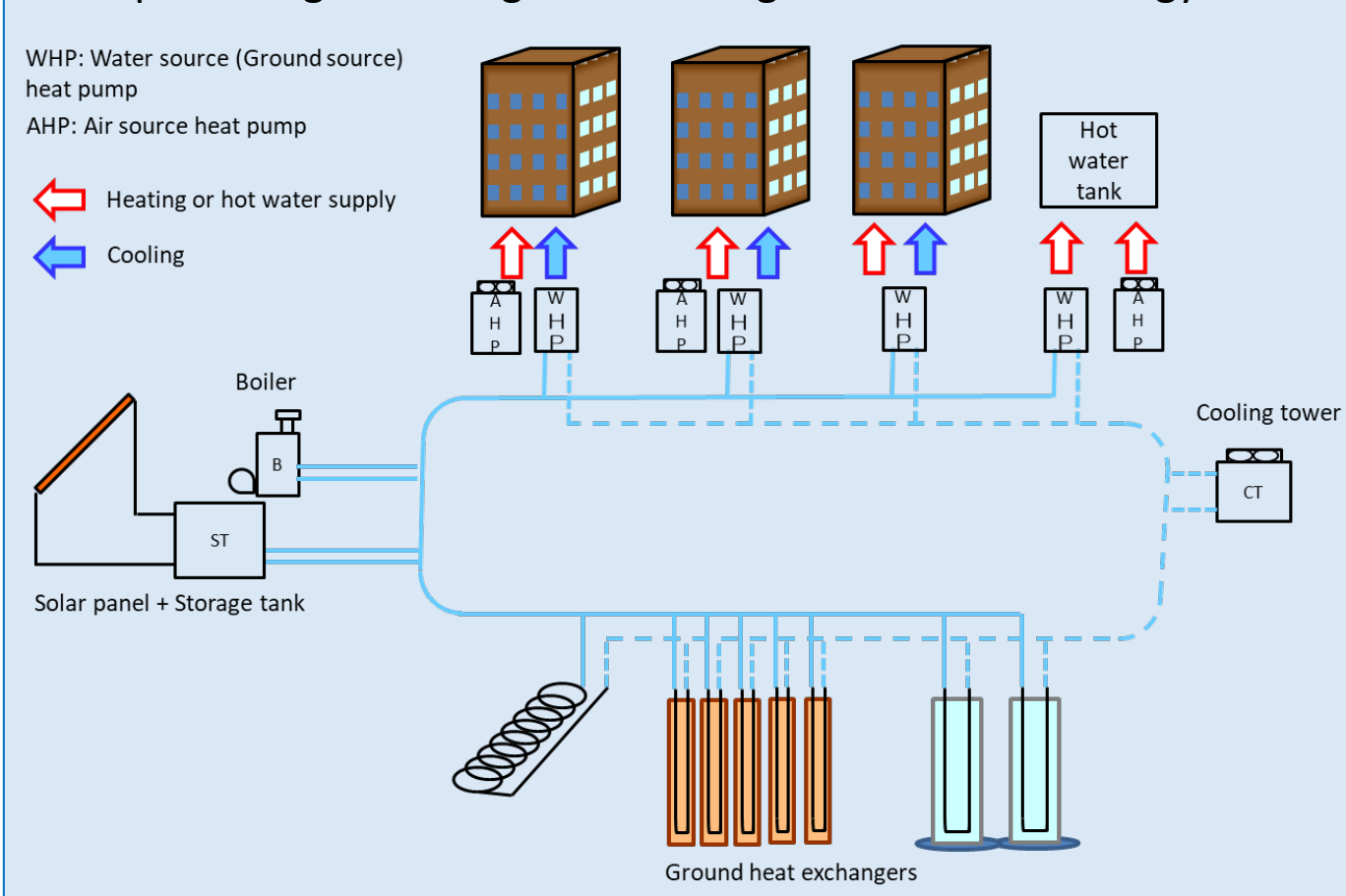


Additionally, there are a growing number of examples of regional use of ground thermal energy (shown in right figure), such as 5th generation district heating/cooling system.



Temperature calculation of the ground surrounding the GHE has become an even more important issue for design and simulation for GSHP systems

Conceptual diagram of regional use of ground thermal energy





Introduction

-Issue of ground temperature calculation -



The calculation method is mainly categorized into mainly three methods

Suitable for system simulation

1) Numerical calculation

Ex. FDM, FEM, FVM

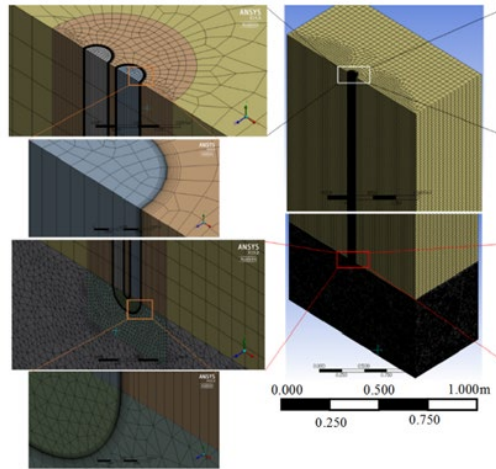
2) Energy balance model

Ex. CaRM, B2G model

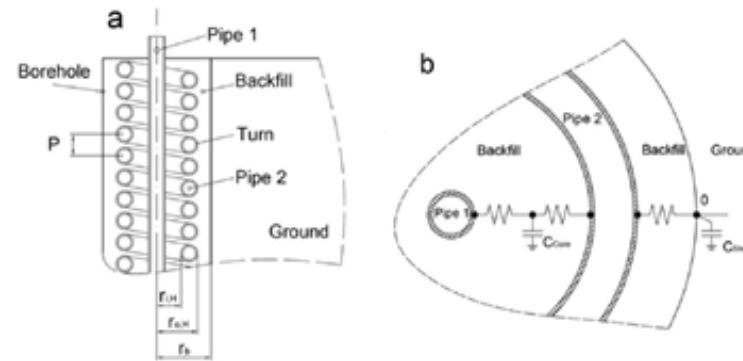
3) Superposition of theoretical model

Ex. ILS, FLS, ICS, MLS

Example

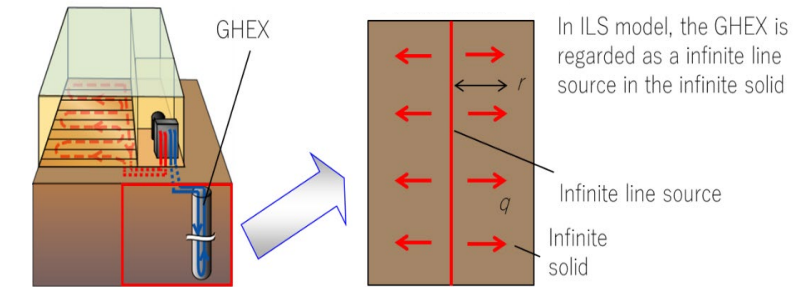


Ahmed A. Serageldin et al. (2018)



Zarrella et al. (2013)

ILS theoretical (Analytical) model



Advantage

- Adaptation to complex heat exchanger geometries and physical phenomena

- Smaller calculation time
- Adaptation to complex GHEs

- Smaller calculation time
- Adaptation to large number of GHEs

Disadvantage

- Large calculation time
- Difficulty in combining with the heat pump and the building thermal load

- Difficult to calculate ground temperature when using large number of GHEs

- Difficult to apply to complex geometries when including the heat carrier fluid in GHEs



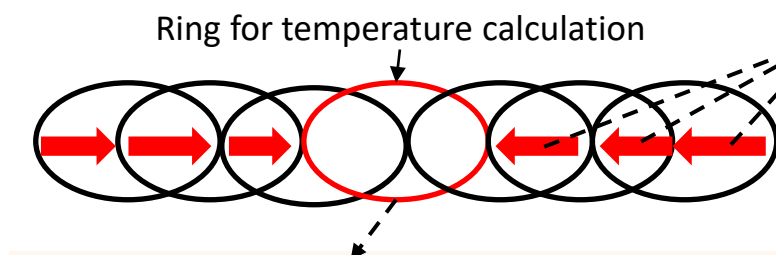
Introduction

-Issue of ground temperature calculation -



Although the theoretical model is said to have a small computation time, the computation time becomes large when multi-point (or average) temperatures over a continuous time period are calculated.

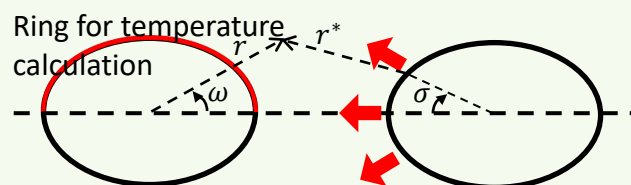
Ex. The ring source model for temperature calculation of the ground surrounding spiral horizontal GHE (Li, Nagano, et al. 2012)



Temperature response affected by the other rings

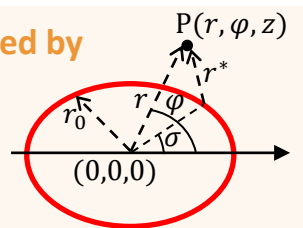
$$\Theta = \frac{1}{4\pi} \times \frac{1}{\pi} \int_0^\pi \int_0^{2\pi} \frac{1}{R^*} \operatorname{erfc} \left(\frac{R^*}{\sqrt{4F_0}} \right) d\sigma d\omega$$

Semi-circular regions are subject to calculation considering the symmetry of the ring



Temperature response affected by the ring

$$\Theta = \frac{1}{4\pi} \int_0^{2\pi} \frac{1}{R^*} \operatorname{erfc} \left(\frac{R^*}{\sqrt{4F_0}} \right) d\sigma$$



Here, $R^* = \sqrt{(R_0 \cos \sigma - R \cos \varphi)^2 + (R_0 \sin \sigma - R \sin \varphi)^2 + Z^2}$, $R_0 = \frac{r_0}{r_p}$, $R = \frac{r}{r_p}$, $\operatorname{erfc}(\mu) = \frac{2}{\sqrt{\pi}} \int_\mu^\infty \exp^{-\beta^2} d\beta$

- Θ : Nondimensional temperature response [-]
- r_0 : Ring radius [m]
- r : Distance from ring center to the point P [m]
- r^* : Distance from ring to the point P [m]
- R, R^* : Nondimensional distance [-]
- σ, φ, ω : Angle [rad]
- z : Depth [m]
- F_0 : Fourier number [-]
- r_p : Pipe radius [m]

Assuming 100 rings and calculating hourly temperature response for 10 years, it takes about **20 hours**.

➡ **Regression model is effective to reduce the calculation time**



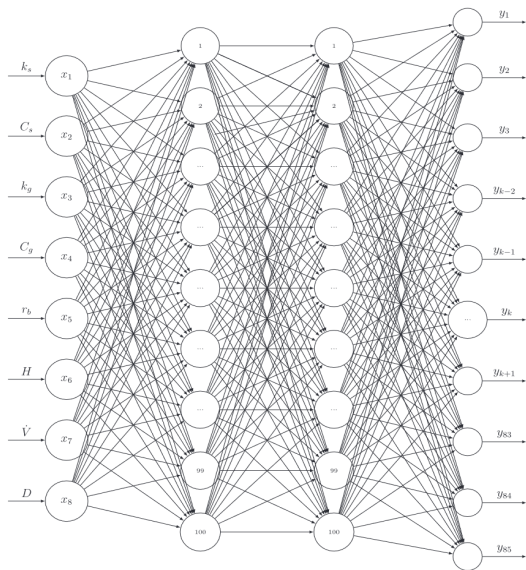
Regression model of temperature response function using ANN



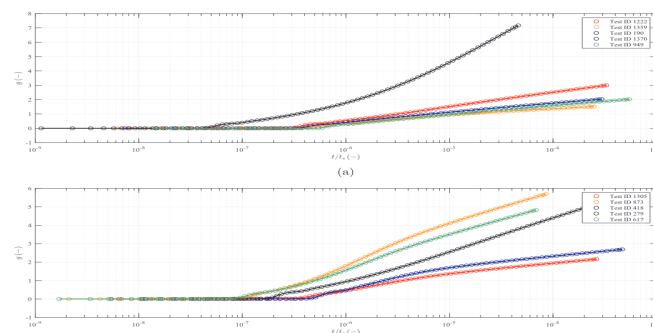
Previous research of regression model of temperature response function using ANN

Pasquier et al. (2018) Application of ANN to near-instant construction of short-term g-fuctions

Architecture of the ANN

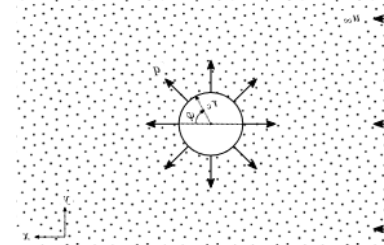


Response function

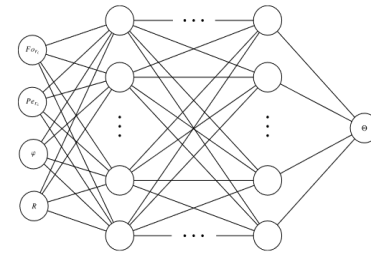


Shoji et al. (2022) ANN model for fast computation of G-function in MICS model

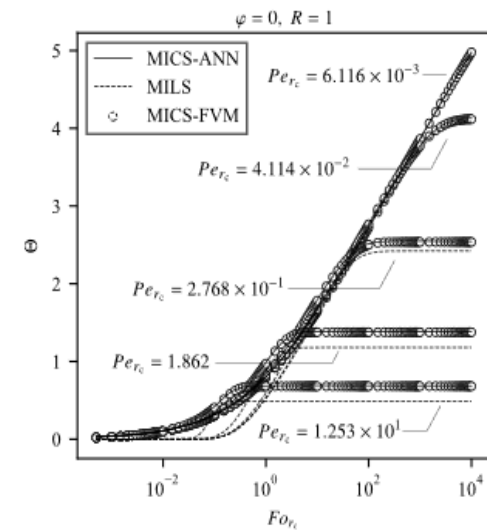
Conceptual diagram of the MICS model



Architecture of the ANN



Response function



Contents of this research

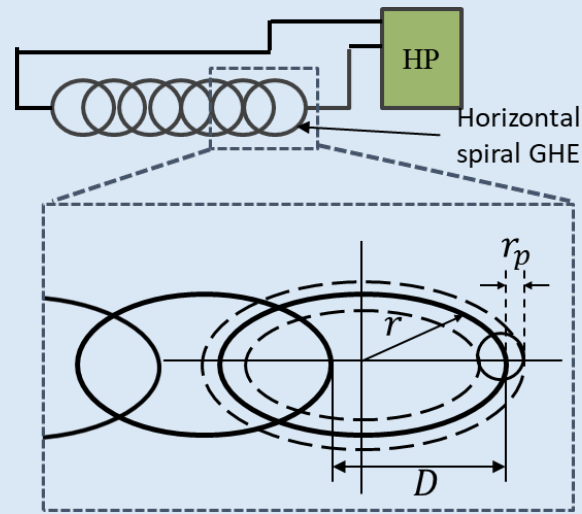
1. A regression model of temperature response function for the ring source model using ANN.
2. Simulation tool for GSHP systems using horizontal spiral GHEs applying temperature response function by ANN



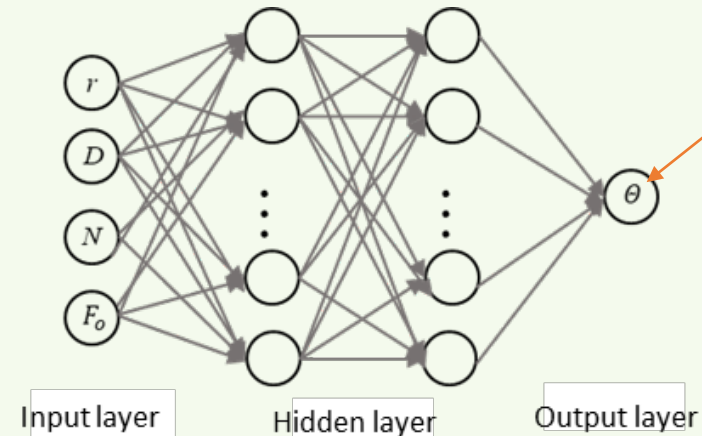
Regression model of temperature response function using ANN



1. Build horizontal spiral GHE model applying the ring source model



3. Construct regression model using ANN



The non-dimensional temperature response as training data was previously calculated by theoretical model (The ring source model)

2. Calculate temperature response function using the ring source model and make dataset

Input : Spiral ring radius : r , Spiral ring interval : D ,
Spiral ring number : N , Fourier number : F_o

Output : Non-dimensional temperature response : θ

$$\text{Here, } \theta = \frac{\theta k r_p}{q_r}, \quad F_o = \frac{\alpha t}{r_p^2}$$

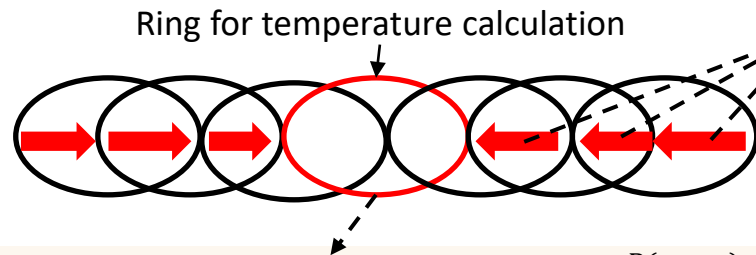
θ : Temperature response [$^{\circ}\text{C}$]
 k : Thermal conductivity [$\text{W} / (\text{m} \cdot \text{K})$]
 α : Thermal diffusivity [m^2 / s]
 r_p : Pipe radius [m]
 q : Heat injection per length [W / m]
 t : Time [s]



Regression model of temperature response function using ANN



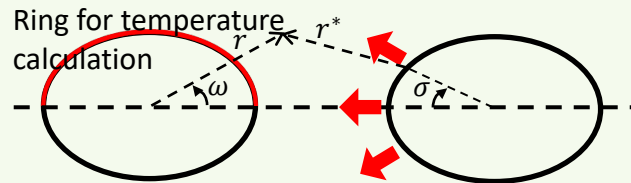
Nondimensional temperature response calculation applying the ring source model (Li, Nagano, et al. 2012)



Temperature response affected by the other rings

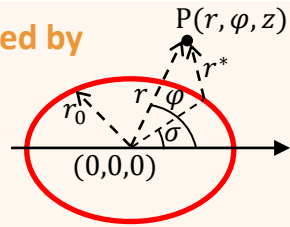
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The temperature response was calculated by changing the ring interval D , the ring radius r , the ring number N .

Total 27 pattern (=3 × 3 × 3)

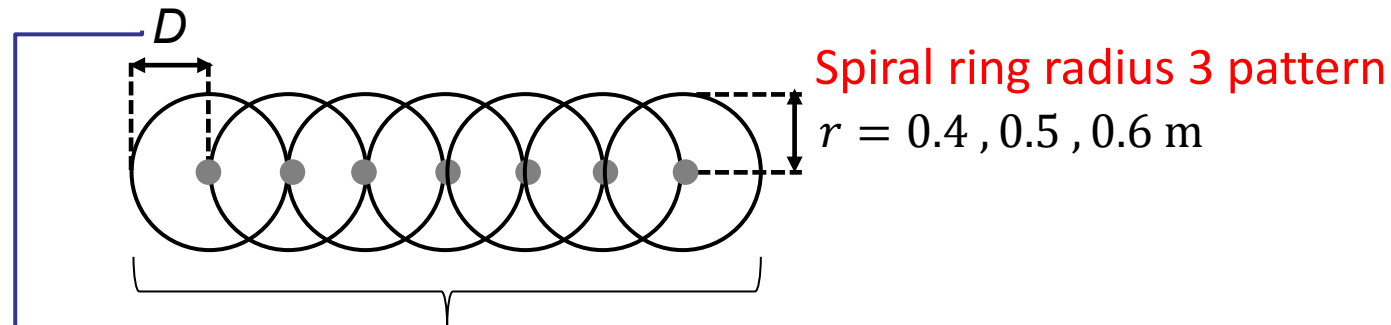
N	10			50			100		
r (m)	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6
D (m)	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6
	0.6	0.75	0.9	0.6	0.75	0.9	0.6	0.75	0.9
	0.8	1	1.2	0.8	1	1.2	0.8	1	1.2



Regression model of temperature response function using ANN



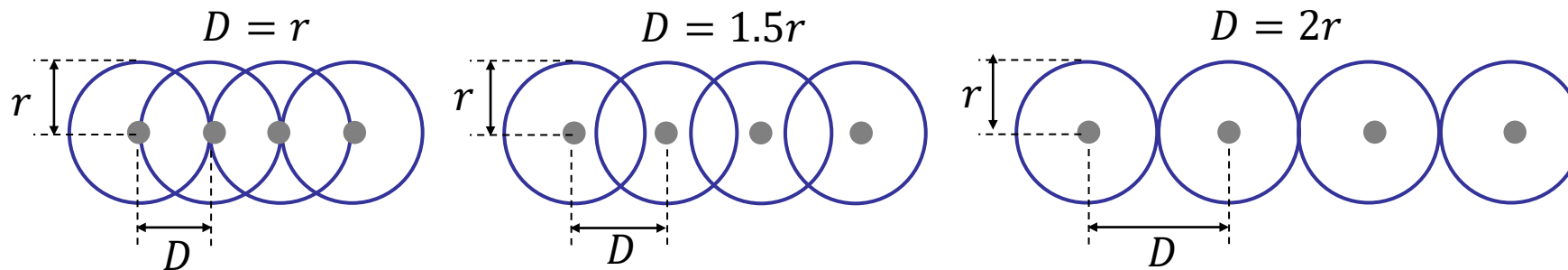
Outline of the ring radius r , the ring number N , the ring interval D .



The temperature response function is calculated for 10 years in 1-hour steps

Spiral ring number 3 pattern $N = 10, 50, 100$

Spiral ring interval 3 pattern

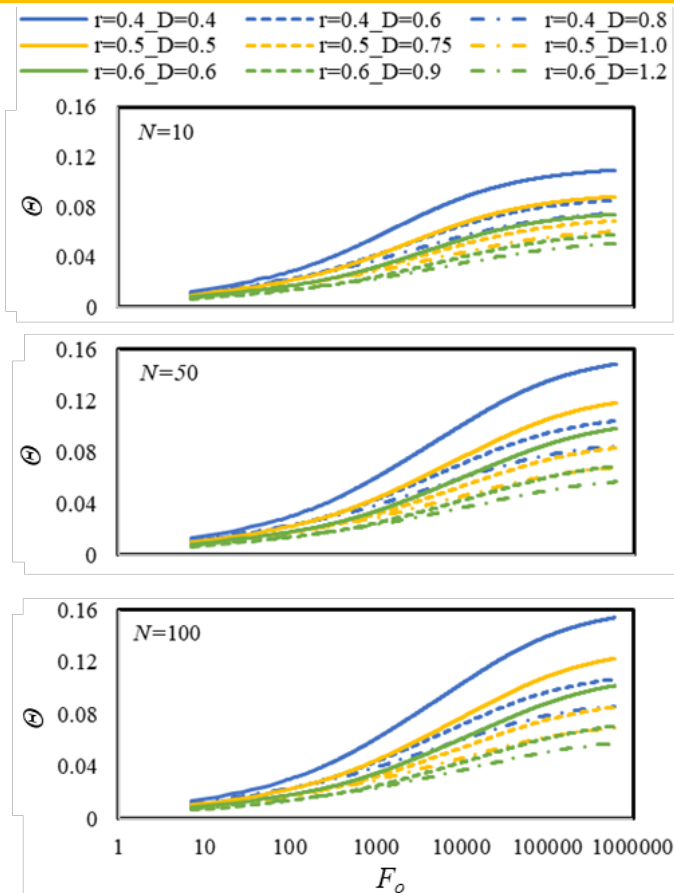




Regression model of temperature response function using ANN

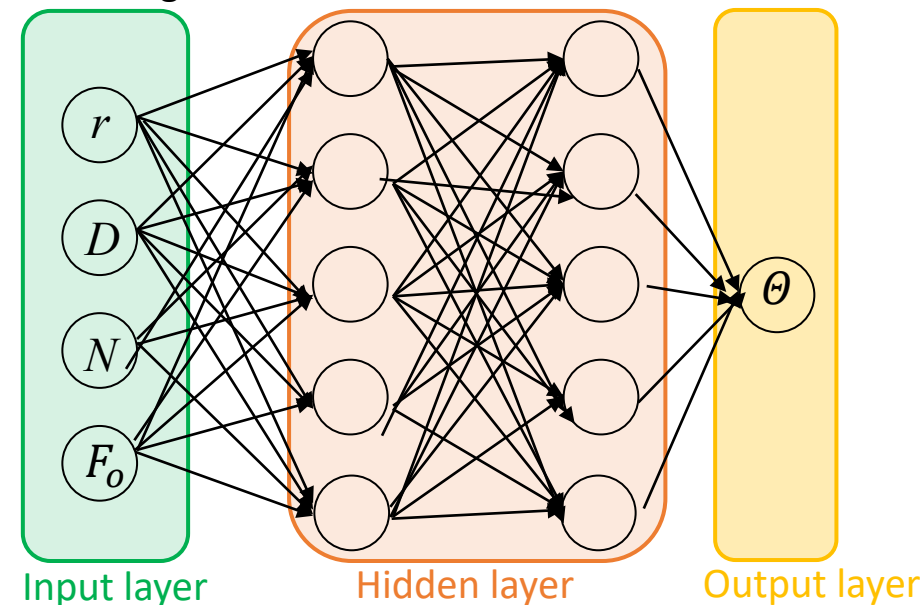


Temperature response obtained by the ring source model



Derivation of temperature response function by ANN

Using feed-forward neural networks



- Activation function : ReLU function
- Total data number : 11,826,000
- Regression model performance validation : Hold-out method
→ The dataset was divided as : Training : Validation : Test = 7 : 1.5 : 1.5
- Loss function : Mean squared error



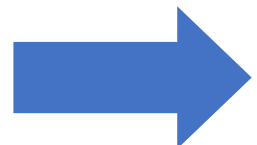
Regression model of temperature response function using ANN



Determination of hyperparameters by Bayesian optimization

Hyperparameters and their search ranges

Parameter	Search range
n_{Hidden}	3-8 (Integer)
n_{Unit}	100-500 (Integer)
LR	$1.0 \times 10^{-6} - 1.0 \times 10^{-4}$
$epoch$	50-120 (Integer)
$Weight_Decay$	$1.0 \times 10^{-12} - 1.0 \times 10^{-8}$

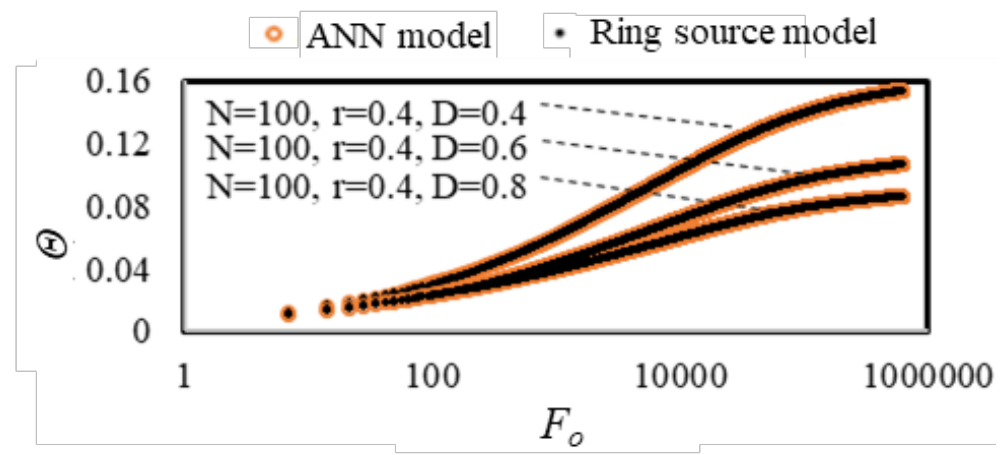


Maximum evaluation time: 72 h
Maximum evaluation number : 50 times

Hyperparameters obtained by Bayesian optimization

Parameter	Optimal value
n_{Hidden}	5
n_{Unit}	499
LR	5.74×10^{-5}
$epoch$	98
$Weight_Decay$	2.52×10^{-12}

Temperature response between the obtained ANN regression model and the ring source model ($N = 100$, $r = 0.4$)



Average mean squared error between two models: 3.71×10^{-9}
Time required for 10-year calculation : Approx. 2 sec



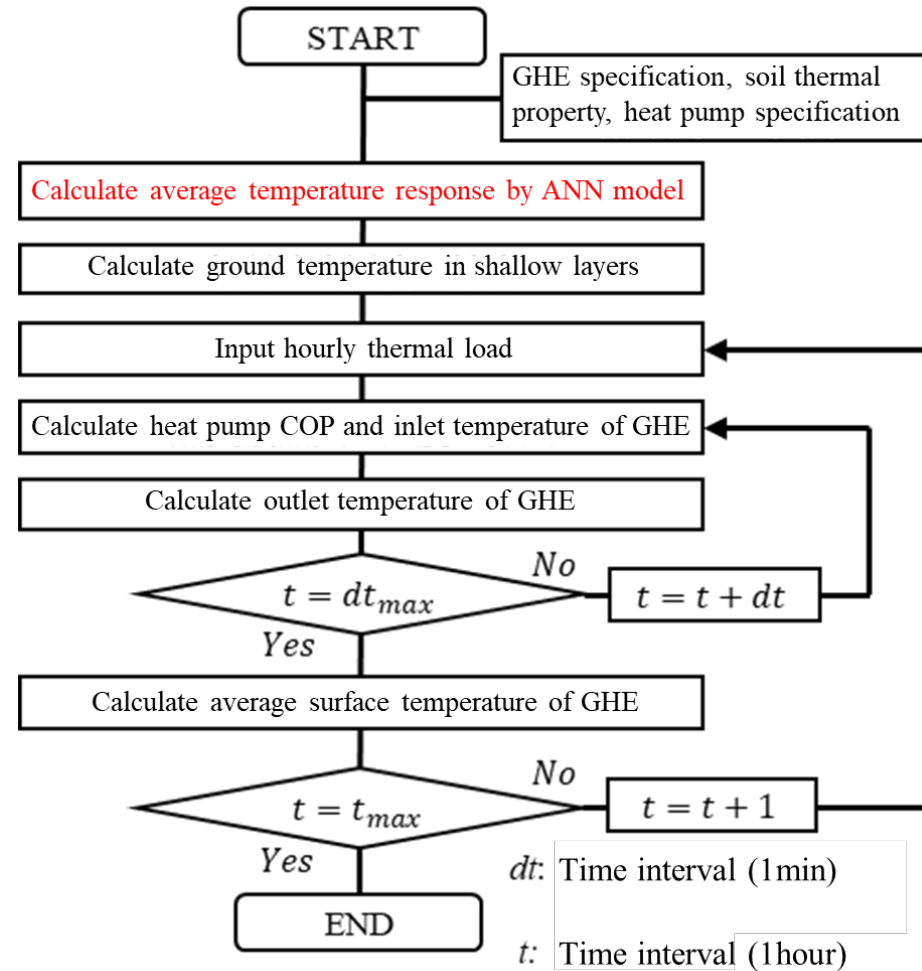
ANN regression model shows good regression performance and significantly reduces the calculation time



Simulation tool for GSHP system using horizontal spiral GHE applying temperature response



Calculation flowchart of simulation tool





Application –Case studies to determine the required GHE length-

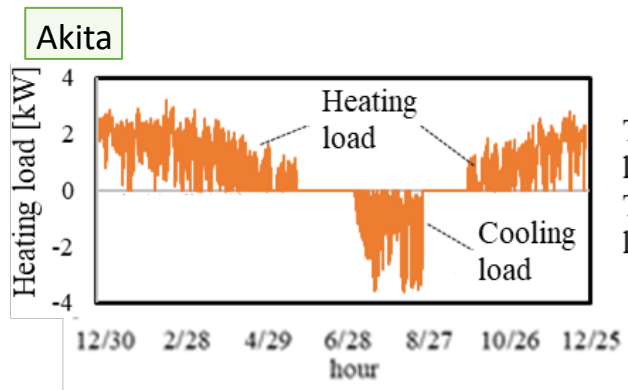
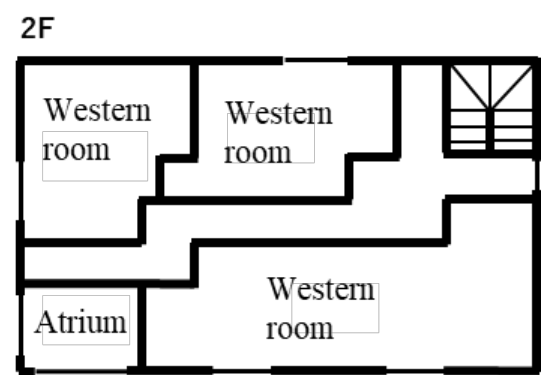
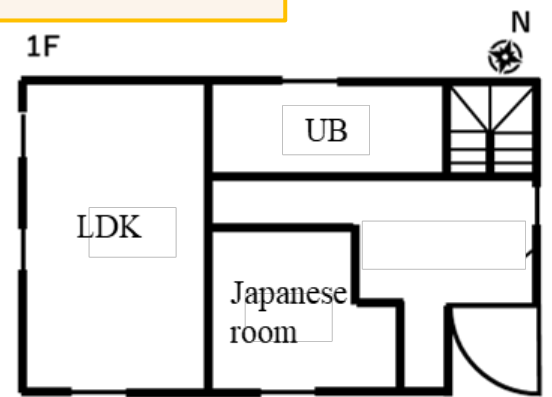


Using the developed simulation tool, it was assumed that the GSHP system with horizontal spiral GHEs was installed in a residential house in Akita and Tokyo and the required GHE length was estimated.

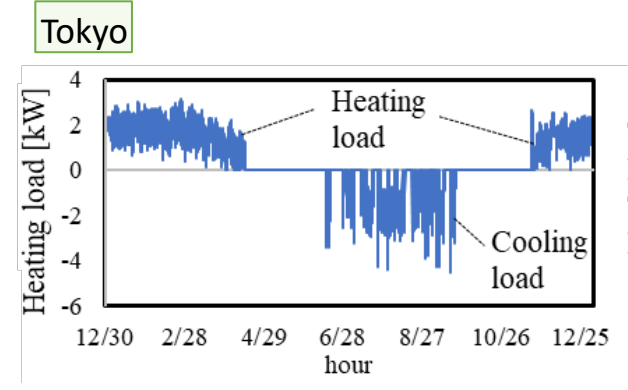
Conditions of residential house and hourly thermal load

Assumed residential house
Floor area: 116m²
Whole-house air-conditioning system with GSHP

Hourly heating and cooling load in annual
(Calculated by AE-CAD/Simheat, which is commercially available thermal load calculation software)



Total heating load: 7164 kWh
Total cooling load: 1003 kWh



Total heating load: 5810 kWh
Total cooling load: 1960 kWh

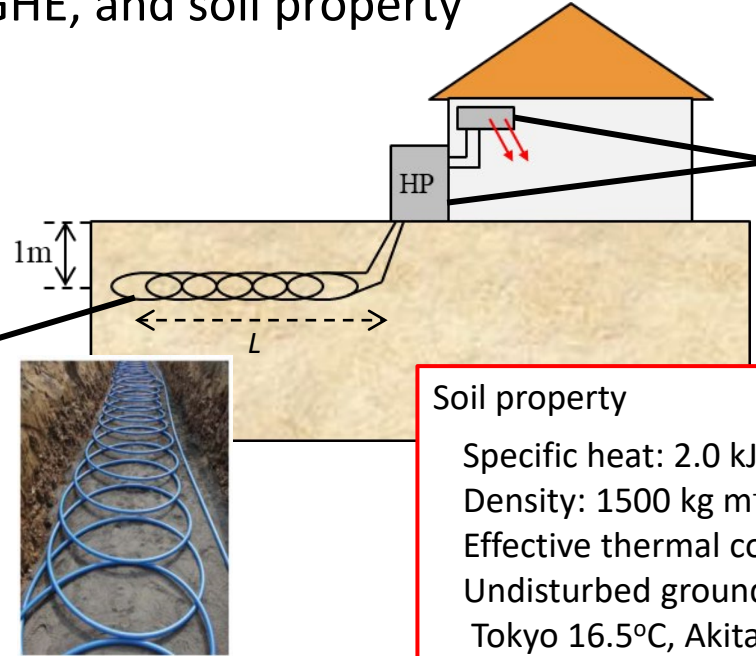


Application –Case studies to determine the required GHE length-



Conditions of GSHP system, GHE, and soil property

GHE condition
 Spiral ring radius : 0.5 m
 Spiral ring interval : 0.5 m
 Spiral pipe inside diameter: 0.025 m
 Spiral pipe outside diameter: 0.032 m



GSHP air-conditioner

Rated heating output: 6.0 kW
 Rated cooling output: 6.3 kW

Soil property

Specific heat: $2.0 \text{ kJ kg}^{-1}\text{K}^{-1}$
 Density: 1500 kg m^{-3}
 Effective thermal conductivity: $1.0 \text{ W m}^{-1}\text{K}^{-1}$
 Undisturbed ground temperature:
 Tokyo 16.5°C , Akita 13.0°C

Determination method of size L

The minimum GHE size (L in above figure), which is the minimum GHE size required to keep the GHE outlet temperature within the range of $-5\sim 35^\circ\text{C}$ throughout the year, was defined as the required GHE size for the GSHP system operation conditions.



Application –Case studies to determine the required GHE length-

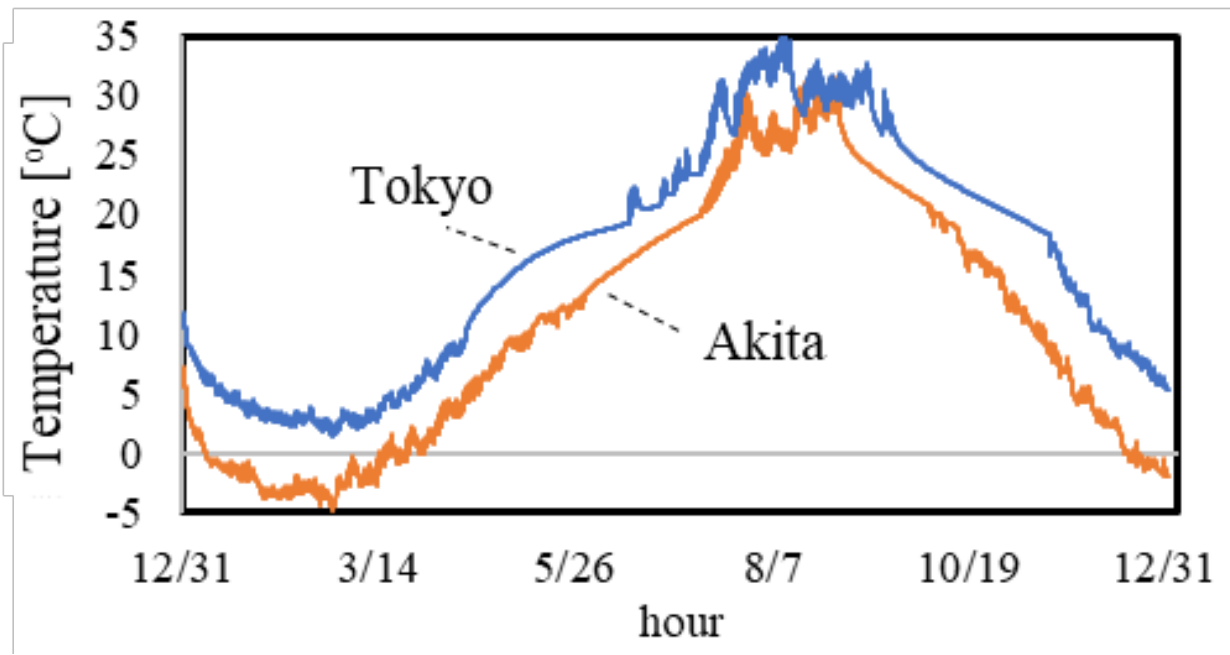


Result

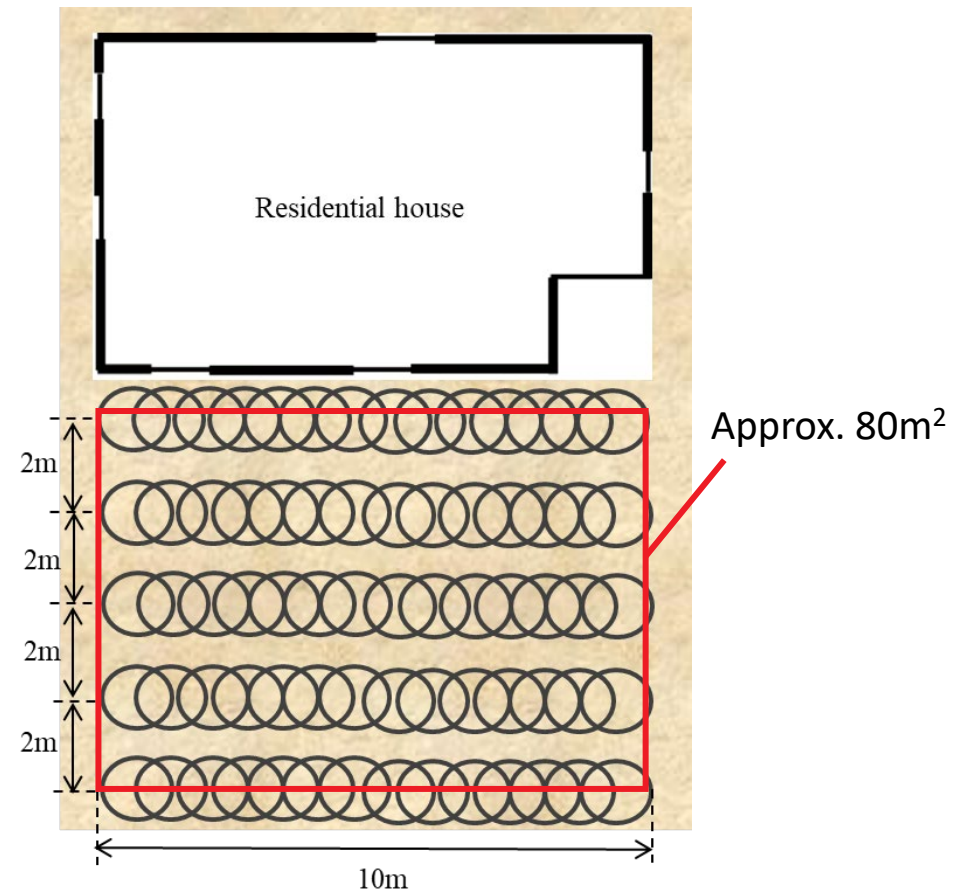
Determined size L

Akita:51m, Tokyo: 60 m

Temperature variation in fluid temperature at the outlet of GHE



Conceptual diagram of installing GHE in Akita



In this study, **an ANN regression model of the temperature response of the ground surrounding horizontal spiral GHE was developed** using dataset obtained by the ring source model. Then, **a simulation tool for the GSHP system using horizontal spiral GHEs was developed** by applying the temperature response. In addition, case studies were conducted in Akita and Tokyo to determine the required GHE length for the residential GSHP system, and the following findings were obtained.

- 1) A regression model of the temperature response function of ring source model was created by training ANN on the results of the theoretical calculation. As a result, a highly accurate regression model with an MSE of **1.46×10^{-9}** was created for the validation data set. Furthermore, the ANN model required only about **2 seconds of computation time over a 10-year period** with 100 number of rings, a significant reduction in the computation load.
- 2) The required GHE length for the residential GSHP system in Akita and Tokyo was examined. The required GHE length was **51 m in Akita** and the GHE length was **60 m in Tokyo**.



Thank you for your attention