Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Regional Evaluation and Statistical Modeling of Required Lengths for a Borehole Heat Exchanger Considering Varied Geology in Japan

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Keywords: Geologic database, Ground thermal conductivity, Heat pump system, Optimization, Gaussian process regression

ABSTRACT

Required lengths of borehole heat exchanger for a ground-source heat pump system is dependent on various factors regarding to building, heat pump, geology and other facilities. Especially in Japan, geology and climate conditions are variable among each site along the long North-South land. The purpose of this study is to evaluate the required sizes over the land considering the variable geology and climate conditions, and to construct a statistical model to determine the required size directly from selected parameters without numerical simulation.

For this purpose, this study constructed the geologic database, which provides ground thermal conductivity at any location and depth as probability-weighted averages. The probability of each soil/rock type was estimated by indicator kriging. The heating/cooling loads were calculated from climate data in an assumed residence of 120 m2 in total area. The ground-source heat pump system was assumed to be composed of 10kW heat pump and one borehole heat exchanger. The length of a borehole heat exchanger was optimized as the least for satisfying the criteria in terms of fluid temperature and COP. The heat pump simulation was performed in a 10km regular grid of Japan, resulting in its nation-scale map and a dataset for statistical modeling.

As a result, the required total lengths were found to vary between <50 m and >150 m, with differences among adjacent grids arising owing to the sharply varying climatic and geologic conditions. The lengths appeared normally distributed with an average of 98 m. This study compared simple estimation models employing liner regression and Gaussian process regression. The latter was much more effective in providing reasonable and practically useful estimates; however, its relative error of >20% was not negligible in several grid points.

1. INTRODUCTION

Ground-source heat pump (GSHP) systems can heat and cool buildings, supply hot water, and melt snow by extracting underground heat energy. They are highly efficient due to the stability of the ground temperature relative to the air, and can potentially contribute to a reduction in CO_2 emissions. In Japan, the number of GSHP has grown rapidly since 2000 (Lund and Boyd, 2015), yet other countries make wider use of this technology (Sakata *et al*., 2018). One practical problem for GSHP implementation is the high initial cost of installing borehole heat exchangers (BHEs). The BHE design is a widely used type of ground heat exchanger and consists of a high-density polyethylene U-tube in a vertical borehole. The borehole is usually several tens of meters long, often reaching depths of >100–200 m. The required borehole length depends on various factors including the building, heat pump, and geologic conditions. Among them, the geologic conditions (e.g., ground thermal conductivity) are the most uncertain in practice. In areas with relatively consistent geology, the ground thermal conductivity can be assumed from previous measurements at nearby sites. However, in other areas such as sedimentary basins (which are common in Japan), the geology varies over relatively short distances depending on the depositional processes. The ground thermal conductivity therefore cannot necessarily be assumed from measurements at nearby sites.

This study aims to evaluate the required lengths of a single BHE for a household GSHP system anywhere in Japan. For this purpose, an indirect method is proposed to estimate ground thermal conductivity at any location and depth by using deep-water well data. The probabilities of each of eight soil/rock types occurring at a given location are estimated by indicator kriging, and then translated into ground thermal conductivities. Next, heating/cooling loads are calculated assuming a standard residence for analysis. Then, GSHP system simulation is performed on a 10 km regular grid over the whole of Japan for various BHE lengths, and the optimal length of BHE is determined as the required length at each grid point. Finally, a simple estimation model is derived by comparing two regression methods.

2. MATERIALS AND METHODS

2.1 Ground Thermal Conductivity

Estimation of the ground thermal conductivity is essential in evaluating the performance of a GSHP system. As in situ measurements are often not obtained in practice, the conductivity can be estimated simply by a thickness-weighted average of the individual conductivities of all the ground components. However, this relies on the unrealistic assumption of complete information of the geology, and it is actually only possible to estimate the probability of each soil or rock type, with the accuracy dependent on the quality and quantity of borehole data from near the site. This study considers the practical problem and estimates ground thermal conductivity as a probability-weighted average as follows (Deutsch, 1998):

$$\bar{\lambda} = \frac{1}{L}\sum_{i=1}^{N} L_i^* \lambda_i = \frac{1}{L}\sum_{i=1}^{N}\sum_{z=1}^{L} p(z;i)\lambda_i \quad (1)$$

where λ_i is the individual conductivity of each soil/rock type ($i = 1, 2, \ldots, N$), L is the length of BHE, and $p(z; i)$ is the probability of soil/rock type i at depth z. The probability of each soil/rock type is estimated by indicator kriging (Nagano *et al*., 2006):

$$p(z;i) = \sum_{a=1}^{n} \omega_\alpha (I(\alpha;i) - p_0(i)) + p_0(i) \quad (2)$$

where ω_α is the kriging weight at borehole data α ($i = 1, 2, \ldots, n$) and I is an indicator of soil/rock type i at α; $I = 1$ if the soil/rock type is the same at depth z in the borehole data, and is 0 if different. The weight ω_α is calculated at each location by a liner matrix system of covariance or variogram functions. The functions of each soil/rock type are determined as exponential or spherical models from the indicator data.

This study defines eight soil/rock types as representative components of the shallow geology of Japan: unconsolidated clay, sand, gravel, volcanic ash, Quaternary volcanic rock, Neogene soft fine rock, soft coarse rock, and hard basement. Data from 46,515 boreholes are analyzed: 15,049 from core-sampling boreholes and 31,466 from deep water wells (Fig. 1). Core-sampling data are more accurate, but are limited in deep zones; therefore, water well data are used to overcome this limitation. This study determines the individual conductivity of each soil/rock type by minimizing the least squares errors to make estimates using Eq. (1) agree with 79 measurements of thermal response data taken around Japan. Good agreements are achieved with root mean square errors (RMSEs) of ~0.3 W/(m·K). Fig. 1b shows the estimated ground thermal conductivity over Japan at a depth of 50 m on a regular 10 km grid. The conductivity exceeds 2.5 W/(m·K) in areas of mountains and hills, which make up most of Japan. On the other hand, in the flat plains containing many cities, including Tokyo, Osaka, and Nagoya, the conductivity is relatively low (<2.0 W/(m·K)) due to the presence of thick unconsolidated sediments.

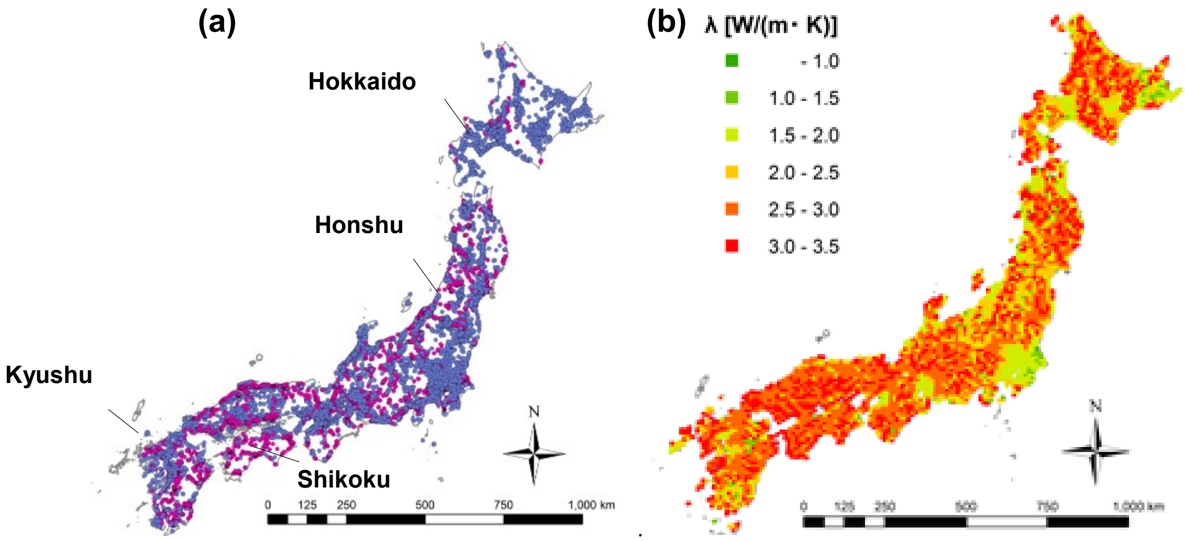

Figure 1: (a) Borehole data for analysis: Large, core sampling data; small, water well data. (b) Estimates on a 10 km-grid of ground thermal conductivity between the surface and a depth of 50 m.

2.2 Heating/Cooling Loads for a Target Residence

This analysis assumes a standard Japanese residence with two floors and a total floor area of 120 m^2. The first floor includes a living room, a traditional room, and a kitchen; the second floor has one master bedroom and two smaller rooms. This study neglects non-living areas including a bathroom, toilets, storages and corridors. The legally required insulation property, heat transfer coefficient U (W/(m^2·K)) of buildings varies across the islands of Japan, being 0.46 in Hokkaido Island, 0.56 in the north and mountainous parts of Honshu Island, 0.46 in the hilly parts of Honshu Island (Fig. 1a), and 0.87 in other parts of Honshu, Shikoku, and Kyushu Islands. Heating loads Q_h (J) and cooling loads Q_c are calculated hourly using the temperature difference between the room and outside, solar radiation, and internal heat sources:

$$Q_h = UA(T_r - T_a)\alpha - S,\ for\ T_a < T_{h'} \quad (3)$$

$$Q_c = \{U(T_a - T_r) + \eta R\} A\alpha + S,\ for\ T_a > T_c, \tag{4}$$

where T_r is the room temperature (20 °C in heating and 27 °C in cooling), T_a is the outdoor air temperature (°C), η is the infiltrative fraction of solar radiation in cooling. R is the solar radiation (J/m^2), A is the external area of the building (m^2), α is the ratio of the living area over the total area, and S is the contribution of internal heat sources (J/h), T_h and T_c are the threshold outdoor air temperatures (15 °C in heating and 27 °C in cooling), for the GSHP system operation, respectively. Fig. 2 shows Annually total heating/cooling loads for an assumed residence on a regular 10 km grid. The heating loads are ranged between 10 to 82 GJ/y, increasing toward the north direction, but the largest load is seen at the mountains in the center of Honshu Island. On the other hand, the cooling loads are ranged between 0 and 15 GJ/y, and is smaller than the heating loads in most grids or almost equal to in the south part of Kyushu.

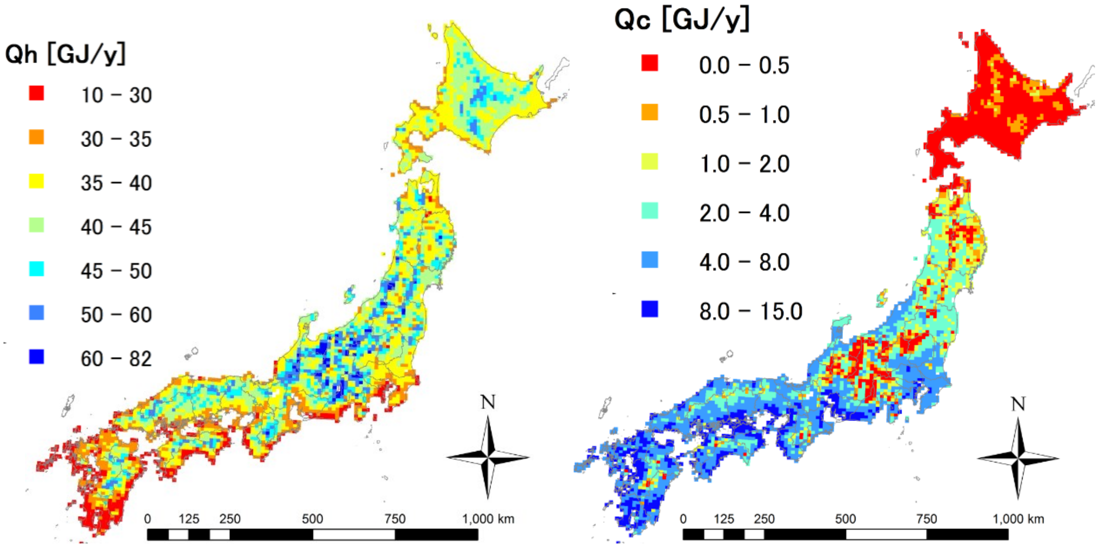

Figure 2: Annually total heating/cooling loads for an assumed residence on a regular 10 km grid.

2.3 GSHP SYSTEM SIMULATION

A GSHP system simulation is performed by using an algorithm based on cylindrical heat source theory (Rasmussen, 2006). The algorithm assumes the BHE as an infinite cylindrical model of homogeneous but variable heating/cooling rates on the surface. The changes of non-dimensional soil temperatures T_s* of the ground around the BHE are calculated as a superposition of their hourly temperature response:

$$\Delta T_s^*(t^*) = \sum_{\tau^*=0}^{t^*} q^*(t^* - \tau^*) \frac{\partial T_s^*(\tau^*)}{\partial \tau^*} \tag{5}$$

where ΔT_s* is the non-dimensional change of soil temperature (= $2\pi\lambda\Delta T_s/q'$, λ is effective thermal conductivity of the ground, q' is heat flow per unit depth of the borehole), t* is the Fourier number (= at/r^2, a is the thermal diffusivity of the ground, r is radius and is non dimension(=1)), and q* is the heat flow per unit area of the cylinder. τ* is the integral number. The soil temperature is calculated hourly, and is modified considering the boundary effects at the ground surface and the bottom of the BHE. Next, the temperature of the heat-transfer fluid in the U-tube is calculated based on the heat balance in relation to the borehole thermal resistance. The algorithm estimates the borehole thermal resistance using the boundary element method. The electric energy consumption of the heat pump is calculated from the calculated inlet temperatures.

This study assumes the heat pump of the household system to be a commercial product with a maximum power of 10 kW. Its coefficient of performance (COP) is calculated as a linear function of the inlet fluid temperature with a slope of 0.15 (1/K). The BHE is assumed to have a common configuration comprising a single, 120 mm diameter, 25 A U-tube buried with a grout filling of silica sand. The ground thermal conductivity and volumetric heat capacity are estimated as probability-weighted averages by Eq. (1) as described above. The initial ground temperature is assumed to be 1.5 K above the average outside temperature, and increases vertically with a gradient of 0.03 K/m.

This study performs GSHP simulations at each grid point across Japan for different borehole lengths between 30 and 195 m at 15 m intervals. The required length L* is determined through interpolation under two necessary conditions. The first condition is that the calculated fluid temperatures (T_b) are not lower than the freezing point (T_f). Note that T_f is set as −15 °C for Hokkaido Island and northern Honshu Island, and 0 °C elsewhere. The other condition is that the moving average of the soil temperature $(\overline{T}_f)$ around the borehole is above that of the outside air temperature $(\overline{T}_a)$:

$$\overline{T}_{\mathrm{b(h)}} - \overline{T}_{\mathrm{a(h)}} \geq \Delta\overline{T}_0 \tag{6}$$

$$\overline{T}_{\mathrm{a(c)}} - \overline{T}_{\mathrm{b(c)}} \geq \Delta\overline{T}_0 \tag{7}$$

where $\overline{T}_{\mathrm{b(h)}}$, $\overline{T}_{\mathrm{b(c)}}$ are averaged temperatures of the inlet fluids into GSHP during heating and cooling periods, respectively. $\overline{T}_{\mathrm{a(h)}}$, $\overline{T}_{\mathrm{a(c)}}$ are the averaged outdoor temperatures during heating and cooling periods, respectively. $\Delta\overline{T_0}$ is the minimum difference (0 K in this study) needed for a GSHP system to have an advantage over an air-source heat pump system in terms of high efficiency. The span for moving averages was 24 hours in this study.

3. RESULTS AND DISCUSSION

The required lengths L^* for a BHE simulated at each grid point across Japan are mapped in Fig. 3, which shows values ranging between <50 and >150 m. The length depends on the heating/cooling loads and the geology at each point. The values do not necessarily vary smoothly across adjacent 10 km grid points owing to the steep topography, which causes heating/cooling loads and geological properties (effective thermal conductivities and ground temperatures) to change suddenly. This demonstrates the importance of determining the required length at each location individually according to the climatic and geologic conditions.

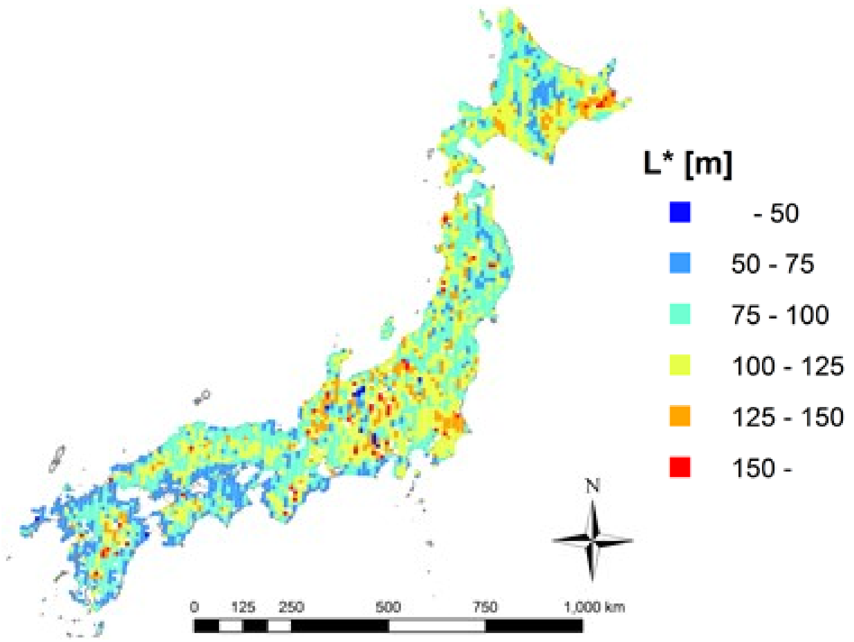

Figure 3: Required lengths of a single BHE for a household GSHP system on a regular 10 km grid.

The distribution of all 3799 calculated L^* lengths is plotted in Fig. 4. The histogram closely follows a normal distribution with an average of 98 m and standard deviation of 22 m. The emergence of a normal pattern, despite the variability, indicates the possibility of constructing a simple model to determine directly the required length of a single BHE, without GSHP simulations.

Thus, this study has developed a simple estimation model for a single BHE in a household GSHP system. Two regression models are compared here. The first is a simple liner regression (SLR) model of multiple variables:

$$\widetilde{L}^* = C_0 + \boldsymbol{C}^T \boldsymbol{X} + \boldsymbol{\varepsilon} \tag{7}$$

where $\boldsymbol{L}^*$ is the vector of L^* at all grid points, C_0 is the constant, $\boldsymbol{C}$ is the matrix of proportionality, $\boldsymbol{X}$ is the matrix of selected parameters (longitude, latitude, ground elevation, average temperature, max and min temperatures, heating/cooling times, ground thermal conductivity, volumetric heat capacity, and insulation levels: U, η) at all grid points, and $\boldsymbol{\varepsilon}$ is the error vector. The second model uses Gaussian process regression (GPR)(Rasmussen and Williams 2006):

$$\widetilde{L}^* = \boldsymbol{\beta}^T \varphi(\boldsymbol{X}) + \boldsymbol{\varepsilon} \tag{8}$$

where $\boldsymbol{\beta}$ is the matrix of coefficients and φ is the kernel function as a function of distances in $\boldsymbol{X}$ from an estimation point to adjacent calculation points. This study applies an exponential model as the kernel function. The model parameters **C** and $\boldsymbol{\beta}$ are determined using least squares by cross-validation of the 3836 calculation results of L^*.

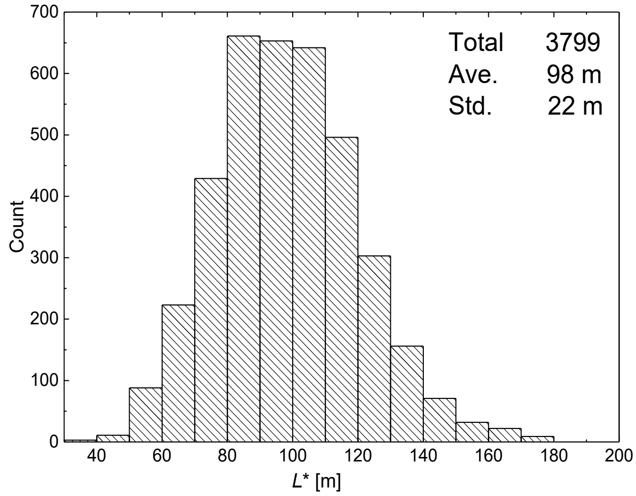

Figure 4: Histogram of required lengths *L of a single BHE.**

Fig. 5 compares the simulated L^* results with those estimated using the simple SLR and GPR models. The SLR results do not agree well with the simulation results; the estimates are distributed in a small range between 80 and 120 m, with a RMSE of 20.86 m, which is close to the standard deviation (22 m in Fig. 4). This means that the SLR model is not very different from the random, normal-distribution model, and is thus not appropriate in estimating the required lengths.

On the other hand, the GPR results agree sufficiently with the simulation results. Most of the required length estimates lie between the lines of $\widetilde{L}^* = 0.8\ L^*$ and $1.2\ L^*$ in Fig. 5; thus, the relative error is <20%, which is acceptable in practice, especially at an initial stage of GSHP system design. The GPR model is therefore an effective way to estimate simply the L^* of a single BHE in a household GSHP system. However, its RMSE of 15.4 m is not a great improvement over the SLR model due to several points of relatively large errors. This indicates the limited applicability of the GPR model in several areas with such large errors; e.g., mountainous areas where geologic conditions are spatially variable.

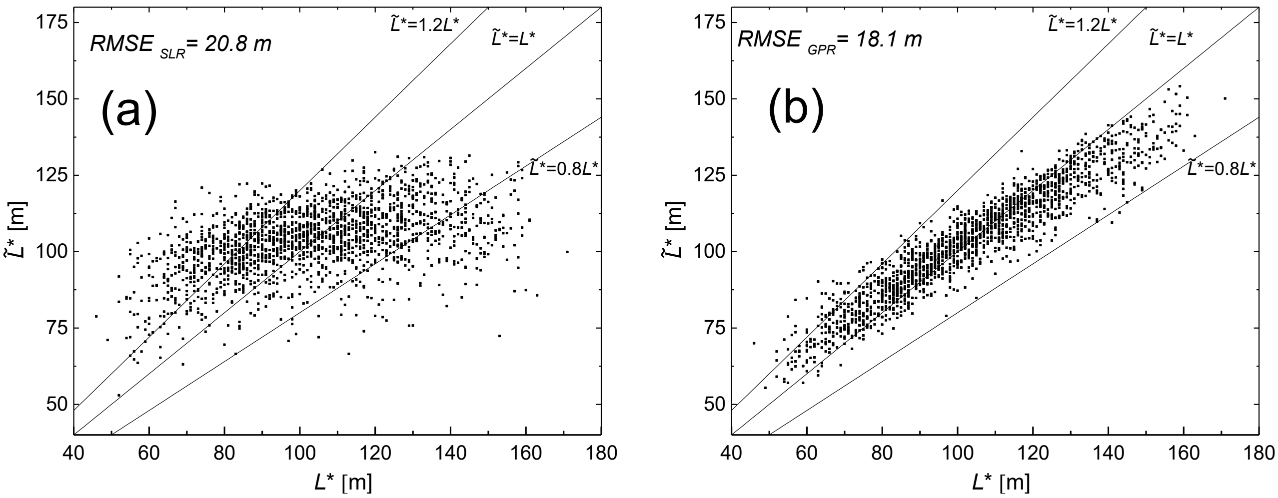

Figure 5: Comparison of required length estimates by the SLR (a) and GPR (b) models.

4. CONCLUSIONS

This study evaluates the required lengths of a single BHE for a household GSHP system at locations across Japan. To address data limitations and uncertainty, the probability of each of eight soil/rock types is estimated at each grid point by indicator kriging; these are then used to calculate ground thermal conductivity via probability-weighted averages. The GSHP simulation then estimates the required lengths at each grid point, finding that the lengths could vary greatly among adjacent grid points depending on the climatic and geologic conditions. A simple liner regression model and a Gaussian progress regression model are compared, with the latter providing more reasonable estimates of the required lengths, although large errors appeared at several grid points. In the near future, other simulations will be performed for office buildings using various other heat pump products, and other necessary conditions such as life cycle costs and CO_2 emission reductions will be considered. A simple estimation model of various building conditions for any target situation will be derived and validated for use in Japan and other countries.

REFERENCES

Nagano, K.: The progress of GSHP in Japan. *IEA Heat Pump Center Newsletter*, vol. **33**, (2015), 21-25.

Lund, J.W. and Boyd, T.L.: Direct Utilization of Geothermal Energy 2015 Worldwide Review, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia (2015)

Sakata Y., Katsura, T. and Nagano, K.: A Study on Estimation of Ground Effective Thermal Conductivity as Probability-Weighted Average. *Journal of Geothermal Research Society in Japan*, vol. **40**, no. 1, (2018),33-44

Deutsch. C.V.: Geostatistical Reservoir Modeling, 376p, *Oxford University Press*, (1998)

Nagano, K., Katsura, T. and Takeda, S.: Development of a design and performance prediction tool for the design and performance for the ground source heat pump system, *Applied Thermal Engineering*, vol. **26**, no. 14–15, (2006),1578-1592

Rasmussen, C. E., Williams, C. K. I: Gaussian Processes for Machine Learning. *MIT Press*, Cambridge, Massachusetts (2006)