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Field Test-Based Comparative Analysis of Heat Exchange Performance in Vertical and Horizontal Ground Heat Exchangers for Geothermal Applications

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ABSTRACT

In Saga Prefecture, Japan, geothermal air conditioning systems have been implemented in public facilities as part of the efforts to achieve carbon neutrality. At Saga International Airport, both vertical and horizontal boreholes have been drilled to utilize geothermal energy for the heating and cooling of the terminal building. This study investigates the heat exchange performance of vertical and horizontal ground heat exchangers (GHEs) through thermal response tests (TRT). In the field experiments, one vertical borehole and two horizontal boreholes were investigated. A double U-tube was installed in the vertical borehole, which extends to a depth of 100 meters, while a single U-tube and a double U-tube were installed in two horizontal boreholes, each extending 100 meters horizontally at a depth of approximately 6 meters. The horizontal boreholes were constructed using the horizontal directional drilling (HDD) method. Water was heated at 4 kW and circulated at a constant flow rate for two days. The ground temperature during circulation, as well as during recovery over the subsequent two days, was measured using fiber-optic thermometers. Heat transfer in the ground was modeled as conduction only, with subsurface temperature estimated using a cylindrical heat source function, and the thermal conductivity along GHEs was determined through a non-linear regression method. The outlet temperatures and ground temperature were calculated and compared with measured data. The matching results for both vertical and horizontal systems showed good agreement between the model and the measurements. The results indicated that the heat exchange ability was highest in the vertical double U-tube GHE, followed by the horizontal double U-tube and the horizontal single U-tube GHEs. Furthermore, the estimated thermal conductivity in the vertical borehole increased with depth, and the thermal conductivity at a depth of 6 meters in the vertical borehole was similar to that of the horizontal borehole which were drilled at 6 meters.

1. INTRODUCTION

The horizontal directional drilling (HDD) method has gained significant attention as a promising installation technique for horizontal ground heat exchangers (GHEs) (Figure 1). This is primarily due to its relatively lower installation costs compared to traditional drilling methods for boreholes, which often involve costly excavation and cause disruption of the surrounding environment. Additionally, the HDD method offers the advantage of being able to install GHEs at arbitrary locations, making it particularly suitable for areas with limited access or where minimal surface disruption is desired. The ability to install GHEs horizontally underground without the need for large excavation sites or surface-level drilling is an appealing feature for various applications, including urban environments and constrained areas.

Figure 1: HDD equipment used for the horizontal GHE in Saga City

In this study, thermal response tests (TRTs) were conducted to assess the heat exchange performance of three distinct types of GHEs installed at Saga International Airport in Kyushu, Japan. The first type is a vertical GHE featuring a double U-tube configuration, which is widely used in many geothermal applications due to its high heat exchange efficiency. The second and third types are horizontal GHEs, both installed using the HDD method. One of these horizontal GHEs uses a single U-tube configuration, while the other employs a double U-tube configuration. The performance of each GHE type was compared based on thermal response testing to understand their efficiency in heat exchange and to evaluate the influence of configurations on their overall performance. By examining the heat transfer characteristics of these different GHE designs, this research aims to provide valuable insights for optimizing the use of HDD in GHE installations and to contribute to the development of more efficient and cost-effective geothermal heating and cooling systems.

2. METHODS FOR CALCULATING THERMAL CONDUCTIVITY

2-1. Graphical Method

The graphical method is an analytical approach commonly used to estimate the effective thermal conductivity (λ) of the subsurface during geothermal heat exchange tests. This method applies Kelvin's line source theory to the average inlet and outlet temperatures of the ground heat exchanger (GHE) during the hot water circulation test. The effective thermal conductivity is estimated by determining the slope of the temperature-time curve. Owing to its simplicity and the ease of implementation, this method is widely adopted, as it can be easily implemented using the linear regression function in Microsoft Excel.

Kelvin's line source theory provides a theoretical framework for determining the temperature distribution in an infinite medium subjected to a constant heat flux from an infinitely long line heat source. When applied to geothermal response tests, the infinite medium represents the ground, and the line heat source models the GHE. This model assumes that the circulating fluid within the GHE embedded in the ground maintains a constant heat flux.

The simplified version of the GHE model can be expressed as follows:

$$T(r,t) = \frac{q}{4\pi\lambda}\ln(t) + \frac{q}{4\pi\lambda}\left(\ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right) + qR_b + T_0 \quad (1)$$

where T is temperature [°C], t is elapsed time [s], r is borehole radius [m], q is heat exchange rate per unit length of ground heat exchanger [W/m], λ is apparent thermal conductivity [W/m/K], α is thermal diffusivity [m²/s], γ is Euler's constant, R_b is thermal resistance of the ground heat exchanger, and T_0 is initial ground temperature [°C]. The equation can be rearranged based on temperature rise in the borehole versus time in logarithmic scale, as follows:

$$T(t) = m\,ln(t) + b \quad (2)$$

By comparing the above equation with the original equation, m and b parameters were defined as:

$$m = \frac{q}{4\pi\lambda} \quad (3)$$

$$b = m\left(\ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right) + qR_b + T_0 \quad (4)$$

The thermal conductivity (λ) can be estimated directly by using *m* parameter which represent the slope of flat section of the temperature plot in the logarithmic scale.

2-2. Analytical Modeling

The U-tube heat behavior analysis program (Fujii,2006) using non-regression analysis was employed to estimate the thermal conductivity profile. To accurately reproduce the thermal behavior of a U-tube Ground Heat Exchanger (GHE), precise calculations of heat conduction in the ground and heat transfer within the heat exchanger are necessary. The ground is divided into multiple layers along the depth direction, and the heat exchange between the GHE and the ground, as well as the heat propagation within each layer, is calculated. Finally, the thermal conductivity of each layer is evaluated. Additionally, the U-tube heat exchanger is modeled as a single pipe, assuming that the U-tubes are bundled and installed together. In this approach, heat conduction within the ground is modeled using the cylindrical heat source function G, and the heat exchange with the heat exchanger is calculated sequentially. To account for the heterogeneity of the ground, different thermal conductivities are considered for each layer, and these values are incorporated into the analytical model. The temporal variation of heat exchange in the geothermal heat exchanger is determined by applying the principle of superposition. The cylindrical heat source function G is defined as: the following equation:

$$G(Z,P) = \frac{1}{\pi}\int \frac{e^{-\beta^2 Z}-1}{J_1^2(\beta)+Y_1^2(\beta)}\left[J_0(P\beta)Y_1(\beta) - J_1(\beta)Y_0(P\beta)\right]\frac{d\beta}{\beta^2} \quad (5)$$

$$Z = \frac{a_s t}{r^2} \quad (6)$$

$$Z = \frac{r}{r_o} \quad (7)$$

where J_0, J_1 are the Bessel functions of the first kind, Y_0, Y_1 are the Bessel functions of the second kind, Z is the Fourier number, P is the dimensionless radius in the cylindrical heat source function, and β is the integration constant.

The thermal conductivity is determined by minimizing the evaluation function F, which involves the residuals between measured and calculated temperatures at both the outlet and the ground during the recovery period. The evaluation function F is defined as:

$$F = \alpha \sum^{nstep}\left(T_{o(obs)} - T_{o(cal)}\right)^2 + (1-\alpha)\sum^{ntest}\left(\sum^{nlayer}\left(T_{ro(obs)} - T_{ro(cal)}\right)^2\right) \quad (8)$$

where T_o is the fluid temperature at the heat exchanger outlet [°C], T_{ro} is the outer wall temperature of the heat exchanger pipe [°C], α is a weighting constant, adjusted based on the convergence behavior of the function, n_{test} represents the number of comparisons between the measured and calculated outer wall temperatures, n_{step} is the number of time steps for comparison.

Increasing n_{test} improves the accuracy of the estimated thermal properties, although excessive comparisons may reduce convergence speed. Therefore, n_{test} should be set to the minimum value necessary based on computational results.

3. INFORMATION ON GHES

In this study, three types of ground heat exchangers (GHEs) installed at Kyushu Saga International Airport, located in the western part of Japan, were subjected to thermal response tests (TRTs) to evaluate their thermal performance when coupled with ground-source heat pump (GSHP) systems (Figure 2).

GHE-1: The first type is a vertical ground heat exchanger (GHE) with a double U-tube completion. A borehole was drilled to a depth of 104 meters, with the double U-tube extending to a vertical length of 103 meters. It was observed that the U-tubes were exposed approximately 1 meter above the borehole entry point, suggesting that the U-tubes were installed at a depth of approximately 100 meters. The U-tube had an inner diameter of 25 mm, an outer diameter of 32 mm, and the borehole had a diameter of 175 mm, and the annular space between the borehole and the U-tubes was filled with grout material, specifically silica sand. The fluid flow within the U-tube system was directed through the inlet pipe (where the fluid enters) and the outlet pipe (where the fluid exits). The double U-tube completion consists of two parallel U-tube sets, each having its own inlet and outlet pipes. During the TRT, a fiber-optic thermometer was installed in one of the outlet pipes to monitor the subsurface temperature distribution.

GHE-2: The second type is a horizontal ground heat exchanger (GHE) with a single U-tube completion. In this configuration, the vertical depth was approximately 6 m and horizontal length was 100 m. The U-tube had an inner diameter of 25 mm, an outer diameter of 32 mm, and the borehole had a diameter of 115 mm, the same as the third type. Horizontal GHEs typically do not require grouting, as gravitational forces naturally fill the annular space between the borehole and the U-tubes. Therefore, no grout was used in this case. Additionally, no fiber-optic thermometer was installed in this GHE.

GHE-3: The third type is a horizontal ground heat exchanger (GHE) with a double U-tube completion. The depth and horizontal length were nearly the same as those of GHE-2, with U-tubes having an inner diameter of 25 mm, an outer diameter of 32 mm, and a borehole diameter of 115 mm. A fiber-optic thermometer was inserted into one of the inlet pipes to measure the subsurface temperature distribution during the TRT.

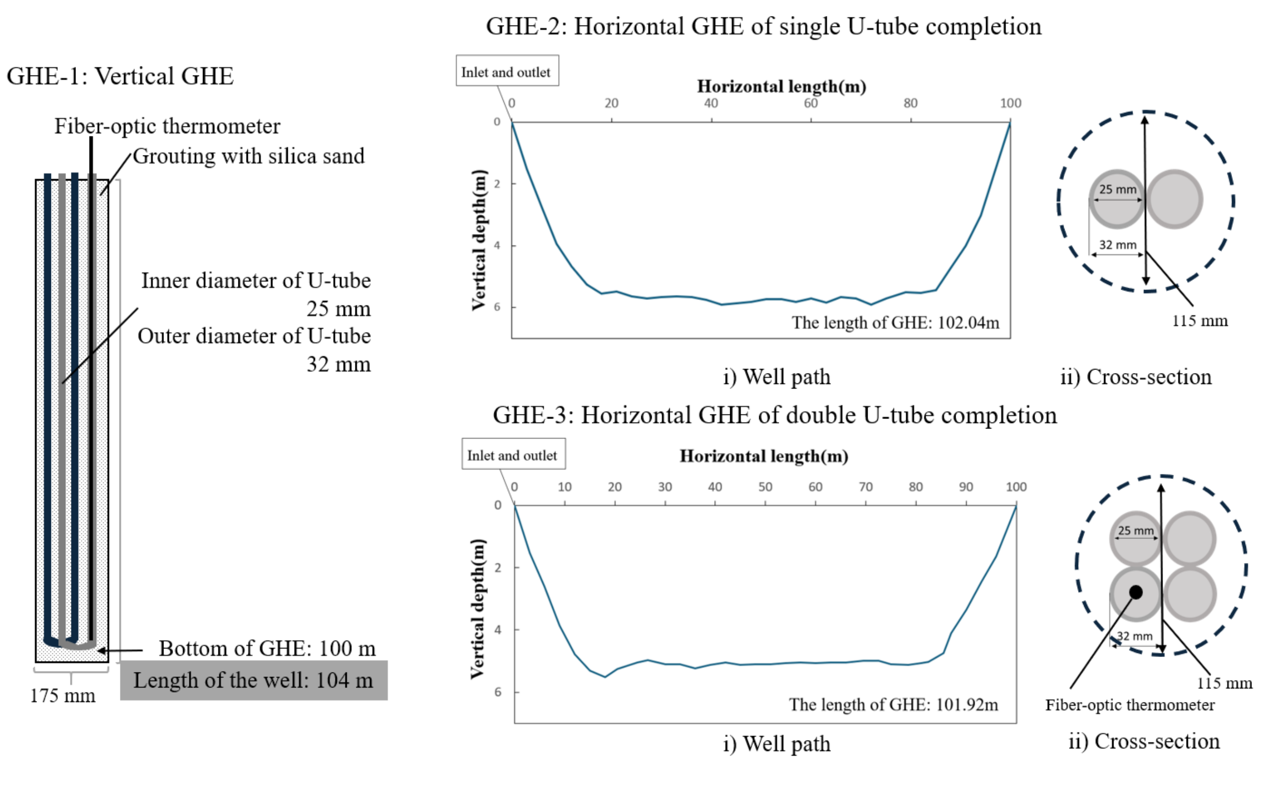

Figure 2: Schematic diagram of GHEs

4. FIELD TESTS

Thermal response tests (TRTs) were performed on the aforementioned ground heat exchangers (GHEs) , GHE-1, GHE -2, and GHE-3, to evaluate their thermal exchange performance. Water was used as the heat transfer fluid for all tests. The experimental parameters, including thermal load, circulation flow rate, and the duration of the test phases (heating circulation and recovery periods), are presented in Table 1. The thermal load and circulation flow rate were determined based on the average values calculated from sensor data collected at 1-minute intervals during the heating circulation phase of the TRT. For clarity, the TRTs conducted on GHE -1, GHE -2, and GHE-3 are designated as TRT-1, TRT-2, and TRT-3, respectively.

Table 1: TRT conditions

	GHE	GHE type	GHE length[m]	Test duration	Heat load		Flow rate [L/min]	Heating period [days]	Recovery period [days]
					[kW]	[W/m]			
TRT-1	GHE-1	Vertical (Double U-tube completion)	103.00	7/25-7/29	4.16	40.47	19.83	2	2
TRT-2	GHE-2	Horizontal (Double U-tube completion)	102.04	9/4-9/6	4.36	42.19	14.86	2	–
TRT-3	GHE-3	Horizontal (Double U-tube completion)	101.92	11/16-11/21	4.28	41.98	19.84	2	3

In all tests, both the thermal load and circulation rate remained stable, confirming that the thermal response tests (TRTs) were conducted under good conditions. The thermal conductivity of the subsurface was estimated based on the results from each TRT, employing the graphical method. The thermal conductivity was calculated from the slope of the temperature increase in the heat transfer fluid during the period of stable thermal exchange, corresponding to the section where the fluid temperature rise remained linear. As a result, the thermal conductivities were 1.20 W/m/K for TRT-1, 1.02 W/m/K for TRT-2, and 1.09 W/m/K for TRT-3.

The relatively low apparent thermal conductivity obtained from all TRT tests suggests minimal groundwater flow in the 0–100-meter depth range, where the vertical GHE (GHE-1) is installed. Similarly, the absence of significant groundwater flow is inferred for the shallow subsurface (0–6 meters), where GHE-2 and GHE-3 are installed. Additionally, the thermal conductivity values obtained from TRT-2 and TRT-3 were similar, likely due to the fact that GHE-2 and GHE-3 were drilled at nearly identical depths and are located in close proximity to each other, 4 meters spacing. Furthermore, these values were lower than the thermal conductivity obtained from TRT-1.

Figure 3: TRT-1 in operation

5. ESTIMATION OF THERMAL CONDUCTIVITY USING ANALYTUCAL MODELING

In this chapter, the thermal conductivity profiles for TRT-1 and TRT-3 were estimated using the U-tube thermal behavior analysis program (Fujii, 2006) with non-regression analysis. The method minimizes the sum of squared residuals (evaluation function F) between the calculated heat medium temperatures and the actual field measurements. Optimization was performed by monitoring the evaluation function's convergence, and once stable, history matching was applied to improve the fit between calculated and observed temperatures. The estimated thermal conductivity profile was validated by comparing it with the graphical method, showing a close match.

5-1 Thermal Conductivity Estimation for TRT-1

Based on the measurement results from TRT-1, a thermal conductivity profile extending approximately 100 meters vertically was developed. To construct this profile, the heat medium inlet temperature measured during the heating circulation of the thermal response test was used to calculate the heat medium exit temperature, and the initial ground temperature, measured one hour prior to the test using a fiber-optic thermometer, was used to calculate the ground temperature during the recovery period. The resulting calculated values were compared with the actual measurement data from TRT-1, and the variable parameters were adjusted as necessary to improve the match. The thermal conductivity values were set as follows: 0.45 W/m/K for the U-tube, 0.61 W/m/K for water, and 2.4 W/m/K for the grouting material. The heat capacities were set to 2.09×10^6 W/m/K for the U-tube, 2.19×10^6 W/m/K for water, and 4.12×10^6 J/m^3/K for grout. The dynamic viscosity of water was set to 0.80×10^{-6} m^2/s.

The calculated values for the heat medium exit temperature and ground temperature during the recovery period showed good agreement with the observed values. The resulting thermal conductivity profile is as follows:

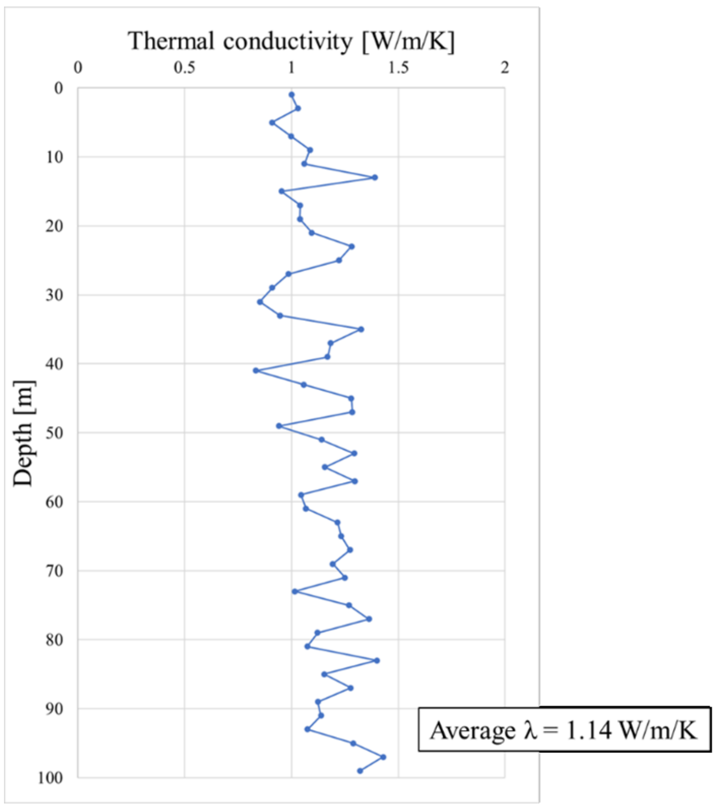

Figure 4: Thermal conductivity estimation for TRT-1

The average value of the thermal conductivity profile in the vertical direction was 1.14 W/m/K, which closely aligns with the 1.20 W/m/K obtained using the graphical method, confirming the validity of the estimated profile. As shown in Figure 4, the calculated thermal conductivity profile exhibits slight variation, which is attributed to the limited precision of the fiber-optic thermometer used for measurements.

While some variation was observed, an increasing trend in thermal conductivity with depth was consistently identified. This phenomenon is likely attributable to soil compaction effects at greater depths, which reduce porosity and consequently enhance thermal conductivity. This trend is consistent with the results obtained using the graphical method and provides an explanation for the lower thermal conductivity estimates from the TRT-2 and TRT-3 compared to TRT-1. TRT-2 and TRT-3 were conducted using horizontal GHEs, estimating thermal conductivity at a depth of approximately 6 meters, whereas TRT-1 was conducted using a vertical GHE, providing an estimate of the average thermal conductivity over a depth range of 0–100 meters. Therefore, the difference in depth is considered to have influenced the thermal conductivity estimates from each test.

5-2 Thermal Conductivity Estimation for TRT-3 Horizontal GHE (Double U-tube Configuration)

Next, based on the measurement results from TRT-3, a thermal conductivity profile in the horizontal direction extending approximately 100 meters at a depth of about 6 meters, was developed. In the horizontal GHE, where grouting material is not filled, the thermal conductivity around the U-tube (the grout section) was set to a value close to the thermal conductivity of the ground. Based on the vertical thermal conductivity profile obtained in section 5-1, the thermal conductivity of 1.00 W/m/K at a depth of approximately 6 meters was adopted for the grout material section. Other material properties were set as in Section 5-1.

The calculated thermal conductivity profile showed good agreement with the observed values. The resulting thermal conductivity profile is as follows:

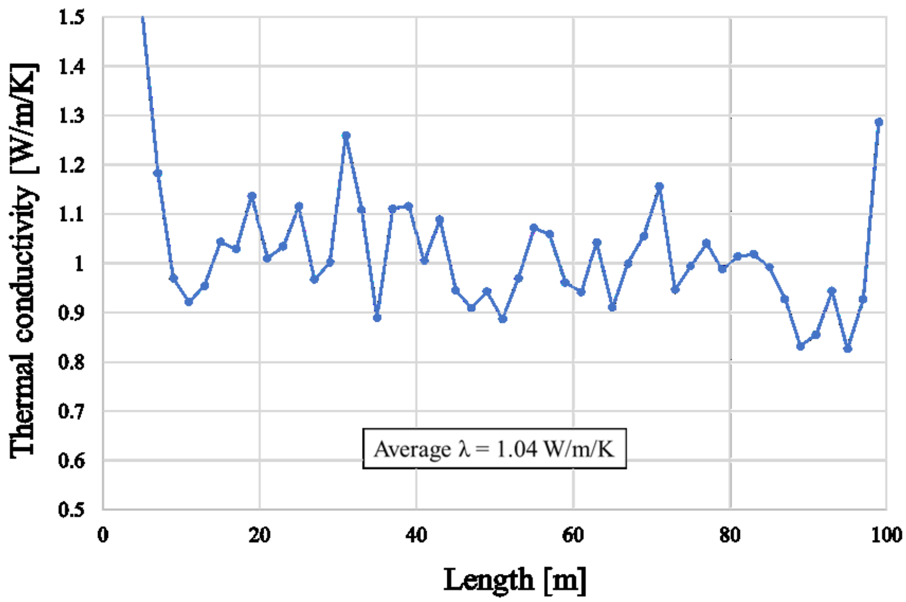

Figure 5: Thermal conductivity estimation for TRT-3

The average value of the thermal conductivity profile in the vertical direction was 1.04 W/m/K, which is close to the thermal conductivity of 1.09 W/m/K obtained using the graphical method, confirming the validity of the estimated thermal conductivity profile. As in TRT-1, the calculated thermal conductivity profile exhibits variation. This variation is likely due to the relatively low accuracy of the fiber-optic thermometer used for the measurements, which led to less stable results.

Moreover, the calculated thermal conductivity profile shows a sharp increase in thermal conductivity at both the 0-meter and 100-meter points. This phenomenon is thought to result from the proximity of these endpoints to the surface, where temperature changes influenced by weather conditions had a stronger effect, making accurate thermal conductivity estimation more difficult. When excluding the 10 meters at each end, which are likely influenced by these factors, the standard deviation of the thermal conductivity estimated from TRT-3 was 0.08 W/m/K. In comparison, the standard deviation of the thermal conductivity estimated from TRT-1 was 0.15 W/m/K, indicating that the variation in TRT-3's results is smaller. This difference is likely due to the differences in the orientation of the analysis between TRT-1 and TRT-3. TRT-1 estimates thermal conductivity at different depths, where heterogeneity in the physical properties and thermal behavior of the soil influences the results. In contrast, TRT-3 estimates thermal conductivity at nearly the same depth, where similar soil conditions result in less variation. The results from TRT-1 show an increase in thermal conductivity with depth, while those from TRT-3, estimating thermal conductivity at the same depth, show less variation. Therefore, the observed differences between TRT-1 and TRT-3 are likely due to the test orientation and the homogeneity of the soil conditions.

6.HEAT EXCHANGE PERFORMANCE

Based on the results of the field tests, a comparative analysis was conducted to assess the heat exchange performance of three types of GHEs: GHE-1 (vertical GHE with a double U-tube completion), GHE-2 (horizontal GHE with a single U-tube completion), and GHE-3 (horizontal GHE with a double U-tube completion). In Figure 6, the vertical axis represents the temperature rise of the heat transfer fluid normalized by the heat exchange rate per unit length of each GHE, while the horizontal axis indicates the elapsed time. Normalizing by the heat exchange rate per unit length eliminates the effects of GHE length and test conditions, facilitating a clearer comparison. A higher value on the vertical axis indicates a greater temperature rise of the heat transfer fluid, signifying that less heat is being exchanged with the ground, which suggests a lower heat exchange performance.

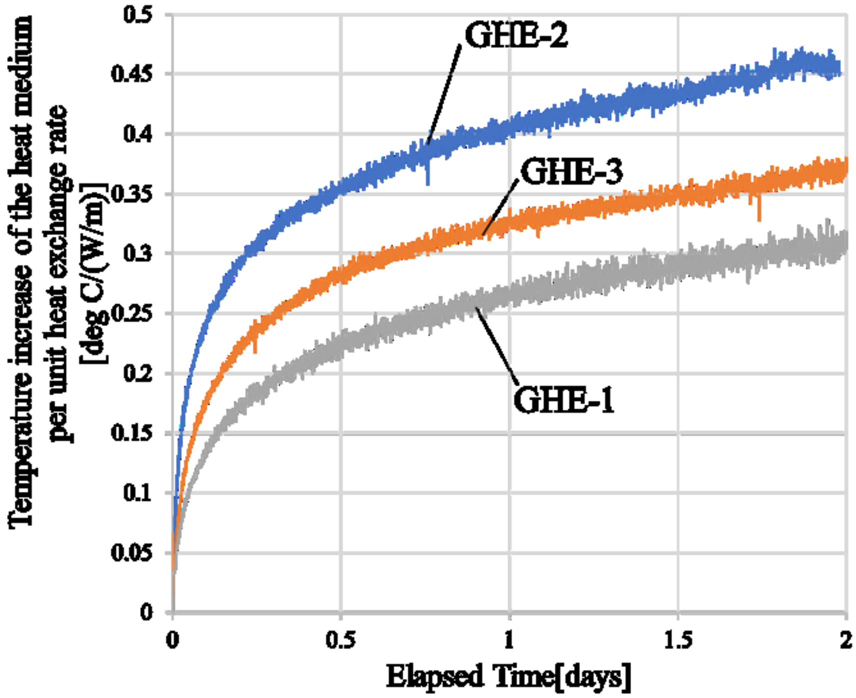

Figure 6: Comparison of heat exchange performance

Figure 6 shows that the highest values were observed for GHE-2, a horizontal ground heat exchanger with a single U-tube configuration, followed by GHE-3, a horizontal GHE with a double U-tube configuration, and GHE-1, a vertical GHE with a double U-tube configuration. This analysis suggests that the heat exchange performance ranks in the following order, from highest to lowest: GHE-1, GHE-3, and GHE-2. The lower heat exchange performance observed in GHE-2 compared to GHE-1 and GHE-3 can be attributed to the structural differences between the single U-tube and double U-tube completions. The double U-tube completion offers a larger surface area and less thermal resistance compared to the single U-tube, thus facilitating more efficient heat exchange with the ground. In addition, a comparison between GHE-1 and GHE-3 reveals that, despite both employing a double U-tube configuration, the vertical GHE (GHE-1) exhibited a higher heat exchange capacity than the horizontal GHE (GHE-3). The results from an analytical model suggest that in the field, the higher thermal conductivity at greater depths allows the vertical GHE, which exchanges heat at deeper levels, to perform more efficiently than the horizontal GHE, which exchanges heat at shallower depths.

CONCLUSION

In this study, thermal response tests (TRT) were conducted to analyze the thermal conductivity profiles of three types of ground heat exchangers (GHEs) installed at Saga International Airport in Kyushu, Japan: GHE-1: vertical GHE with a double U-tube configuration, GHE-2: horizontal GHE with a single U-tube configuration, and GHE-3: horizontal GHE with a double U-tube configuration. The tests were performed to compare the thermal exchange capacities of each GHE, and an analytical model was used to generate thermal conductivity profiles for both the vertical direction (0–100 m depth) and the horizontal direction (approximately 6 m depth). The analysis revealed that the thermal conductivity of GHE-1 (vertical GHE) was higher than that of GHE-2 (horizontal single U-tube GHE) and GHE-3 (horizontal double U-tube GHE), as confirmed by graphical method analysis. Additionally, the thermal conductivity profiles calculated using the analytical model showed that the standard deviation of thermal conductivity for GHE-2 was 0.08, whereas it was 0.15 for GHE-1. This indicates that thermal conductivity variation is greater in the vertical direction, likely due to the heterogeneous nature of the strata in which GHE-1 is installed compared to the horizontally installed GHEs. The GHE-1 profile also showed an increasing trend in thermal conductivity with depth, which can be attributed to compaction effects that reduce soil porosity as depth increases. In comparison, the thermal exchange capacity of GHE-1 (vertical GHE, double U-tube configuration) was found to be the highest, followed by GHE-3 (horizontal GHE with a double U-tube configuration), and GHE-2 (horizontal GHE with a single U-tube configuration). This is consistent with the analytical model results, which suggest that GHE-1 exchanges heat more efficiently at greater depths, where higher thermal conductivity is observed. These findings suggest that in areas where there is no groundwater flow in specific layers, such as the field site in this study, GHE-1 effectively utilizes the higher thermal conductivity at deeper depths and demonstrates superior heat exchange performance over GHE-2 and GHE-3 systems.

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