

Field Test of Horizontal Ground Heat Exchangers Installed Using Horizontal Directional Drilling Technology

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ABSTRACT

In Ground Source Heat Pump (GSHP) systems, the drilling cost of Ground Heat Exchangers (GHEs) needs to be minimized for the dissemination of the systems. Horizontal Directional Drilling (HDD) is a no-dig drilling technology which is commonly used for drilling tunnels or for the installation of urban infrastructures, i.e., pipes, cables, etc., in the shallow ground. Since the cost of HDD and the requirement of surface land area are significantly smaller than those of conventional excavation, the combination of HDD and horizontal GHE (HGHE) is expected to improve the competitiveness of GSHP systems, especially in urban areas.

In this research, a horizontal hole was drilled using HDD technology in Saga City, western Japan as an experimental GHE. The hole has a diameter of 230 mm, a length of 63 m and an approximate depth of 8 m from ground surface. The hole was completed as a GHE with a 52 mm ID polyethylene pipe inside. A thermal response test (TRT) was then performed with a heat load of 35-45 W/m to investigate the heat exchange capacity. The TRT well-demonstrated the good heat exchange ability of the HGHE due the larger heat exchange surface and the lack of thermal interference between pipes. Next, a numerical simulation model was developed using a commercial software based on the GHE design and the geological information at the test site. The model was validated through the history matching of the heat medium temperatures measured during the TRT and was used for sensitivity studies for the optimum design of the GHE. The sensitivity studies showed that the unit heat exchange rates decline with the increase of GHE length, while the increased diameter of GHE enhance the heat exchange rates significantly. The deeper installation of GHE was found to be insignificant due to the delayed seasonal change of the ground temperature.

1. INTRODUCTION

In Japan, drilling cost of the vertical Ground Heat Exchangers (GHEs) in Ground Source Heat Pump (GSHP) systems is much higher (could be more than twice) than that in other Asian, European, American countries, which hampers the promotion of the system. The use of horizontal GHE could be one of the measures to reduce the drilling cost, since the GHE can be constructed using common excavating machines instead of using expensive drilling machines. On the other hand, the selection of horizontal GHEs (HGHEs) has been difficult in countries of high population density like European countries or Japan, since the installation of horizontal GHEs requires larger land space and the removal of the surface coverage.

Horizontal Directional Drilling (HDD) is a trenchless method of installing underground pipes in a relatively shallow formation along a prescribed underground path by using a surface-launched drilling equipment (Figure 1). HDD is commonly used for drilling tunnels or for the installation urban infrastructures, i.e., pipes, cables, etc., in the shallow ground. The drilling cost of HGHEs by HDD is lower than the that of conventional HGHEs due to the short construction hours and the land surface requirement of construction is extremely small since the hole is drilled without disturbance to the surface. These advantages could make the HDD the most cost-effective and easy choice for HGHEs in urban areas if the performance of the GHE is reasonable and well-predictable.



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

Several researches have been carried out to investigate the performance of HGHEs through field tests or numerical simulations. Hamada et al. (2002) investigated the performance of a spiral-shaped HGHE installed HDD through field tests in Sapporo, Japan. Fujii et al. (2012) and Fujii et al. (2013) developed a numerical model and carried out sensitivity studies for single-layer and double-layer Slinky-coil HGHEs based on the field test results in Fukuoka, Japan. Also, researches have been carried out to use the underground space for HGHEs. Energy Geo-Structure (EGS) is a prefabricated panel containing horizontal heat exchangers inside which can be set on the walls of subway or railway tunnels (e.g., Bourne et al., 2016). Fordl et al. (2010) investigated the optimum design and installation method of EGS in the Brenner Base Tunnel in the Austrian Alps. Nicholson et al. (2013) studied the temperature performance and the stress distribution change with the operation of EGS in a subway tunnel in the U.K. Bourne-Webb et al. (2016) investigated the effect of the temperature, wind velocity in the tunnel, and the thermal conductivity of the ground on the heat exchange performance in GSHP system with EGS using a FEM model. Barla et al. (2016) evaluated the energy saving and the environmental impact of EGS in a subway tunnel in Milan using a FEM model. In the above studies, however, intensive investigations on HGHEs using HDD have not been performed with the combination of field tests and numerical analysis.

In this research, a HGHE was drilled using HDD technology in Saga City, western Japan to perform basic researches for the practical use of the HGHE in GSHP systems. A thermal response test, numerical modeling and sensitivity studies are performed to investigate the performance of the HGHE and to clarify its optimum design.

2. INFORMATION ON EXPERIMENTAL WELL

In 2018, a HGHE was drilled using HDD technology in the western suburbs of Saga City, Kyushu Island, Japan to perform researches for the practical use of the HGHEs by HDD in GSHP systems. The horizontal hole has a diameter of 230 mm, a length of 63 m, a displacement of 59 m, and the depth of approximately 8 m from ground surface. The path of the hole is shown in Figure 2. The hole reaches the deepest section after drilling 17m (displacement: 15 m) and remains nearly horizontal to 44 m (displacement: 42 m). The hole was then drilled upwards to the outlet. In the hole, a polyethylene tube of 52/60 mm ID/OD was inserted as the ground heat exchanger. The hole is not grouted since the space between the ground and the pipe is naturally filled by surrounding soil. The type of soil is mainly clay with some fine sand intervals indicating a low thermal conductivity (λ) of the formation. A TRT carried out at the same location using a U tube yielded a λ value of 0.9 W/m/K, which is a common value of clay formation. Though the groundwater level at the test site is 2 m below the ground level, the effect of groundwater flow is considered negligible, since the hydraulic conductivity and the hydraulic gradient are estimated to be quite small at the test site.

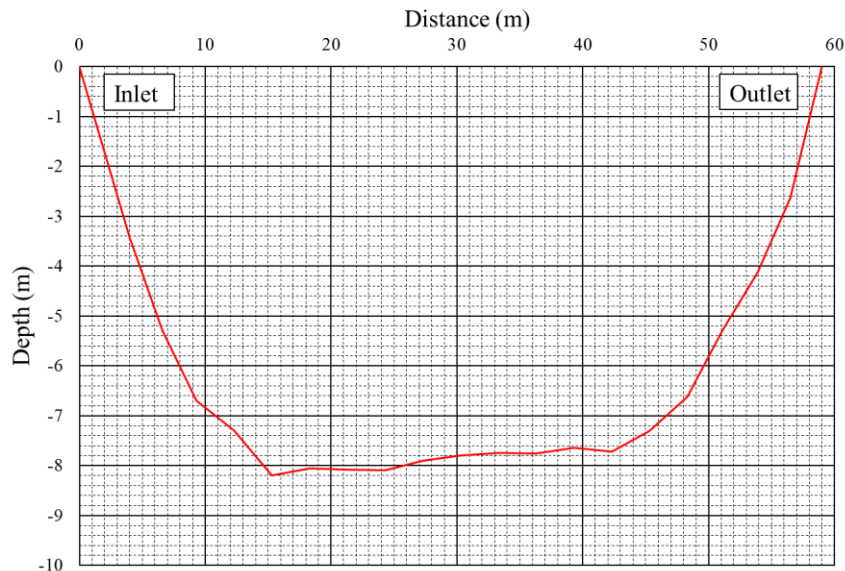


Figure 2: Well path of the GHE

3. RESULTS OF FIELD TESTS

Using the HGHE, a thermal response test was performed from Feb. 24 to 26, 2018 applying a constant heat load of 3 kW by an electrical heater. The inlet, outlet and ambient temperatures, the circulation rate and the heat exchange rate are shown in Figure 3. The average circulation rate of the heat medium (water) was well maintained at 17.7 L/min. Since the inlet and outlet of the HGHE are located 59 m apart, the heat medium was returned through a surface piping from the outlet to the inlet of the HGHE with careful insulation using polystyrene forms. The average heat exchange (disposal) rate in the ground, however, showed a fluctuation (as shown in the Figure 3) with the change of ambient temperature. The average heat exchange rate was calculated as 2.44 kW (38.8 W/m), indicating the heat loss of around 20% in the surface piping. During the TRT, the inlet temperature showed an increase to above 35 °C, while the temperature got

almost stabilized after 24 hours. The early stabilization of the heat medium temperature regardless of the large heat exchange rate per unit GHE length suggests good heat exchange capacity of the HGHE. This characteristic would be attributed to the large surface area of the heat exchange pipe (OD: 60 mm) and the lack of thermal interference between the downflow and upflow pipes which negatively affects the performances of conventional U tube GHEs.

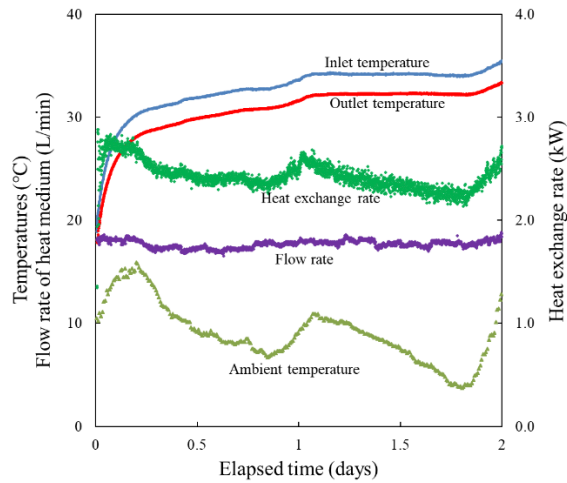


Figure 3: Measured data during TRT

The shape of the one-way HGHE requires a large land space as well as the conventional Slinky-coil HGHEs if the distance between the inlet and outlet of the HGHE is large. This restriction, however, could be overcome by drilling the HGHE using a circle-shape well path and letting the inlet and outlet of the HGHE close to each other, since the HDD technology allows any shape of horizontal holes. This minimum requirement of surface land space will be a significant advantage of the HGHEs by HDD especially when constructing the HGHEs in urbanized areas.

4. NUMERICAL SIMULATION AND CASE STUDIES

In this section, a numerical simulation model of the HGHE is developed and validated through a history matching between the measured and simulated outlet temperatures in the TRT. Prediction runs are then performed to optimize the design of the HGHE under realistic operation conditions.

4.1 Model construction

For the numerical simulation of the HGHE installed by HDD technology, the well path needs to be defined arbitrarily in a 3D volume. Since the function was not available in the recent version of FEFLOW (Diersch, 2014), which is commonly used for the modeling of GHEs, the developer of the software (DHI A/S) modified the software on our request. In the modified model, the well path can be defined even when the well is deviated or curved. The 3D view and the cross-sectional view of the simulation mesh for the HGHE are shown in Figures 4 and 5, respectively. In Figure 4, the red line shows the top of the cross section on which the HGHE is placed.

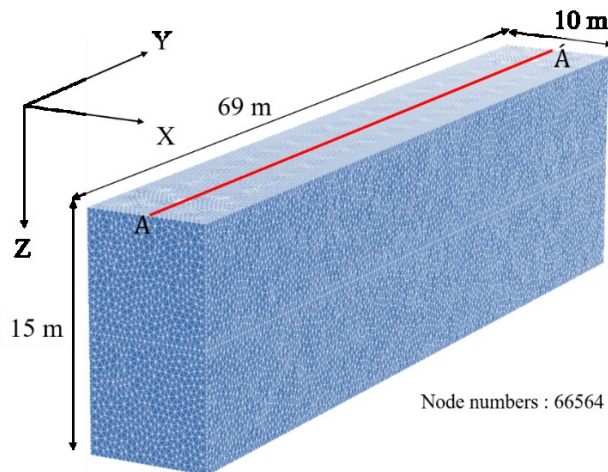


Figure 4: 3D view of the simulation grid of the HGHE model

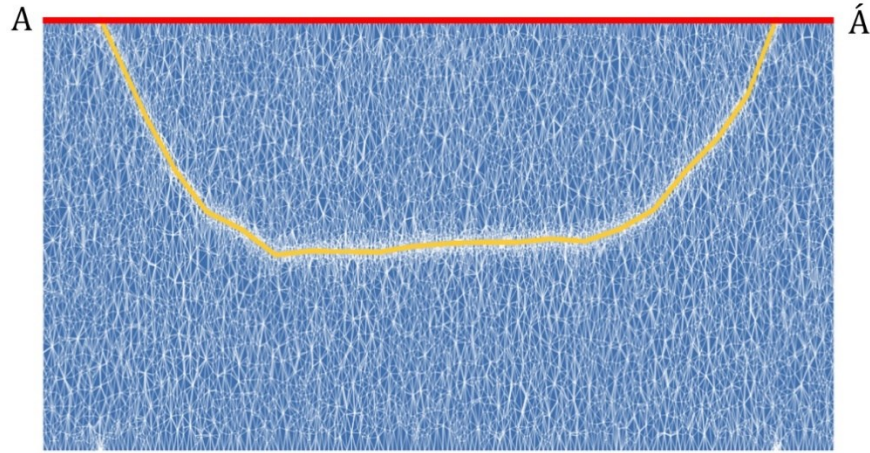


Figure 5: Cross sectional view of the Simulation grid of the HGHE model

Figure 5 shows the refined finite element mesh around the GHE to enable the accurate modeling of the mass and heat transport. The mesh was defined large enough to allow 5 meters of blank mesh outside the HGHE mesh and to eliminate the boundary effects. No groundwater flow is defined in the model. The thermal conductivity of the saturated soil was set as 0.9 W/m/K based on the TRT result. The volumetric heat capacity of the soil was determined 2.5×10^6 J/m³/K, which is a typical value of clay formation. The ID/OD and the λ of the heat exchange pipes are 52/60 mm and 0.42 W/m/K, respectively.

The boundary conditions for fluid transport is set as no flow for all boundaries. The boundary condition for heat transport is set as adiabatic at peripheral boundaries, while the temperature at the bottom boundary at the depth of -15 m was set as 19.5 °C based on the measured data. The boundary condition of the surface, however, needs to be carefully determined based on the climate data and the condition of the ground surface coverage since the ground temperature in the shallow ground is strongly influenced by the surface heat balance. In the numerical model, sol-air temperature (SAT) is used to consider the energy balance on the land surface, which is defined as follows:

$$\text{SAT} = \theta_0 + 1/\alpha_0 ((1 - \alpha_s) J - \varepsilon J_{\text{eh}}), \quad (1)$$

where,

SAT	: Sol-air temperature (°C)
θ_0	: Ambient temperature (°C)
α_0	: Coefficient of overall heat transfer between air and soil (W/m ² /K)
α_s	: Albedo (= 0.3 for soil)
J	: Total solar radiation (W/m ²)
ε	: Longwave emissivity (-)
J_{eh}	: Effective emission (W/m ²)

The weather data for the model was determined with reference to the published data by the local observatory in Saga City. The annual average temperature and annual precipitation were 17.4 °C, and 1887 mm, respectively, in 2018. The model was run for initialization for a period of 3 years before the operation of HGHE started.

4.2 History matching

In the history matching, the inlet temperature and circulation rate of the heat medium were input to calculate the outlet temperature. Figure 6 shows the history matching result of outlet temperature during the TRT. A reasonably good matching was obtained through the entire period of the TRT, which demonstrates the validity of the numerical model. Figure 7 shows the temperature distribution in the ground at the end of the 2 days' heating period in the TRT. This figure shows gradual temperature drop of the heat medium while flowing though the HGHE. The temperature changes are steeper near the inlet and outlet of the HGHE since the TRT was carried out in winter and the near-surface ground temperature was significantly lower than that in the deeper ground, which resulted in the larger temperature difference between the ground and the heat medium.

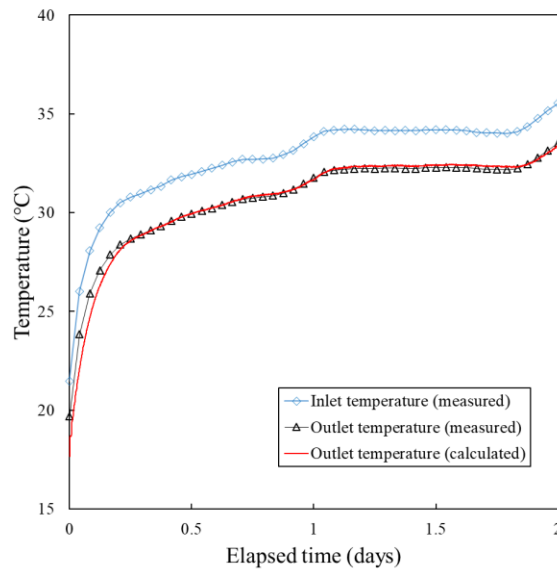


Figure 6: History matching result of outlet temperature using TRT data

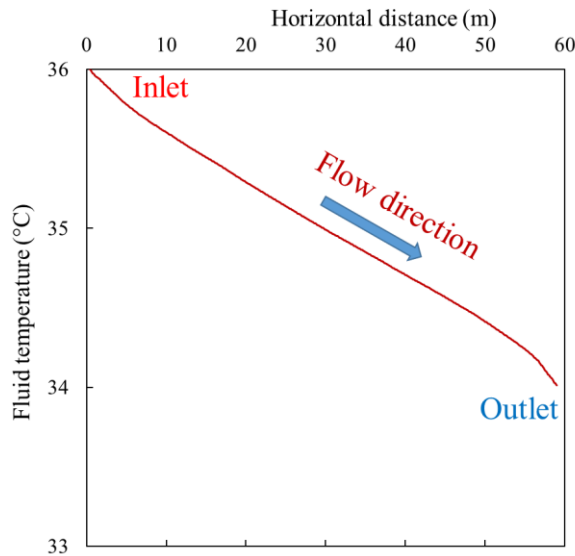


Figure 7: Temperature distribution in the ground at the end of TRT

4.3 Case studies

After validating the numerical model, we carried out three kinds of sensitivity studies for the optimum design of the HGHEs by changing the pipe diameters, horizontal distance of the GHE, and installation depth of the GHE from the ground surface. In the simulation runs, the ground properties and temperatures at the test site and the SAT in Saga City were applied. The followings show the conditions and results of the sensitivity studies.

4.3.1 Effect of pipe diameters

The simulation runs were carried out using the same well path as the test site and an inlet temperature and a flow rate of 35 °C and 30 L/min, respectively, assuming four types of commonly used pipe diameters. The diameter of the hole was fixed at 230 mm assuming the use of same drilling bit. Figure 8 shows the average heat exchange rate during a 24 hours cooling operation for 10 days. The diameters of the pipes in the figure (25 mm, 50 mm, 75 mm and 100 mm) indicate the nominal inner diameter of the pipes and the actual inner and outer diameters of the four pipes are 28mm/34mm, 52mm/60mm, 78mm/89mm and 102mm/114mm, respectively. As can be seen from the results, nearly linear increase of the heat exchange rate was calculated with the increase of pipe diameter. This can be explained by the increase of the heat exchange area (the outer surface of the pipe), which is proportional to the square of the diameter of the pipes. The

results indicate that the size of the pipe should be set as large as possible to enhance the heat exchange capacity of the HGHE, though the cost of the pipe and the safe inserting operation needs to be considered in the actual design of the HGHEs.

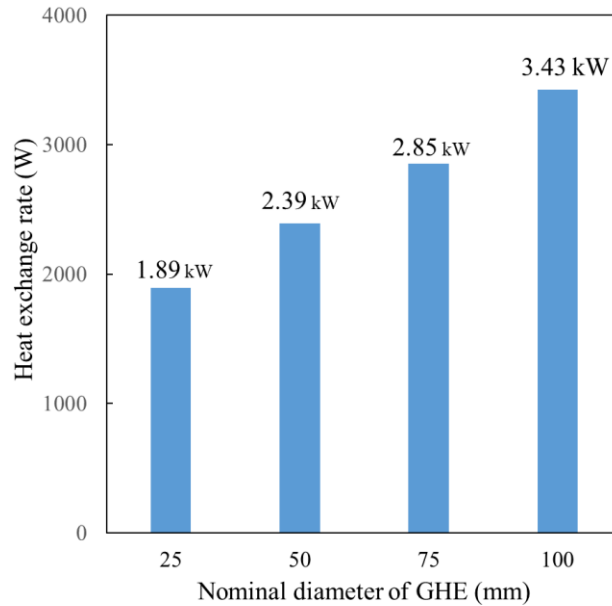


Figure 8: Relationship between pipe diameter and heat exchange rate

4.3.2 Effect of horizontal length

Next, the length of the horizontal section of the HGHE was examined using the model assuming an inlet temperature and a flow rate of 35 °C and 30 L/min, respectively. The configurations of the curved section at the inlet and outlet of the HGHE were set as same in all cases. The horizontal sections, located at -8 m, were defined as completely horizontal. The length was varied from 15 m to 200 m.

Figure 9 shows the average heat exchange rates and the heat exchange rate per unit GHE length during a cooling operation of 24 hours for 10 days. The heat exchange rate increased almost linearly with the increase of well length. On the other hand, the heat exchange rate per unit well length slightly decreased since the temperature of the heat medium becomes closer to the formation temperature when the GHE length is increased. Considering that the rate of decline was not steep even the length reached 200 m, however, the large length of the GHE is not disadvantageous since the drilling cost per unit length by HDD can be reduced by drilling longer holes.

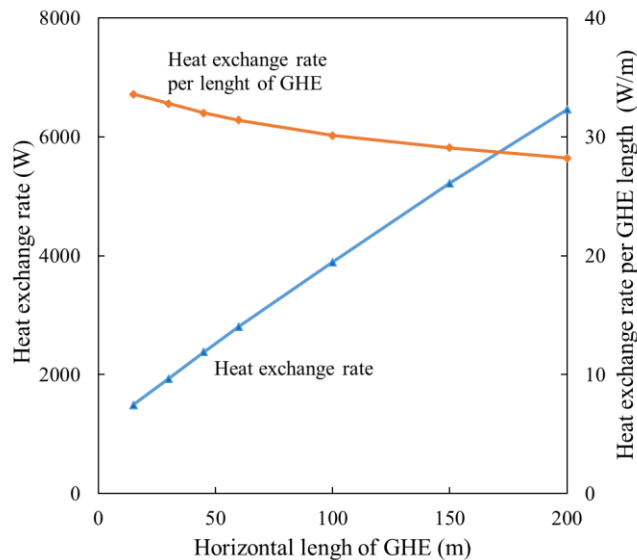


Figure 9: Relationship between GHE length and heat exchange rate

4.3.3 Effect of installation depth of HGHEs

In conventional HGHEs, the pipes are commonly buried between 1 m and 2 m below ground surface restricted by the capacity of the excavating machines. In such depth ranges, the deeper installation of the pipe is more preferable in terms of heat exchange capacity since the ground temperature is more stable at deeper depths (Fujii, et al, 2012). In the case of HGHEs by HDD, however, this trend could be different considering the more flexible installation depth.

To avoid the influence of the different length of the curved section from GL to the horizontal section, only the horizontal part of the HGHE was defined as the heat exchanger in the model. The length of the horizontal section was set as 100m in all cases. The circulation rate of heat medium was set as 30 L/min, while the heat load in the heating and cooling operation were set as 20 W/m with an operation hour of 24 hours/day. The two plots in Figure 10 show the average heat medium temperatures during heating and cooling operation using different installation depth, -5 m, -10, m -15 m. The left plot shows the average temperature of the heat medium in the heating operation of 3 months from December to February. As can be seen from the plot, higher heat medium temperature was obtained in the case of -5 m installation than in other two cases. Since the higher temperature is more advantageous in the heating operations, -5 m installation was judged as the best case among the 3 cases, which is quite different from the case of conventional shallow HGHEs. The reason can be explained by the average ground temperatures at the pipe depth captioned in the same figure. Due to the delay of ground temperature change, the ground temperature at -5 m was higher than those at -10 m and -15 m, which resulted in the higher heat medium temperatures in the -5 m case. Since the maximum difference of the temperature is around 1.0 °C, the difference does not significantly affect to the COP of the heat pump. But it is important to recognize that the deeper installation is not advantageous when designing the HGHE using the HDD technology. A similar trend was observed in the results of the cooling operation shown in the right plot of Figure 10. The average temperature of the heat medium was lower when the HGHE was installed at -5 m than other cases, especially in the hottest months, July and August, which is advantageous in the cooling operations.

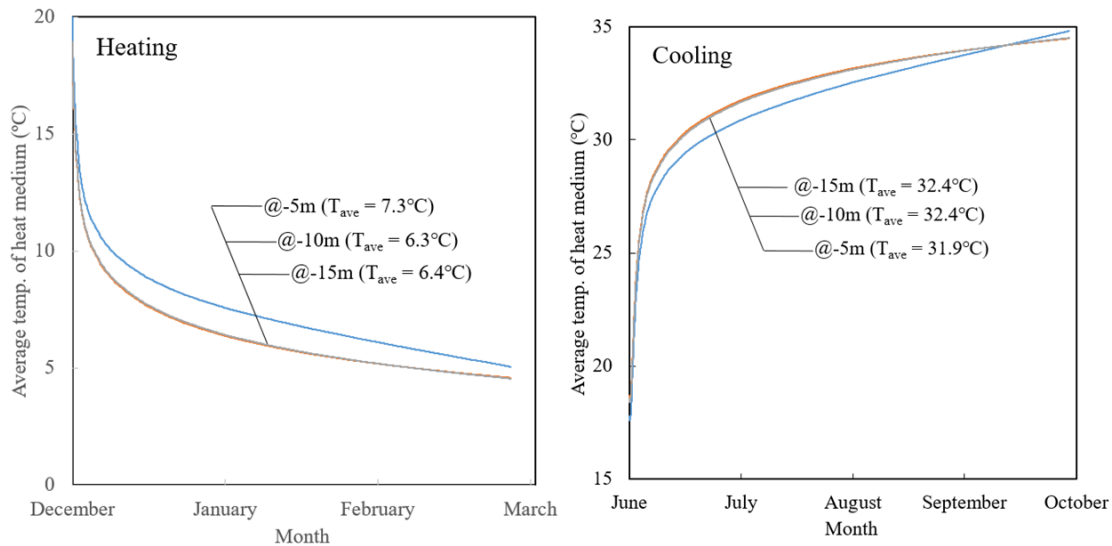


Figure 10: Relationship between GHE depth and heat exchange rate

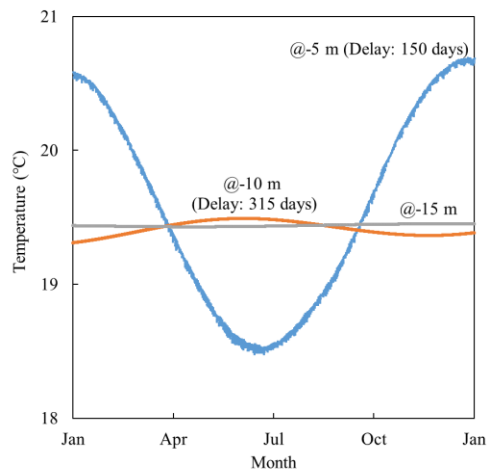


Figure 11: Temperature distribution in the ground at -5 m, -10 m and -15 m

To confirm the delay of the ground temperature change, the ground temperature was calculated throughout a year using the SAT as the surface boundary condition as shown in Figure 11. The ground temperature at -5 m shows a delay of 150 days in comparison with the ambient temperature with an annual amplitude of 1.2 °C. This delay positively affects the heat exchange performance of the -5 m case since the ground becomes warmer in winter, while it is cooled in summer. On the other hand, the delay of the seasonal temperature changes at -10 m is about 11 months, which negatively affects the heat exchange performance. The seasonal temperature changes at -15 m is negligible due to attenuation.

5. CONCLUSIONS

In this research, field test and numerical simulation were performed for the practical application of HDD technology to the installation of horizontal GHEs of GSHP systems. The field test was performed in a horizontal hole drilled using HDD in Saga City, western Japan. The hole has a diameter of 230 mm, a length of 63 m and a depth of 8 m from the ground surface. A thermal response test (TRT) was performed with a fixed heat load of 35-45 W/m, which demonstrated the superior performance of the HGHE in comparison with U tube GHEs due to the enhanced surface area and the lack of thermal interference between pipes.

Then, a numerical simulation model was developed using a commercial software based on the HGHE design and the geological information at the test site. The model was validated through the history matching of the heat medium temperatures which were measured during the TRT. The sensitivity studies using the validated model showed that the unit heat exchange rates increased with the increased diameter of GHE, while the heat exchange rate per GHE length decreased with the increase of GHE length. The deeper installation of GHE was found to be insignificant due to the delayed seasonal change of ground temperatures.

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