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Field Test and Numerical Simulation of Horizontal Ground Heat Exchangers Installed Using Horizontal Directional Drilling

Hikari Fujii[1], Shunsuke Tsuya[1], Retsu Harada[2], Hiroyuki Kosukegawa[1]

[1]Akita University, 1-1 Tegata Gakuencho, Akita, 010-8502, Japan, [2]Biotex Inc., 3134, Hisadomi, Kubotacho, 849-0202, Saga, Japan

fujii@mine.akita-u.ac.jp

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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, two horizontal holes were drilled using the HDD technology in Saga City, western Japan, as experimental GHEs. GHE-1 has a hole diameter of 230 mm, a length of 63 m and an approximate depth of 8.1 m from land surface, which was completed by inserting a 52 mm ID polyethylene pipe into the hole. GHE-2 has a hole diameter of 230 mm, a length of 47 m and an approximate depth of 6.6 m from land surface, which was completed with a 27 mm ID polyethylene U-tube. Thermal response tests (TRTs) were first performed to investigate the heat exchange capacity of the GHEs. Next, numerical simulation models were developed using a commercial software based on the GHE design and the geological information at the test site. The models were reasonably validated through the history matching of the heat medium temperatures measured during the TRTs. The models then were used in the sensitivity studies for the optimum design of the GHE, which showed the superior capacity of GHE-1 to that of GHE-2 due to the larger surface area of the pipe and the lack of thermal interference between the downflow and upflow pipes. The sensitivity studies also showed that the unit heat exchange rate declines with the increase of GHE length, while the increase of the diameter of GHEs 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 temperatures.

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 HGHEs could be one of the measures to reduce the drilling cost, since the HGHE can be constructed using common excavating machines instead of using expensive drilling machines. On the other hand, the application of HGHEs has been difficult in countries of high population density like Japan, since the installation of HGHEs requires larger land space and the removal of the surface soil or buildings.

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 that of conventional HGHEs due to the short construction hours and the surface land requirement for 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 installation method for HGHEs in urban areas if the performance of the HGHE by HDD is well-predictable.

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

Several research projects 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 using 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, research has 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, investigations on HGHEs using HDD have not been performed with the combination of field tests and numerical analysis.

In this research, experimental HGHEs were drilled using HDD technology in Saga City, western Japan, to perform basic researches for the practical use of the HGHEs by HDD in GSHP systems. Thermal response tests, numerical modeling and sensitivity studies are performed to investigate the performance and to optimize the design of the HGHEs.

2. INFORMATION ON EXPERIMENTAL WELL

In January 2018, two experimental HGHEs were drilled using HDD technology in the western suburb of Saga City, Kyushu Island, Japan to perform basic researches for the practical use of the HGHEs by HDD. The two GHEs adopted different types of heat exchange pipes; a one-way pipe and U-tube. The well paths of the two GHEs are shown in Figure 2. GHE-1 has a hole diameter of 230 mm, a length of 63 m and a maximum depth of 8.1 m from land surface. GHE-1 was completed by inserting a polyethylene pipe of 52/60 mm ID/OD into the hole. GHE-2 has a hole diameter of 230 mm, a length of 47 m and a maximum depth of 6.6 m from land surface. GHE-2 was completed with a 27/34 mm ID/OD high-density polyethylene U-tube. Because U-tube GHEs require a hole size twice as much as the OD of the tube, the necessary hole size for GHE-1 and GHE-2 is considered to be close. The holes have not been grouted since the space between the ground and the pipe is naturally filled by the surrounding soil. The ground in which the GHEs penetrated mainly consists of clay and silt of low hydraulic conductivity.

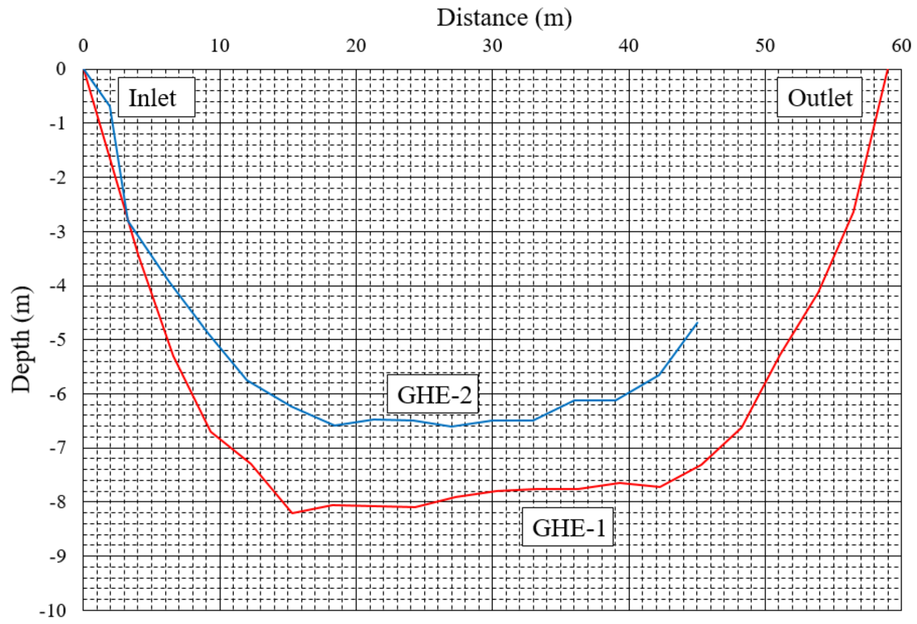
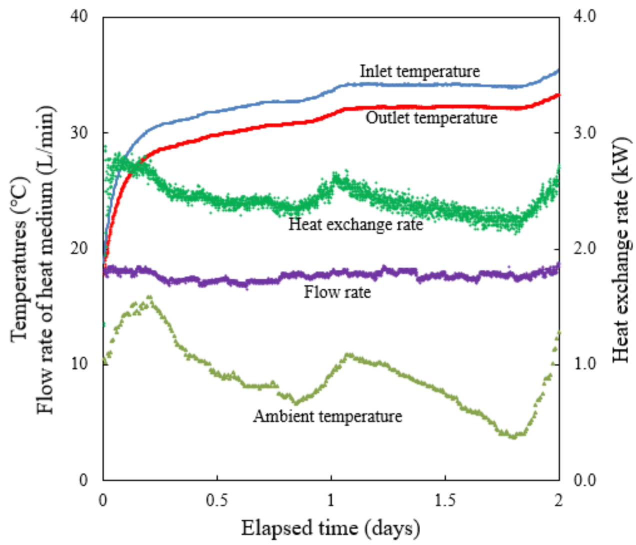


Figure 2: Well path of the horizontal GHEs

3. RESULTS OF FIELD TESTS

Using the above HGHEs, thermal response tests were carried out in Feb., 2018 applying a constant heat load (TRT-1: 3.0 kW, TRT-2: 1.5 kW) to the circulating fluid (water) using an electrical heater for 48 hours. The TRTs for GHE-1 and GHE-2 are named as TRT-1 and TRT-2, respectively. The inlet, outlet and ambient temperatures, the circulation rates and the heat exchange rates measured during the TRTs are shown in Figure 3. The average circulation rate of the heat medium (water) was well maintained at 17.7 L/min and 14.9 L/min in TRT-1 and TRT-2, respectively. Since the inlet and outlet of GHE-1 are located 59 m apart, the heat medium was returned through a surface piping from the outlet to the inlet of the GHE with careful insulation using polystyrene forms. Nevertheless, the average heat exchange (disposal) rate into the ground from GHE-1 showed fluctuations as shown in the left plot of Figure 3 with the change of ambient temperatures. The average heat exchange rate in TRT-1was calculated as 2.44 kW (38.3 W/m), indicating the heat loss in the surface piping was averaged as around 20%. Because there is no heat loss in GHE-1 with the use of U-tube, the average heat exchange rate in TRT-2 was calculated as 1.53 kW (38.8 W/m), which is close to the rated output of the electrical heater (1.5 kW) and the unit heat exchange rate in TRT-1 (38.3 W/m). The heat medium temperature during TRT-2 showed a constant increase for the entire heating period. The average heat medium temperatures after 2 days' heating were 34.2 ºC and 37.0 ºC in TRT-1 and TRT-2, respectively, which indicates the superior heat exchange capacity of the one-way GHE. This observation will be confirmed through a numerical simulation in the next section. Using the convectional interpretation, TRT-2 gave a λ value of 0.90 W/m/K, which is a common value of clay or silt deposit. 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.



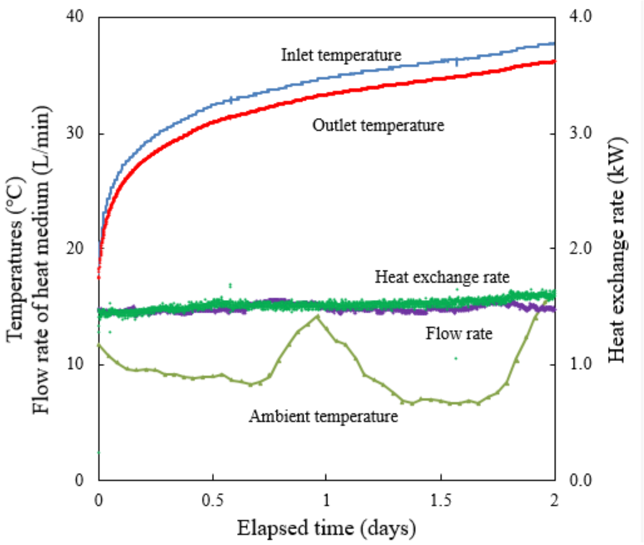


Figure 3: Measured data in TRT-1 (left) and TRT-2 (right)

4. NUMERICAL SIMULATION AND CASE STUDIES

In this section, numerical simulation models of the HGHEs are developed and validated through history matching calculations using the TRT results. Prediction runs are then performed to compare the efficiency of the GHE-1 and GHE-2 and to optimize the design of the HGHEs 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 this function was not available in the recent version of FEFLOW (Diersch, 2014), which is commonly used for the modeling of GHEs, the software was modified by the developer of the software (DHI A/S) on our request. Using the modified software, 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 GHE-1 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. GHE-2 was also modeled using the same procedures.

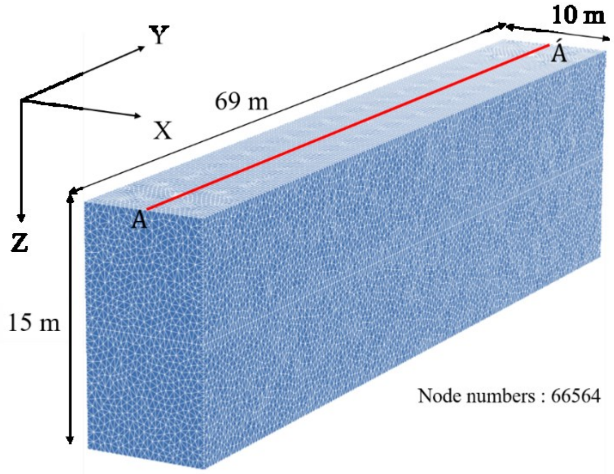


Figure 4: 3D view of the simulation grid of the HGHE model

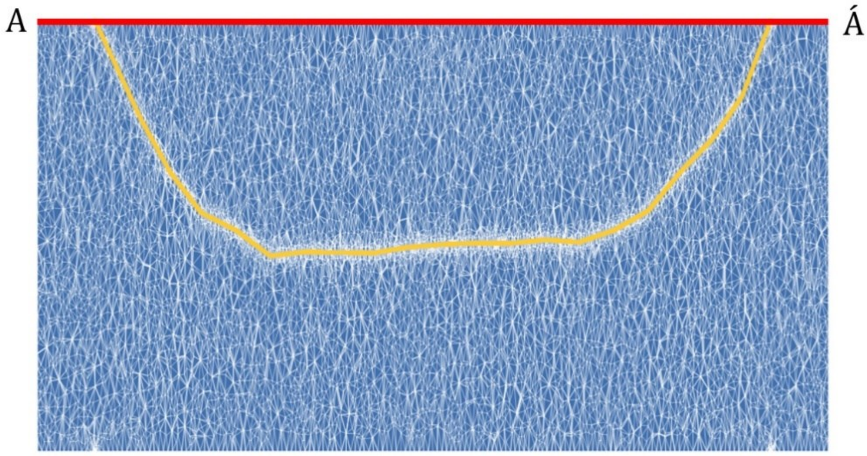


Figure 5: Cross sectional view of the Simulation grid of the HGHE model

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 0.90 W/m/K based on the TRT results. The volumetric heat capacity of the soil was determined to be 2.5×10^6 J/m^3/K, which is a typical value of clay formation. The ID/OD and the λ of the heat exchange pipes are 52/60 mm (GHE-1) and 27/34 mm(GHE-2) 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 ºC 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:

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

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/m²)
ε	: Longwave emissivity (–)
J_{eh}	: Effective emission (W/m²)

The weather data for the model was determined with reference to the published data by the nearby observatory in Saga City. The annual average temperature and annual precipitation were 17.4 ºC, and 1887 mm, respectively, in 2018. The model was run for a period of 3 years before the TRTs started to obtain the initial temperature distribution in the ground.

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. The two figures in Figure 6 show the history matching result of outlet temperature during the TRT-1 and TRT-2. In both TRTs, reasonably good matching results were obtained through the entire period of the TRTs demonstrating the reliability of the numerical model.

Figure 7 shows the temperature distribution along GHE-1 at the end of the 2 days' heating period. This figure shows gradual temperature drop of the heat medium while flowing though the GHE. 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 caused the larger temperature difference between the ground and the heat medium.

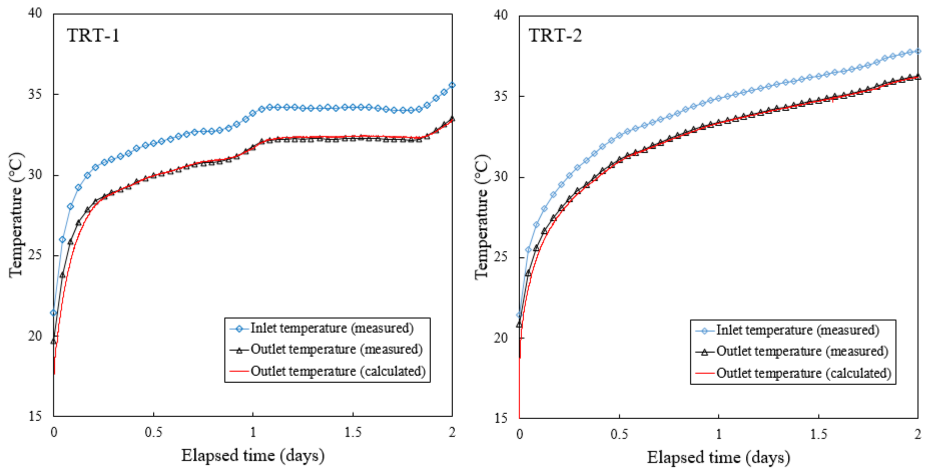


Figure 6: History matching result of outlet temperatures in TRT-1 (left) and TRT-2 (right)

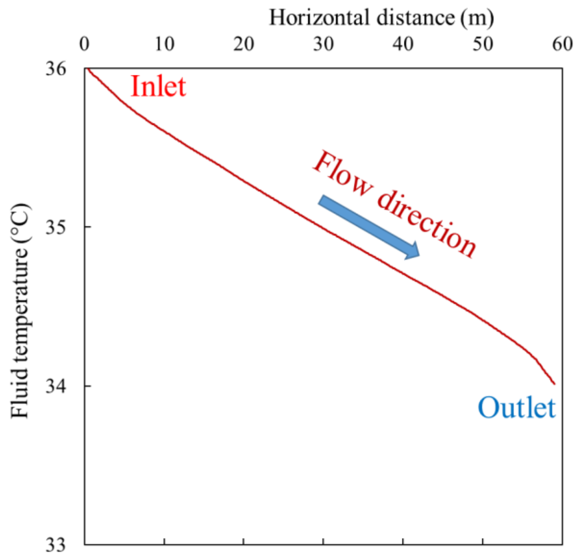


Figure 7: Temperature distribution along GHE-1at the end of TRT-1

4.3 Comparison between one-way GHE (GHE-1) and U-tube GHE (GHE-2)

After validating the numerical model, we compared the heat exchange performance between the one-way GHE (GHE-1) and the U-tube GHE (GHE-2) using simplified numerical models. We assumed a HGHE of 80 m long without curved sections buried at 8 m below the land surface. The initial temperature of the ground was set as 19.5 ºC and the thermal properties of the ground were set same as the values at the field test site. The GHEs were heated by applying a heat load of 40 W/m with a circulation rate of 30 L/min for 90 days.

The increase of ground temperature during the simulation period is shown in Figure 8. At the end of the simulation period, the average temperature of heat medium of GHE-1 and GHE-2 were 8.3 ºC and 8.8 ºC. This result indicates that the one-way GHE is more efficient than U-tube GHE though the cost of drilling is in a similar range. The main reasons of the difference would come from the larger surface area of GHE-1 and the absence of thermal interference between the downflow and the upflow pipes in GHE-1.

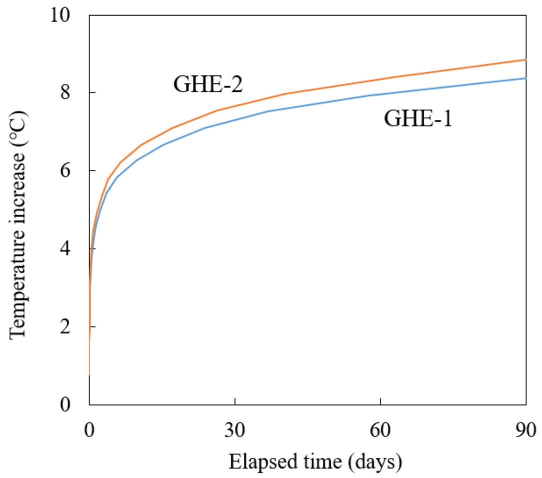


Figure 8: Simulated temperature increase in GHE-1 and GHE-2

4.4 Case studies

Using the numerical model, we carried out three kinds of sensitivity studies for the optimum design of the one-way GHE (GHE-1) which was determined as the superior design to U-tubes. In the sensitivity studies, we change the pipe diameters, horizontal distance of the GHE, and installation depth of the GHE from the ground surface and see their effects. In the simulations, the ground properties and temperatures at the test site and the SAT in Saga City were applied. The following shows the conditions and results of the sensitivity studies.

4.4.1 Effect of pipe diameters

The simulation runs were carried out using the well path of GHE-1 as well as an inlet temperature and a flow rate of 35 ºC 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 9 shows the average heat exchange rate during a 24 hour 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 27mm/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 diameters. 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 GHEs, though the cost of the pipe and the safe inserting operation needs to be considered in the actual design of the GHEs.

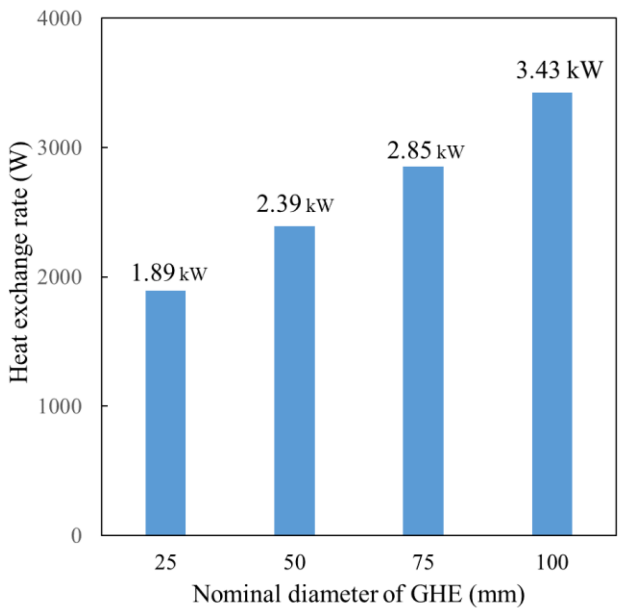


Figure 9: Relationship between pipe diameter and heat exchange rate

4.4.2 Effect of horizontal length

Next, the length of the horizontal section of the GHE was examined using the model assuming an inlet temperature and a flow rate of 35 ºC and 30 L/min, respectively. The configurations of the curved section at the inlet and outlet of the GHE 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 10 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 becomes longer. 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.

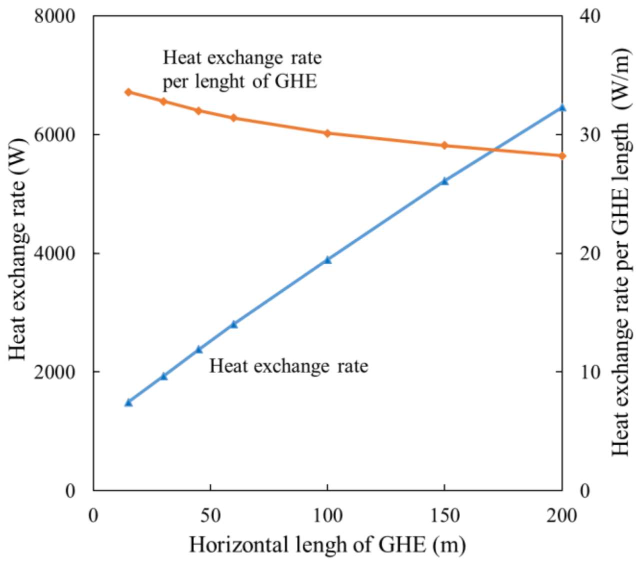


Figure 10: Relationship between GHE length and heat exchange rate

4.4.3 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 cost of the excavation. In such depth ranges, the deeper installation of the pipe is generally 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 selection enabled by HDD.

To avoid the influence of the different length of the curved section from GL to the horizontal section, only the horizontal part of the GHE 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 time of 24 hours/day. The two plots in Figure 11 show the average heat medium temperatures during heating and cooling operation using different installation depths, 5 m, 10, m, and 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 ºC, the difference does not significantly affect 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. A similar trend was observed in the cooling operation from June to September as shown in the right plot of Figure 11. The average temperature of the heat medium was lower when the HGHE was installed at 5 m than other two cases, especially in the hottest months, July and August, which leads to energy savings in the cooling operations.

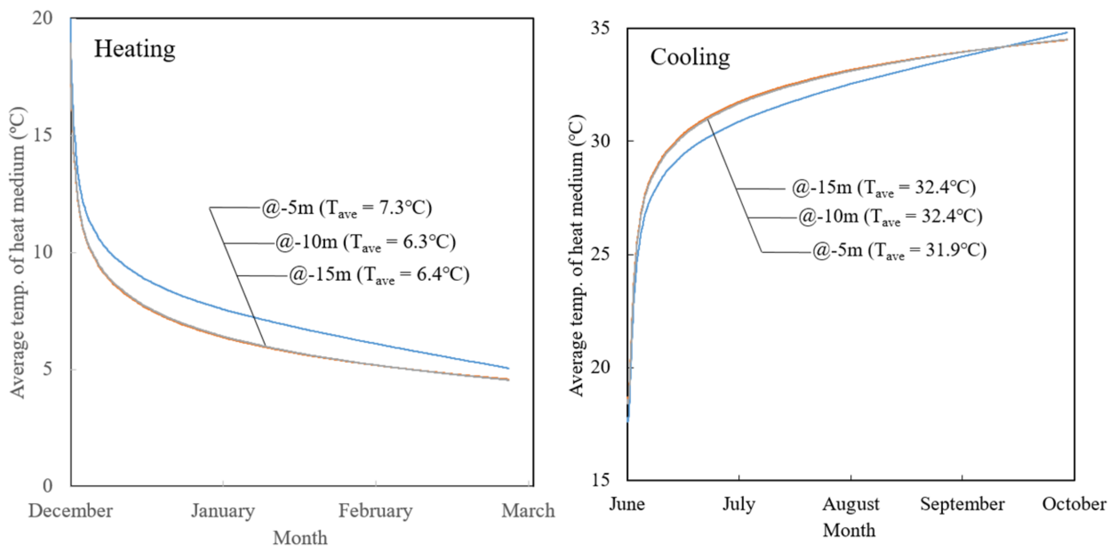


Figure 11: Relationship between GHE depth and heat exchange rate

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 12. 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 ºC. 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 the thermal attenuation.

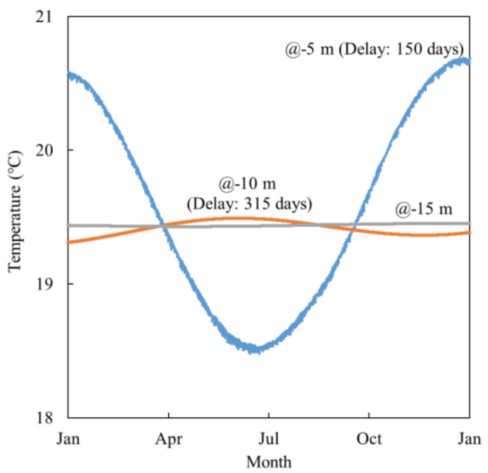


Figure 12: Temperature distribution in the ground at -5 m, -10 m and -15 m

The one-way HGHE used in GHE-1 requires two surface locations, which could restrict the application of the HGHE. This restriction, however, could be overcome by drilling the HGHE using a circle-shape well path to keep the inlet and outlet of the HGHE close to each other thanks to the flexibility of the HDD technology. 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.

5. CONCLUSIONS

In this research, field tests and numerical simulations were performed for the practical application of HDD technology on the installation of horizontal GHEs in the GSHP systems. Two horizontal holes were drilled using HDD technology in Saga City, western Japan, as experimental GHEs. GHE-1 was completed with one-way polyethylene pipe, while GHE-2 used polyethylene U-tube. Thermal response tests (TRTs) were first performed by applying a constant heat load to the ground to investigate the heat exchange capacity of the GHEs.

Numerical simulation models were then developed using a commercial software based on the GHE configurations 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 TRTs. The prediction runs using the validated model showed the superior performance of GHE-1 to that of GHE-2 due to the larger surface area of the pipe and the absence of thermal interference between the downflow and upflow pipes. The sensitivity studies using the model showed that the unit heat exchange rates increased with the increased diameter of GHEs, 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.

ACKNOWLEDGEMENTS

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REFERENCES

Barla, M., Di Donna, A., Perino, A.: Application of energy tunnels to an urban environment, *Geothermics*, **61**, (2016) 104-113.

Bourne-Webb, P., Freitas, T., Gonçalves, R.: Thermal and mechanical aspects of the response of embedded retaining walls used as shallow geothermal heat exchangers, *Energy and Buildings*, **125**, (2016) 130-141.

Diersch, H.J.G.: FEFLOW Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media, Springer, (2014), 996 p.

Frodl, S., Franzius, J., Bartl, T.: Design and construction of the tunnel geothermal system in Jenbach, *Geomechanics and Tunnelling*, **3**, (2010), 658-668.

Fujii, H., Nishi, K., Komaniwa, Y., Chou, N.: Numerical modeling of slinky-coil horizontal ground heat exchangers, *Geothermics* **41**, (2012), 55–62.

Fujii, H., Yamasaki, S., Maehara, T., Ishikami, T., Chou, N.: Numerical simulation and sensitivity study of double-layer Slinky-coil horizontal ground heat exchangers, *Geothermics*, **47**, (2013), 61-68.

Hamada, Y., Nakamura, M., et al.: Study on improved heat exchanger by using no-dig method for space heating and cooling, *Transactions of the Society of Heating, Air-conditioning and Sanitary Engineers of Japan*, **86**, (2002), 59-66. (In Japanese with English abstract)

Nicholson, D.P., Chen, Q., Pillai, A., Chendorain, M.: Development in the thermal pile and thermal tunnel linings for city scale GSHP systems, *Proceedings*, 38th Stanford Geothermal Workshop, Stanford University, Stanford, CA (2013).