Thermal response tests of horizontal ground heat exchangers under tidal influences

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Abstract

In GSHP systems, Horizontal Ground Heat Exchangers (HGHEs) are widely used in areas with abundant land availability. However, the heat exchange rate of the HGHEs is generally lower than that of vertical GHEs because the shallow ground lacks groundwater flow and is subject to seasonal temperature changes. In this research, we carried out field tests to investigate the performance of deep (> 5 m) HGHEs drilled using Horizontal Directional Drilling (HDD) technology. The advection effect of groundwater flow caused by tidal fluctuations was also considered for further improvement of efficiency. We first drilled vertical GHEs of 20 m deep at 3 locations near the coastline in Saga Prefecture, western Japan, where tide-induced groundwater movement is expected and performed Thermal Response Tests (TRTs) at these GHEs. The measured ground temperatures showed sinusoidal increases at 2 locations. Based on the measured temperatures, the vertical distributions of apparent thermal conductivity (λ) were calculated in all sites and a site in Karatsu City was selected for further investigation due to high λ and tidal influences. In this site, we drilled 4 HGHEs of 101 m long using HDD method. The HGHEs were drilled along 2 lines parallel to the coastline at 10 m and 15 m deep and were completed with double U-tube HDPE pipes. The TRTs consisted of a heating of 3 days with a heating load of 20 W/m. The interpretation of TRTs showed that the λ values ranged from 1.55 to 1.80 W/m/K based on the temperature behavior between 1 day and 3 days. Then, considering the chance of near-well formation damage while drilling, the late-time λ values were also calculated using temperature between 2 days and 3 days. The interpreted λ showed an increase of over 30%, suggesting the importance of performing longer TRTs in GHEs with possible formation damages.

Keywords: Ground souece heat pump; thermal response test; tidal effect

1. Introduction

Horizontal Ground Heat Exchangers (HGHEs) are widely used for collecting heat from the shallow ground. HGHEs are a cost-effective choice for Ground Source Heat Pump (GSHP) systems since they can be installed using common excavating machines of low operation cost. The installation number of HGHEs, however, is much less than that of vertical GHEs except the northern American countries [1] since the HGHE requires large land space for installation. Another drawback of HGHEs is the low heat exchange rate per HGHE length in comparison with vertical GHEs. Since HGHEs are commonly installed 1 m – 2 m deep due to the increasing excavation cost with depth, the performance of HGHEs is affected by the seasonal change of ground temperatures, which reduces the energy efficiency of GSHP systems. The low thermal conductivity (λ) of the unsaturated shallow ground also leads to low heat transfer rates in the ground. Hence, the installation of HGHEs at larger depth, which minimizes the influence of ambient temperatures and increases λ of the ground, is important to enhance the capacity of HGHEs. In this research, we apply the Horizontal Directional Drilling (HDD) technology, which is commonly used for the installation of infrastructure pipes and cables, for setting HGHEs at larger depth. Then we demonstrate the superiority of the deep HGHEs to shallow HGHEs through thermal response tests (TRTs).

The existence of groundwater flow is recognized to improve the heat exchange capacity of GHEs due to the thermal advection effects ([2-3]). Since the existence of natural groundwater flow strongly depends on the permeability and the hydraulic gradient of the ground, the distribution of fast groundwater flow is uneven and difficult to estimate without drilling. To increase the chance of encountering groundwater flow, in this study, we focus on the groundwater flow in the shallow ground near the coastlines, which is caused by tidal fluctuations.

Several studies have investigated HDD-based GHEs as an alternative to conventional vertical systems. Existing research has primarily focused on thermal performance, installation geometry such as borehole length and depth, etc. These studies demonstrate the feasibility and potential advantages of HDD GHEs; however, they do not consider transient groundwater dynamics driven by external forcing mechanisms such as tides. One of the earliest experimental studies, conducted by Hamada et al. [4], carried out an experimental analysis of an HDD-based HGHE for a space heating and cooling system on the Hokkaido University campus in northern Japan. Their findings discovered a potential reduction in primary energy consumption for installation by 78 % compared to vertical GHE. Lein et al. [5] conducted an experiment in Saga City, Japan, to address the impact of rainwater on a double-layer HDD-based HGHE. They developed a numerical model in FEFLOW software that simulate the injection of rainwater into the annular space between the pipe and soil. The results showed that the impermeable top layer allowed water to flow along the pipe path with an injection rate of 1 L/min and the temperature could be reduced by 38 % compared to the case of no injection. Bina et al. [6] evaluated the techno-economic aspect of HDD technology in a pilot system installed in Saga City, western Japan. The economic calculation showed that the HDD system could save 71–78 % in GSHP system costs. Tsuya et al. [7] carried out a field test and numerical simulations to investigate the heat exchange capacity of an HDD-based GHE. They found out that the conventional graphical interpretation of TRTs is applicable to the interpretation of TRTs and estimate the λ of the ground.

To date, only one study has investigated the influence of tidal effects on GHE performance, and this work was limited to vertical GHEs rather than horizontal GHEs. In the study by Moreira et al. [8], the effect of tidal fluctuations though a TRT of vertical GHE was confirmed in Ecuador. Consequently, the effects of tidal groundwater fluctuations on HDD-based GHEs remain essentially unexplored. The only available investigation addressing tidal influences on HDD GHEs is the authors' previous work, which provided an initial assessment but was limited in scope. Fujii et al. [9] carried out a heating cable-based TRT in Okinawa, southern Japan and found that the apparent thermal conductivity values at each depth are strongly affected by tidal fluctuations. They also developed a numerical model considering tidal effect and carried out sensitivity studies to predict the heat exchange capacity of HGHEs drilled in various depths. However, no trials have been made to evaluate the long-term performance of HGHEs, drilled below groundwater levels, under the influence of tidal fluctuations. Therefore, a comprehensive understanding of tidal impacts on HDD-based HGHE performance is therefore still lacking, motivating the present study.

In this research, we carry out series of field tests and analyze the results as shown in Figure 1. In Step 1, we conduct heating cable-based TRTs at 3 locations near the coastline in Saga Prefecture, western Japan. In Step 2, we select one location where the effect of groundwater flow is most clearly observed based on the TRT results at each location. Step 3 is spent on the drilling of four horizontal GHEs of about 100m in length using the HDD technology. The HGHEs are drilled along 2 lines parallel to the coastline and double U-tube of HDPE are inserted into all holes. At the same location, two vertical groundwater observation wells are also drilled to investigate the relationship between the fluctuation of the tide level and the groundwater levels. In the last step, Step 4, we perform conventional TRTs in all HGHEs to evaluate the heat exchange performance of each HGHE and investigate the relationship between heat exchange capacity and groundwater movement due to tidal fluctuation.

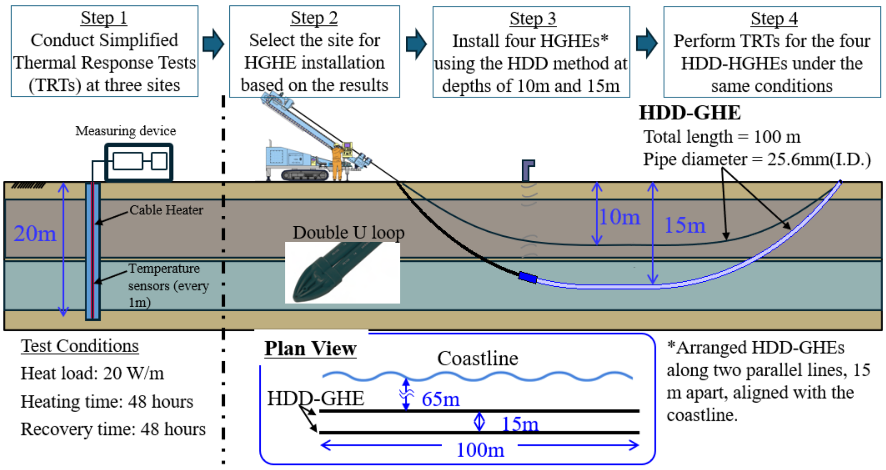

Figure 1. Flow of current study.

2. Site Selection of HGHEs based on TRTs

The field tests of this research were carried out in Saga Prefecture located on Kyushu Island, western Japan. Site A is located on the coastline of Ariake Bay, while Sites B and C are located near the Sea of Japan as shown in Figure 2. The distance from the coastline to the test wells ranged 60 m - 70 m. The depth and diameter of the test wells were 20 m and 86 mm, respectively. Steel rods of 27.5 mm ID (Inner Diameter) and 40.5 mm OD (Outer Diameter) were inserted to the bottom of each hole and the space between the formation and rod was filled with silica sand of high λ. To promote heat transfer, the bottom of the rod was closed by caps and water was filled up to the surface.

We carried out heating cable-based TRTs in each well in January and February 2025. The TRTs consisted of a heating period of 2 days followed by a recovery observation period of 2 days. The heating power was set as 20 W/m and the ground temperatures were measured using the DTS device every 1 minute with an interval of 0.5 meters. The measured temperatures during the TRT at Sites A through C are presented in Figure 3. At Sites A and C, the effects of tidal fluctuations are clearly observed especially in the heating periods. In these trends, temperatures dropped steeply when the tide rose to maximum, while they showed an increase as the tidal level dropped. The intervals of this trend were located in the highly permeable zones and no significant changes were observed in less permeable depths at Sites A and C. The increase of the temperature will be explained by the downward movement of heated water from upper zones as the tidal drop leads to the flow of groundwater to the ocean. During the heating periods, the temperature of the upper and less permeable zones is generally higher than that of the permeable zones due to the lack of groundwater movement and lower λ of the deposit. At Site B, on the other hand, the effects of the tidal fluctuations were not observed because this site is located in a large-scale sea port and the concrete embankment could have minimized the tidal influence on the groundwater flow near the coastline.

To select the site for further analysis using HGHEs, we aimed to find a depth where tidal fluctuations are clearly observed, and the temperature increase from the initial temperature is small. Hence, we selected the formation around 15 m of Site C because the temperatures during heating period stabilized at 22 ˚C, which suggests an increase of only by 3 ˚C from the initial temperature, while any depth at Site A showed larger temperature increase of over 5 ˚C.

Figure 2. Locations of three TRT sites (A, B and C) in Saga Prefecture, western Japan.

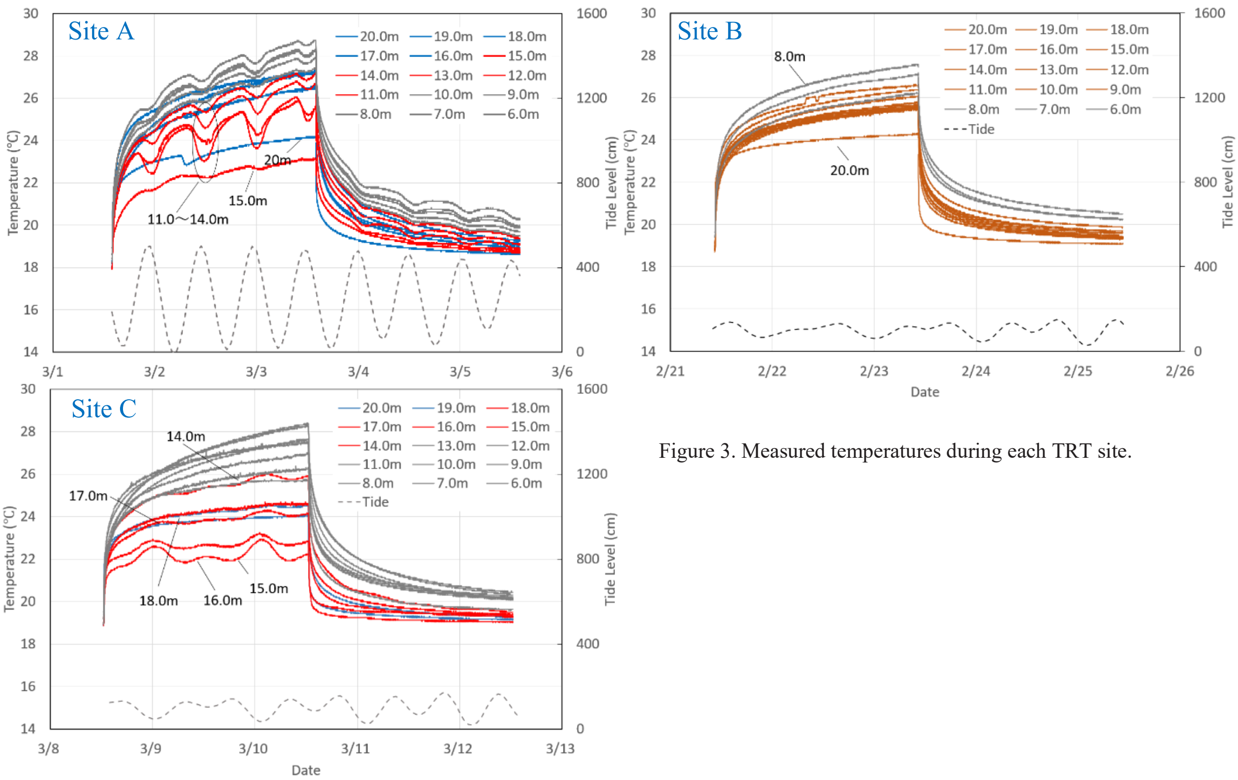

Figure 3. Measured temperatures during each TRT site.

Figure 4 shows the profiles of λ during the heating (left) and recovery periods (center) based on the conventional graphical interpretation method using the infinite line-source model (ILS) [10] and the geological column at the well location (right). The λ values were obtained by applying the ILS model to individual temperature curves in Figure 3 replotted on a semi-log graph with logarithmic time on the horizontal axis. The groundwater level was measured as 3.9 m below the ground level. Heating and recovery data showed good agreement. From the ground level to the groundwater level, low λ was obtained since the ground is not fully saturated by groundwater. High λ was observed around 5 m because the coarse sand would allow the movement of groundwater. Between 6 m to 14 m, the effect of groundwater flow is not observed due to the low permeability. Between 14 m and 16 m, we could not determine λ because the slopes of the temperature increase were nearly flat. This indicates that an active groundwater movement is generated through this interval due to tidal fluctuations. The permeable geology in this interval also justified the results.

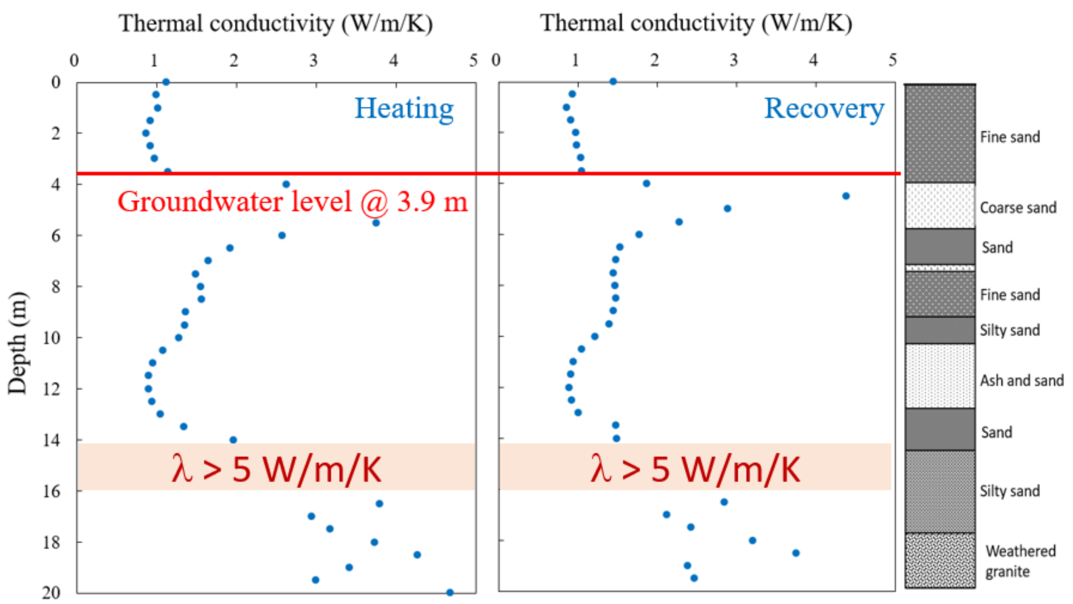

Figure 4. Thermal conductivity profiles (heating left, recovery right) and geological column at Sites C.

3. Information on TRTs of HDD-based HGHEs

In Step 3 of this research, we drilled two shallow vertical holes of 20 m deep (Wells P1 and P2) to measure the groundwater levels at Site C. The right figure of Figure 5 shows the well placement in Site C including the wells used for the TRT discussed in the previous section. The distance between the coastline and TRT well is 65 m and the distance between the coastline and Wells P1 and P2 are 65 m and 80 m, respectively, though the distance constantly changes due to tidal fluctuations. The left figure of Figure 5 shows the measured groundwater levels at Wells P1 and P2 and the tide levels measured at the local observatory located 7 km away from Site C. Since the observatory and Site C are located along the same coastline in the same bay, the tide levels measured at the observatory are expected to match the tide levels at the coastline of Site C.

In the left figure of Figure 5, the tide level and the groundwater levels are corrected to have the same average of 0 m (mean sea level). In this figure, the tide level and groundwater levels show very clear correlation, indicating that the tidal fluctuation causes the movement of groundwater flow near the coastline. The figure shows that there are short delays of approximately 0.5 hours between the tide level and the groundwater levels at P1 and P2. The delays are relatively small due to the good permeability of the shallow ground at Site C. The amplitudes of the tidal fluctuation and groundwater levels in Wells P1 and P2 were 1.00 m, 0.35 m and 0.30 m, respectively, which indicates that the amplitude decreased as the distance from the coastline increases due to the decay of tidal effect.

Next, we drilled four HGHEs in Site C as shown in the bottom figure of Figure 1. Two HGHE are drilled along 2 lines, which are parallel to the coastline with a distance of 65 m and 80 m from the coastline, respectively. The depths of the horizontal sections of holes are set as 10 m and 15 m. The HGHEs at 15 m are expected to take advantage of the groundwater flow, while the HGHEs at 10 m are drilled as a comparison with 15 m installation. The selection of 2 lines of different distance from the coastline is determined to investigate the effect of decay of the tidal effect. The two HGHEs near the sea were named S-10 and S-15, where S indicates sea and numbers express depth. Similarly, the two HGHEs on the mountain (M) side were named as M-10 and M-15. The HGHEs were drilled in June 2025 using the HDD method. The total drilling length of each hole ranged 109 m – 111 m and the hole diameter was 165 mm after reaming operations. In all holes, double U-tube heat changers of HDPE pipes (ID/OD: 26 mm/32 mm) were inserted to 101 m drilling depth. The drilling operations used bentonite-based drilling mud to avoid the collapse of the wall of horizontal holes. The drilling mud was partially circulated out to the surface, but most of the mud remained in the hole or invaded into the formation, which could have reduced the permeability of the formation near the HGHEs (formation damage). The space between the U-tube and the borehole wall was not grouted but the space is considered to be filled naturally by the deformation of the soil around the hole. The drilling periods gradually became shorter as more know-hows for the drilling deep HGHEs were accumulated, finally taking only 6 hours including drilling and inserting U-tubes. This demonstrates the fast drilling and hence the high economy of the installation of HGHEs using HDD technology.

Figure 6 shows the well paths of S-10 and S-15. The planned depths of the horizontal sections of S-10 and S-15 were 10 m and 15 m, respectively, and actual depths were close to the scheduled ones, though the well path control of the deeper hole (S-15) was more challenging. Similar well path was used for M-10 and M-15.

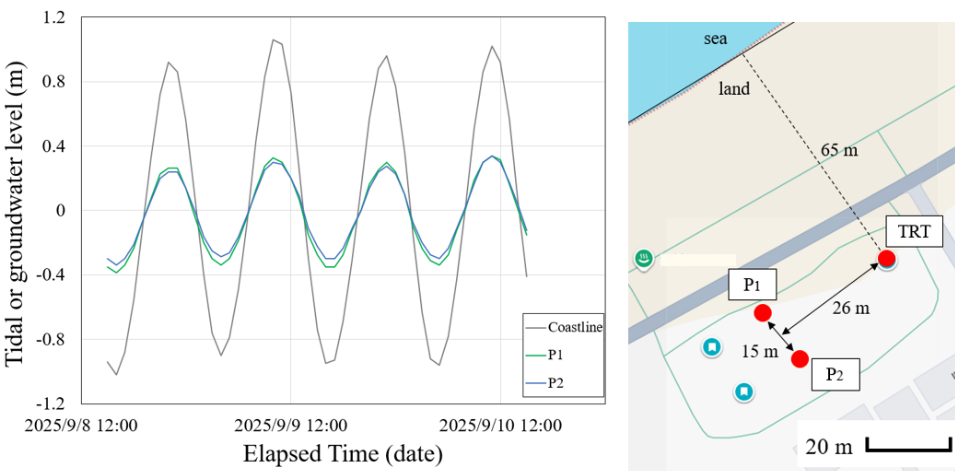

Figure 5. Measured groundwater levels at Wells P1 and P2 and tidal fluctuation measured by of Japan Meteorological Agency at Karatsu observatory 7 km from Site C (Left) and the schematic of Site C.

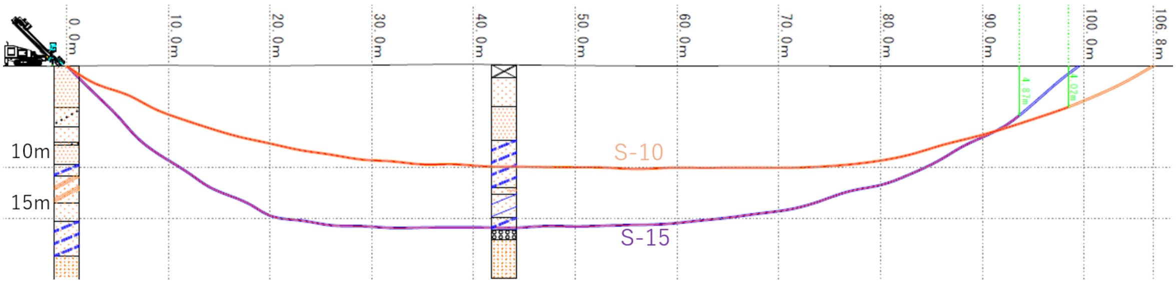

Figure 6. Well paths of S-10 and S-15.

In the 4 HGHEs, we carried out conventional TRTs using the TRT equipment (Figure 7) manufactured in Akita University. The equipment automatically controls the output power at any specified values up to 10 kW using Programmable Logic Controller (PLC), which enables the supply of stable heat load, even when the voltage of power supply is unstable. The TRT data can be monitored remotely through Wi-Fi, and the operation can be switched on and off online.

All TRTs consisted of a heating period of 3 days by applying a heating load of 20 W/m and a water circulation rate of 20 L/min. In the TRTs of S-15 and M-15, the temperature recovery after the circulation period was measured along the HGHE using DTS device for 5 days. The TRTs were carried out consecutively in the order of S-15, M-10, S-10, M-15 to avoid the thermal interference between HGHEs.

Figure 7. TRT equipment used in all TRTs.

4. Results and Discussion

4.1. TRT Results and Interpretations

Figure 8 presents the measured inlet and outlet temperatures of the HGHE, the circulating rates and heat loads in all TRTs. All figures show the TRTs were carried out in good conditions, and the heat loads are well controlled at 2kW in all TRTs. The increasing trend of the inlet/outlet temperatures shows a weak fluctuation, suggesting the influence of tidal fluctuations. In all TRTs, the temperatures nearly stabilized after 2 days of heating. This would be due to the advection of groundwater induced by the tidal fluctuations.

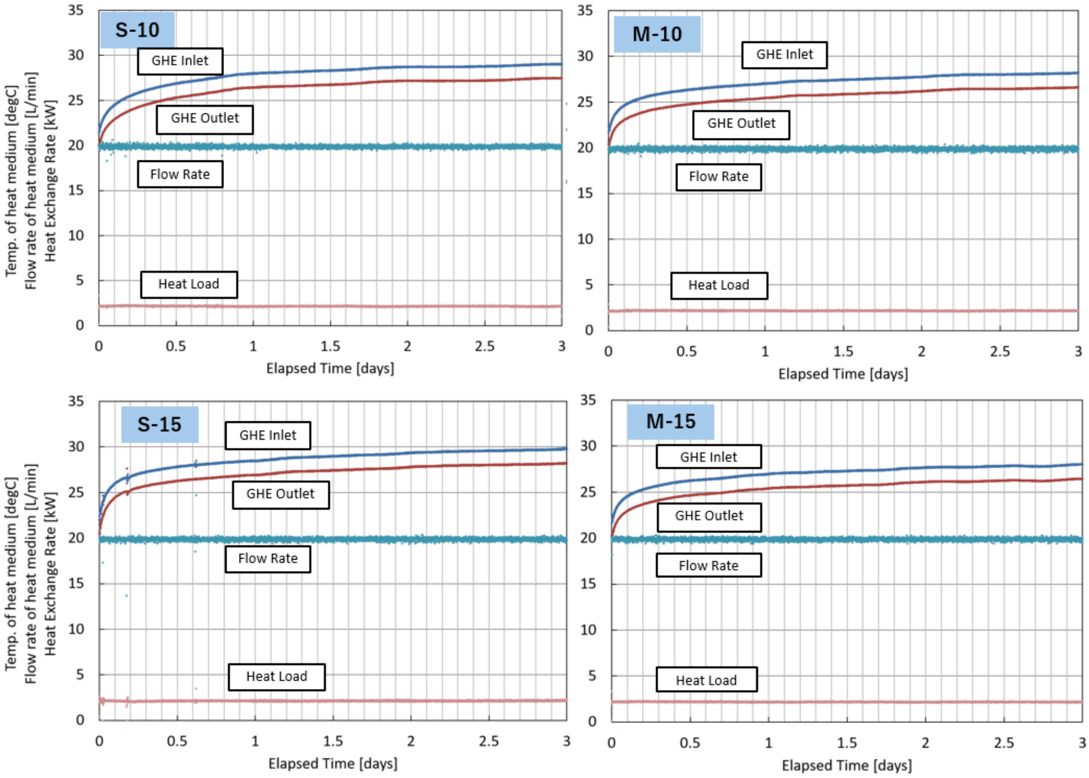

Figure 8. Measured inlet/outlet temperatures, flow rates and heat loads in all TRTs.

Figure 9 shows the results of graphical interpretation using semi-log plots of all TRTs. The straight lines for determining the λ were drawn between 1 day and 3 days to eliminate the influence of thermal properties in and near the HGHE. The λ values ranged from 1.55 W/m/K to 1.88 W/m/K, which are relatively high values in a deposit of sand and silt. However, the estimated λ in S-15 and M-15 were much lower than the λ at 15 m deep obtained in the TRT at the vertical hole (> 5/m/K). The relationship between HGHE locations and the interpreted λ values is shown in a schematic in Figure 10. It is evident that the distribution of λ does not agree with the prior information obtained in the TRT at the vertical hole because S-10, which was drilled in a layer of low permeability, showed the largest λ, while S-15 had the lowest λ, though the HGHE was expected to show the largest λ considering the proximity to sea and the high permeability of the sand layer. These results will come from the discontinuity of the shallow deposits and the heterogeneity of the formation near the coastline. For the optimum placement of HGHEs, therefore, further field tests and investigations will be necessary.

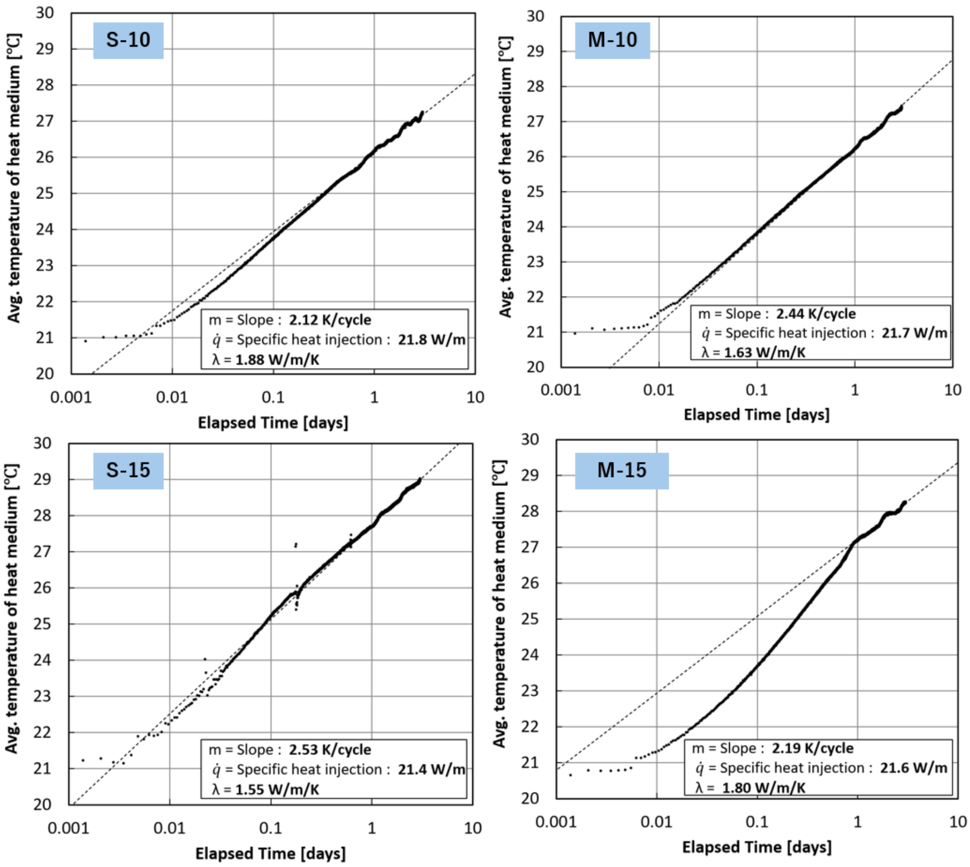

Figure 9. Results of graphical interpretation of all TRTs based on data between 1 day and 3 days.

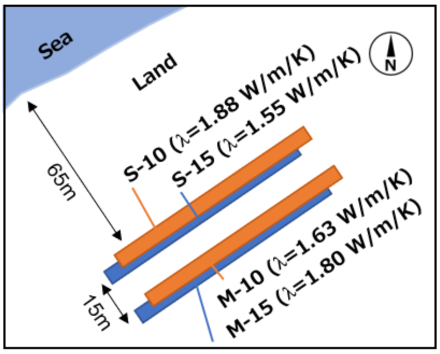

Figure 10. Distribution of TRT determined λ at Site C based on Interpretation Results in Figure 9.

4.2. Interpretation Considering Formation Damages Occurred in Drilling Operations

During the drilling of HGHEs using the HDD method, bentonite-based drilling mud was used as the drilling fluid for stabilizing the hole conditions. Most of the drill cuttings and drilling mud are not discharged to the ground surface, but they are pushed to the well wall and part of them percolate into the formation. This results in the reduction of near well permeability, which hinders the groundwater flow near the HGHEs. The volumes of drilling mud used during the drilling operations were 1,800 m^3, 3,450 m^3, 4,950 m^3 and 4,950 m^3 in S-10, S-15, M-10 and M-15, respectively. The chronological order of drilling operations are M-10, M-15, S-15 and S-10, which indicates that the volume of spent mud reduced as the drilling company obtained more experience in drilling deep HGHEs. Since the volume of mud was smallest and the groundwater flow could enhance the heat transfer around the GHE most effectively, S-10 considered to show the highest λ among the 4 HGHEs.

The thermal resistance in the TRT of S-10, S-15, M-1o and M-15 are calculated as 0.16 mK/W, 0.21 mK/W, 0.16 mK/W and 0.20 mK/W, respectively using the ILS model. A weak correlation was observed between the mud volume and the thermal resistance.

As mentioned above, we obtained the slope of straight lines between 1 day and 3 days in semi-log interpretation of TRTs in Figure 9 as customly done in TRT analysis. However, the HDD-based holes are more subject to formation damage due to mud loss, so the physical properties of the undamaged formation would appear later than the conventional TRTs. To clarify this, we changed the section of slope determination to 2 days to 3 days aiming for the expansion of the radius of investigation and applied the graphical interpretation to the same TRT data as shown in Figure 11. Though fluctuations due to tide were observed in all trends, straight lines could be reasonably drawn using the least square method. The interpreted λ values in Figures 9 and 11 are compared in Table 1. In all TRTs, the λ values showed an increase exceeding 30% indicating the appearance of the effect of groundwater movement as the radius of investigation reached deeper. The obtained λ values around HDD-based HGHEs under the influence of tidal fluctuation could be significantly higher than those of conventional HGHEs (commonly, 0.5 W/m/K – 1.0 W/m/K), which suggests the high performance of the HDD-based HGHEs.

Also, the above results suggest the possibility of underestimating the λ values in a short TRT in case the permeability of the formation around the HGHE has been reduced due to the invaded mud and there is fast groundwater flow. For accurate long-term performance prediction of GSHP systems, λ values in the undamaged zone should be determined though longer TRTs.

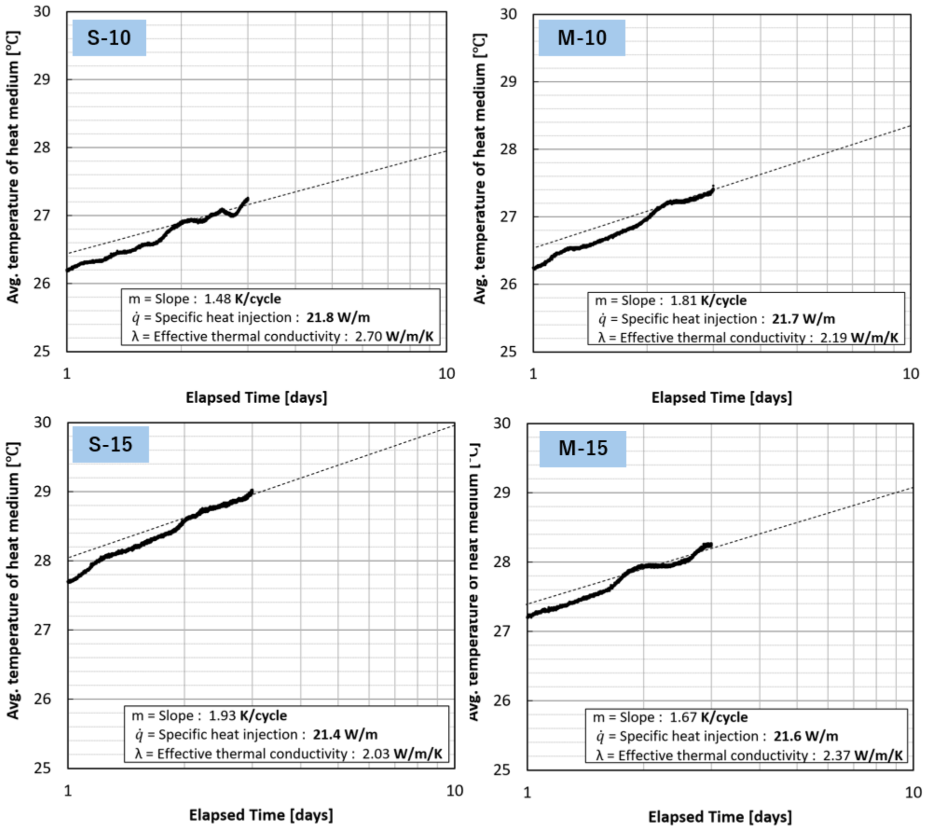

Figure 11. Results of graphical interpretation of all TRTs based on data between 2 day and 3 days.

Table 1. Comparison of TRT Interpretation results using Different Slope Selections

HGHE names	λ based on data between 1 day to 3days (W/m/K)	λ based on data between 2days and 3days (W/m/K)
S-10	1.88	2.70 (+44%)
S-15	1.55	2.03 (+31%)
M-10	1.63	2.19 (+34%)
M-15	1.80	2.37 (+32%)

5. Conclusions

In this research, field tests and their interpretations were carried out to investigate the ability of Horizontal Ground Heat Exchangers (GHEs) drilled using the Horizontal Directional Drilling (HDD) technology. First, vertical holes of 20 m deep were drilled at 3 different locations near the coastline, where a groundwater flow due to tidal fluctuation is expected to exist, in Saga Prefecture, western Japan. Heating cable-based Thermal Response Tests (TRTs) were performed in the 3 GHEs. The TRT results clearly showed a sinusoidal increase of ground temperatures affected by the tidal fluctuations at 2 of the 3 locations.

In the next step, we drilled 4 HGHEs of 101 m long using HDD method at one of the sites with tidal fluctuations of groundwater in the ground. The HGHEs were drilled along 2 lines parallel to the coastline at 10 m and 15 m deep and double U-tube of HDPE pipes were inserted into all holes. The TRT consisted of a heating period of 3 days with a heating load of 20 W/m. The interpretation of TRTs showed that the λ values ranged from 1.55 to 1.80 W/m/K based on the temperature data between 1 day and 3 days. Then, considering the chance of near-well damage while drilling using HDD method, the late-time λ values were also calculated based on the temperature data between 2 days and 3 days. The results showed an increase of over 30%, which shows high heat exchange capacity of HDD-based HGHEs near coastlines, and the importance of extending the TRT duration to eliminate the effect of the formation damage while drilling.

Acknowledgements

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