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Long Term Simulation and Well Path Optimization for Water Injection into Horizontal Directional Drilled Ground Heat Exchangers

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Abstract

Horizontal Ground Heat Exchangers (HGHE) installed by utilizing Horizontal Directional Drilling (HDD) have been proven to be a cost-efficient alternative to install new Ground Heat Exchanger (GHE). A big advantage of this technology is the possibility to install HGHE in places where otherwise space would be a limiting factor.
For this research two HDD drilled boreholes were installed in Saga City, Japan. The boreholes have a diameter of 114,3 mm and a length of 59 m and 56 m as well as a depth of 5 m and 9,5 m respectively. In March 2022 a Thermal Response Test (TRT) was conducted and showed the influence of rain on the system. Bases on this test, the installed HGHE and the geology of the location a numerical model was developed in FEFLOW and validated using the measured temperatures at the turning point and the outlet of the system. The model was then used to conduct long time simulations to show the influence of water injection into the borehole. Furthermore, sensitivity studies have been conducted to investigate the influence of the borehole on the efficiency of water injection and determine optimal well design. The results showed the influence of different well paths, the distance between the boreholes and the long-term effects of water injection on the ground.

1. Introduction

Under the Paris Agreement, Japan and other countries have pledged to reduce their greenhouse emission drastically. In the case of Japan, the goals are to reach net zero by the year 2050. For this reason, developing technologies to reduce carbon emission is one of the main factors for achieving this goal. In Japan about 74.3 millions tons of CO2 emissions were caused by the residential sector for heating cooling and hot water production. (The Government of Japan, 2021)

One way to reduce these emissions are ground source heat pumps (GSHP), which have been used frequently worldwide. These heat pumps are commonly installed either as vertical boreholes or horizontally in trenches. In Japan, GSHP systems face the problem of high drilling costs compared to other regions like Europe or Asia. For this reason, the use of HGHE has been focused by researchers more extensively.
However, these systems usually require large areas of land, which in Japan, are also often not available. (Bina et al., 2020) For this reason several forms of HGHE and reducing their land usage have been investigated. Fujii et al. (2012) and Fujii et al. (2013) investigated the use of slinky coil HGHE and double layered slinky coil HGHE. They utilized FEFLOW to investigate the optimum design and considered the energy balance at the land surface to compare the performance for a HGHE installed in Fukuoka Japan. Shi et al. (2022) focused on several arrangements of HGHE and compared their performance, while also conducting an economic analysis. They found that serial connected HGHE perform the best die to the minimum interference between the tubes.

Over the years many other researches have also improved these kind of systems, with Rashid et al. (2023) giving a good overview about most of the work conducted in recent years.

A third, less commonly used, way to install GSHP systems is by using HDD. This was first introduced by Shibata et al. (2002) and Hamada et al. (2007) who showed the general applicability of this method to install GHEs and developed the first numerical models.

HDD is a technology that allows for the trenchless installation of pipelines and pipes. HDD is known as an extremely flexible application, that allows the installation of all kinds of pipes for water, gas, electricity, or telecommunications. One of its biggest advantages is the possibility to track the exact location of the drill bit and the option to steer, combined with a high rate of penetration. (Gomaa et al., 2020)

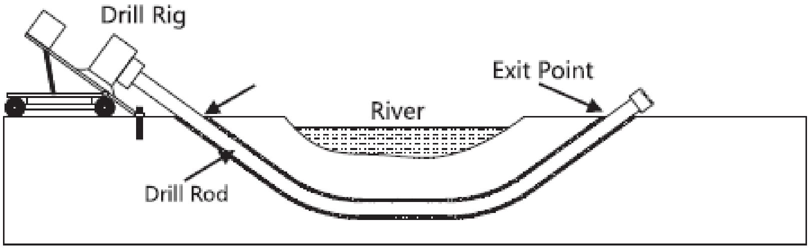
The process of HDD drilling is usually split in three steps highlighted in Figure 1.

(a) Drilling the pilot hole along a predetermined path by a drill rig.

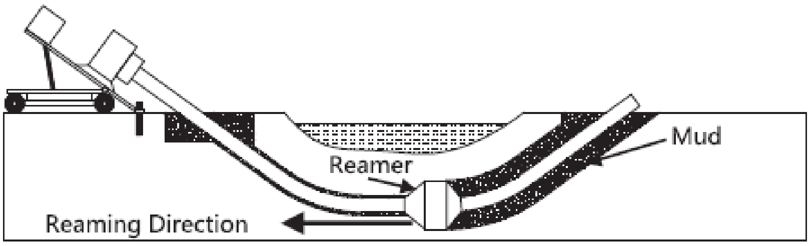
(b) Enlargement of the borehole with a reamer. This process can be repeated several times.

(c) The intended installation is pulled back into the borehole from the exit towards the entry

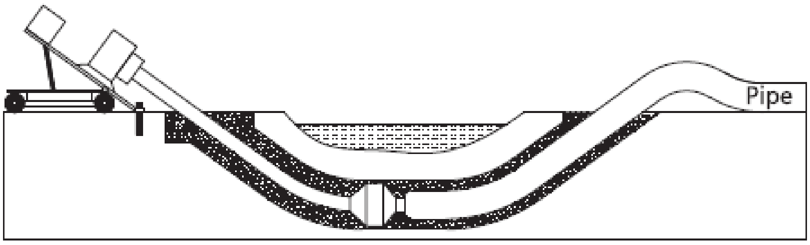
The process furthermore utilizes high performance drilling fluids to transport cuttings and cool down the drill bit. (Yan et al., 2018)



(a) Pilot hole drilling



(b) Reaming process



(c) Pullback process

Fig. 1: Process of HDD (Yan et al., 2018)

Further research on the use of HDD for GSHP has been conducted by Bina et al. (2020). They installed a GHE in Saga, Japan, for research purposes. After conducting a TRT they developed a model in FEFLOW ver. 7.1 and used it to investigate the effect of several parameters on the performance of the system. They showed the effect of the diameter, pipe length, installation depth and groundwater flow. They identified especially the groundwater flow as important parameter, while the length and installation depth were shown to be less important on the performance of the system. They also conducted an economical study and showed that compared to conventional GHEs, HDD could save about 78% of the system costs. On the same system Tsuya et al. (2021) showed the applicability of the common TRT and the conventional graphic interpretations can be used for results.

Lein et al. (2024) introduced a second borehole to the same location and expanded the system. In their results they showed that water injection can be used to improve the performance of this kind of system and investigated several parameters affecting it. They showed that increasing the injection rate benefits the performance to a certain degree after which no more improvement can be observed. The also showed the influence of the injection temperature and the injection point and determined that injection in all boreholes results in the best results. Lastly, they conducted a simulation to show the influence of the permeability on the system showing that impermeable layers with a flow path generate the best results.

This is where this study will continue the work. Based on the same field test, this work will examine several parameters to determine the optimum well path for achieving the optimal performance of the system. For this the effect of the percentage of the well in the impermeable layer, the well angle, the effect of a shallower well and the influence of the vertical distance between wells will be investigated. Furthermore, a long-term simulation was conducted covering a total span of 10 years has been conducted to show the long-term performance of the system.

2. Field Test and Numerical Model

2.1 Field Test

In Saga City, located on the southern Japanese island of Kyushu, a double layered HDD drilled HGHE was installed. The installation of this GHE is under the parking lot of the company Biotex Co. Ltd.. Both boreholes have a diameter of 114.3 mm. The upper borehole has a depth of 5 m while the lower borehole reaches a depth of about 9.5 m. Both boreholes have a total length of about 60 m. The installation path can also be seen in Figure 2. Into both boreholes a high-density polyethylene pipe was inserted, with an outer diameter of 60 mm, an inner diameter of 52 mm and a thermal conductivity of 0,42 W/m/k. The gap between the pipe and borehole was naturally backfilled by the soil, making the use of grouting or a casing not necessary.

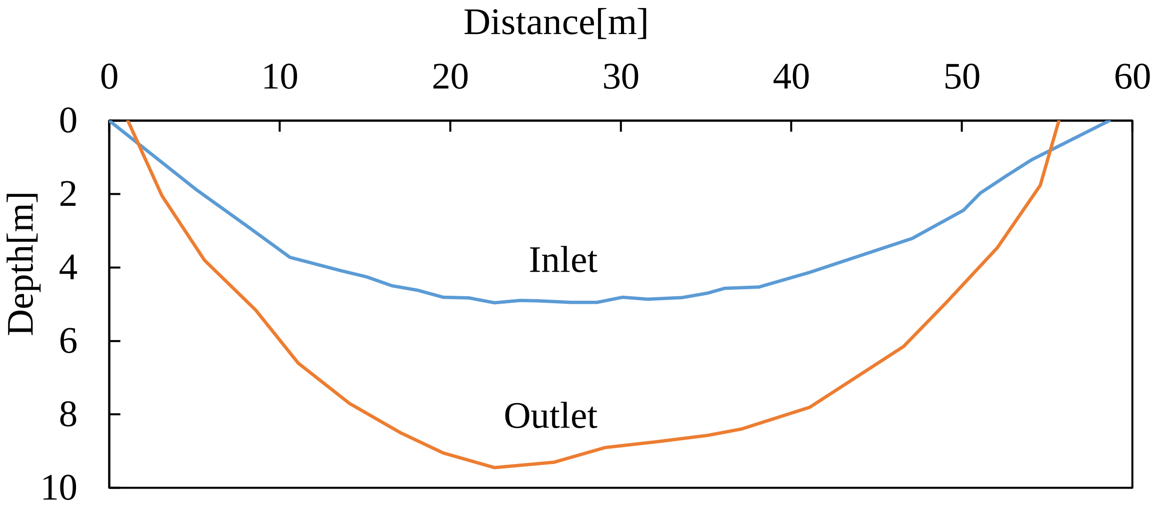


Fig. 2 Well Path of the field test

The geology at the test location consists mainly of clay and sand in the upper 10 m if the underground as showcases in Figure 3. The clay layer at the surface is disrupted at a depth of 3.8 m by a sand layer with a thickness of 20 cm. Afterwards the clay layer continues until a depth of 7 m, where a large sand layer follows. Laboratory tests conducted on soil samples showed a thermal conductivity of 0.951 W/m/K for clay and 1.261 W/m/K for sand in water saturated conditions. The groundwater level was measured at -0.98 m.

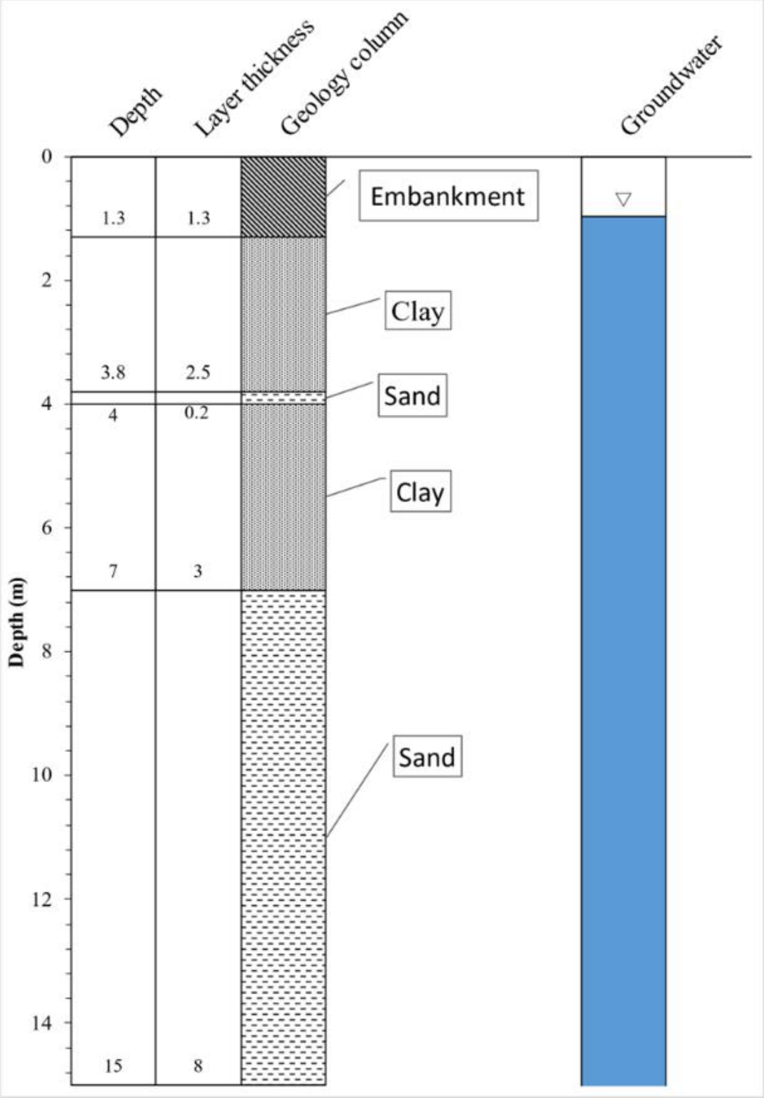


Fig. 3 Geology of the location

The location of the test field is characterized by hot summers with high precipitation and moderate cold winter with low precipitation, typical for the island of Kyushu. In the Köppen climate classification this area is described as temperate climate zone with no dry season and hot and humid summers (Cfa). (Kottek et al., 2006)

From March 24th to March 26th, a two-day long TRT was conducted. During this test a constant heat load of 5 kW and a flowrate of 20 L/min was applied over the course of the test and the temperatures were measured at the inlet, the turning-point, and the outlet. The data collected can be seen in Figure 4. From the measured data the heat exchange rate was calculated to be 5.21 kW on average. During the second night of the test rain started to fall, which along with the ambient temperature was recorded at the local weather station. The rain recorded led to a decrease in the measured temperatures in all three points observed. This strong influence can be explained by the not completed completion of the well at the time of the TRT.

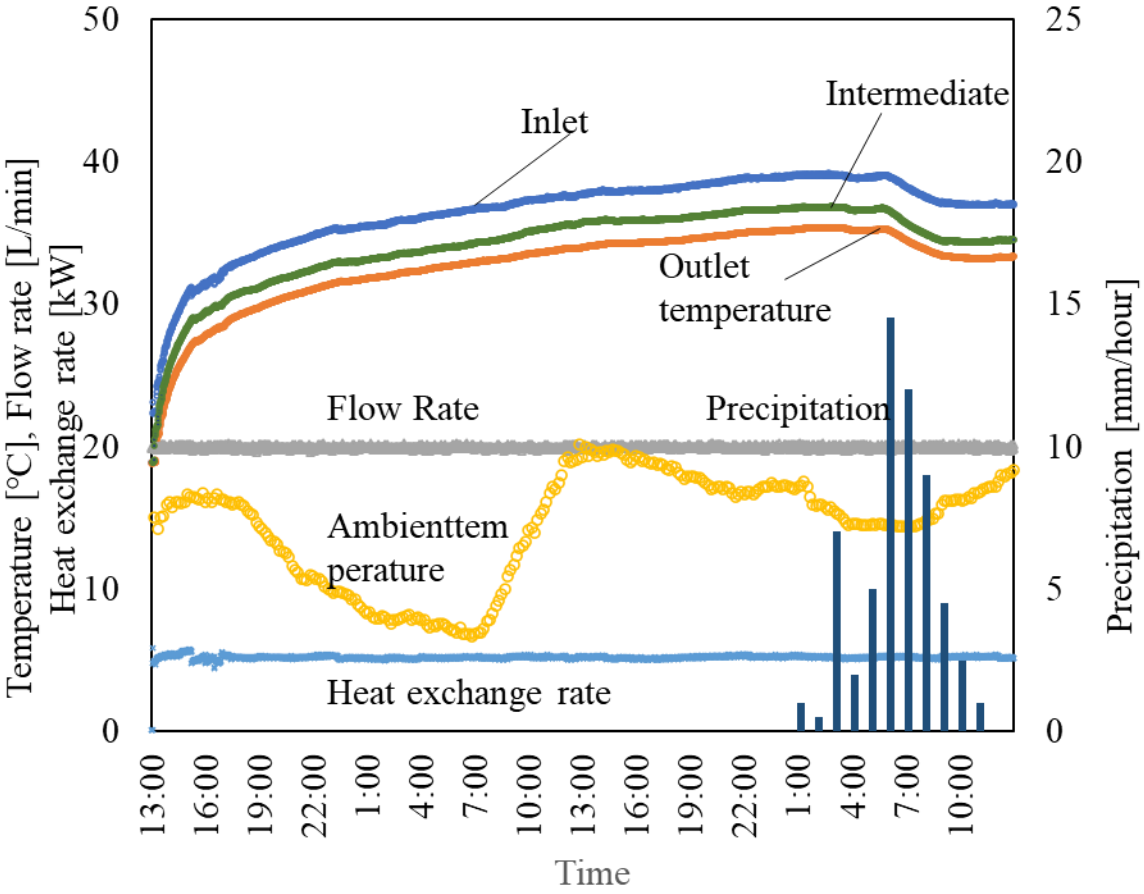


Fig. 4 Results of the TRT

2.2 Numerical Model

Based on the location in Saga and the field test conducted a numerical model was created in the software FEFLOW ver. 8.1. The model was created using the map import function of FEFLOW. This was utilized by first drawing the outline of the well in AutoCAD and afterwards importing this file into FEFLOW. To prevent the influence of boundary effects, the model was set up in a way that would allow at least 5 m of blank mesh around the HGHE. The total element number of the model counts as 162,252 elements. For the model to work the gravitational settings in FEFLOW were changed to the negative y-axis. The outline of the model can be seen in Figure 5.

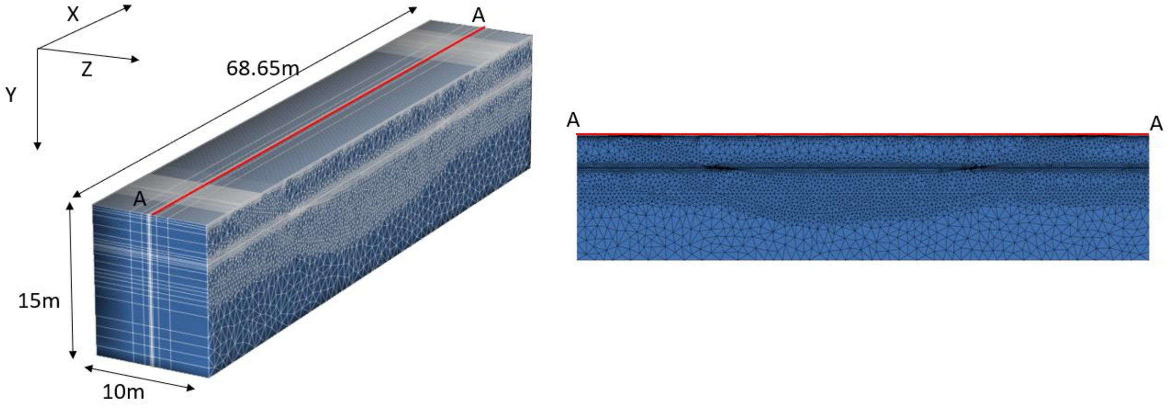


Fig. 5 Outline of the model created in FEFLOW ver. 8.1

The initial underground temperature was set by running a 2.5-year long simulation utilizing the sol-air temperature (SAT). Based on the results of this simulation Equation 1 was created to import the temperature into the model.

$$T = -0.00388092 * y^3 - 0.15539878 * y^2 - 2.04325121 * y + 10.91131541 \qquad (1)$$

With T being the temperature in °C and y being the depth in m.

The SAT was used to consider more atmospheric influences instead of the atmospheric temperature. This method was chosen as it had been previously successfully used at the location. The SAT is defined in Equation 2:

$$SAT = \theta_0 + \frac{1}{\alpha_0(1-\alpha_s)} * J - \varepsilon * J_{eh} \qquad (2)$$

With $\theta_0$being the ambient temperature (°C) and J the solar radiation (W/m²). Both were derived from the local weather station in Saga City. α_0 and α_s are the coefficients for heat transfer between air and soil (W/m²/K) and the Albedo (0.3 for soil), respectively. Lastly, ε is the dimensionless factor for long wave emission and *Jeh* the effective emission (W/m²).

More model properties are shown in Table 1:

Table 1: Model Properties

Fluid Flux	No inflow from the bottom or the sides of the model, inflow from the top according to rainfall observed
Hydraulic Head	No groundwater flow
Boundary Condition	Adiabatic at peripheral boundaries 19.7°C at the bottom boundary of 15 m (average of SAT) SAT from the surface
<u>Soil</u>	
Thermal Conductivity	Clay: 0.951 W/m/K, Sand: 1.261 W/m/K
Heat Capacity	2.52 MJ/m³/K
<u>Pipe</u>	
Thermal Conductivity	0.42 W/m/K

The model was validated using the data collected during the TRT. With the inlet temperature used as an inlet parameter, the calculated results of the temperature at the turning point and outlet have then been compared to the data measured during the test. The results of the history matching can be seen in Figure 6.

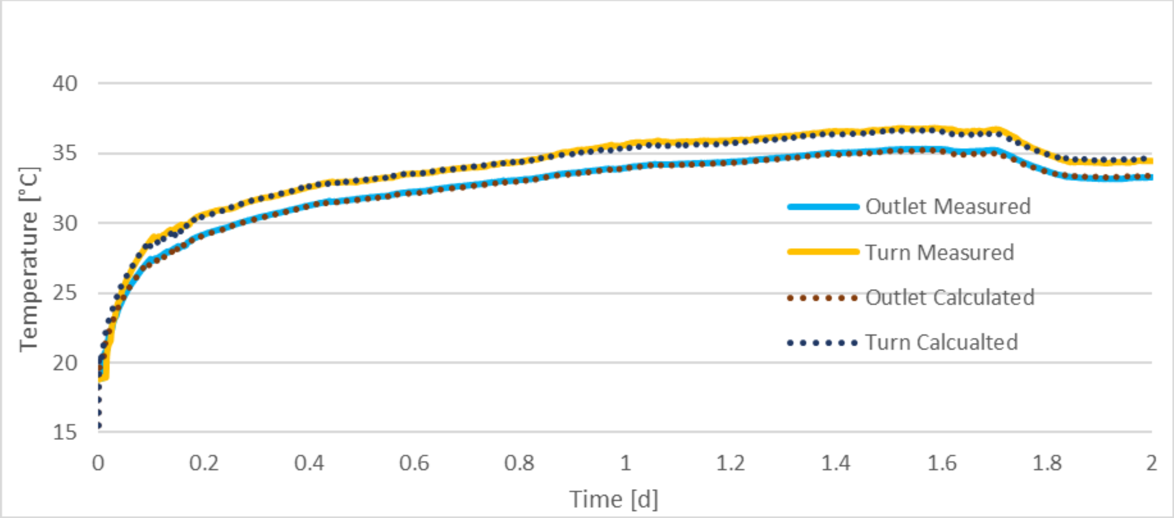


Fig. 6 Results of History Matching

2.3. Heat Load Calculations

For the long-term simulations calculations of the heat loads of a gym adjacent to the installed GHE will be used. The gym is used by the employees of Biotex Co. Ltd., and its outline and location can be seen in Figure 7.

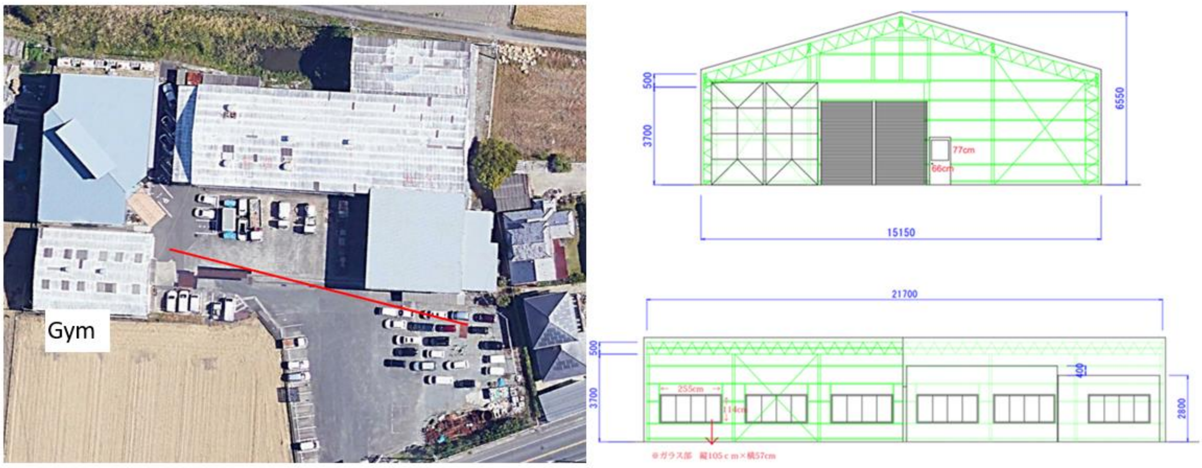


Fig. 7 Location and outline of the gym

Based on this outline and the weather data for 2023, Equations 3 and 4 have been used to calculate cooling and heating loads respectively for a total surface area of 1027.35 m² and a floor area of 327.76 m².

$$Q_h = \frac{U * A_e(T_i - T_o)}{A_f} - \frac{I * \eta}{A_f} \tag{3}$$

$$Q_c = \frac{U * A_e(T_o - T_i)}{A_f} + \frac{I * \eta}{A_f} \tag{4}$$

Where Q_h and Q_c are the heating and cooling heat loads (W), U the average heat transfer coefficient (0.87 in the case of Saga City), A_e the surface area of the building (m²), A_f the roof area of the building (m²), T_i the target room temperature (°C), T_o the outside Temperature, I the solar radiation (W/m²) and η the average solar heat gain rate.

Based on these heat loads the required heat exchange rate for the heat exchanger was calculated using Equation 5.

$$q = \dot{Q} * Cp * \rho * \Delta T \tag{5}$$

Where q is the amount of heat transfer (W), $\dot{Q}$ is the volumetric flowrate (m³/s), Cp the specific heat of the heat exchange fluid (kJ/kg*°C), ρ the density of the fluid (kg/m³) and ΔT the temperature difference between inlet and outlet.

The results of the calculation can be seen in Figure 8, additionally more operation conditions can be seen in Table 2.

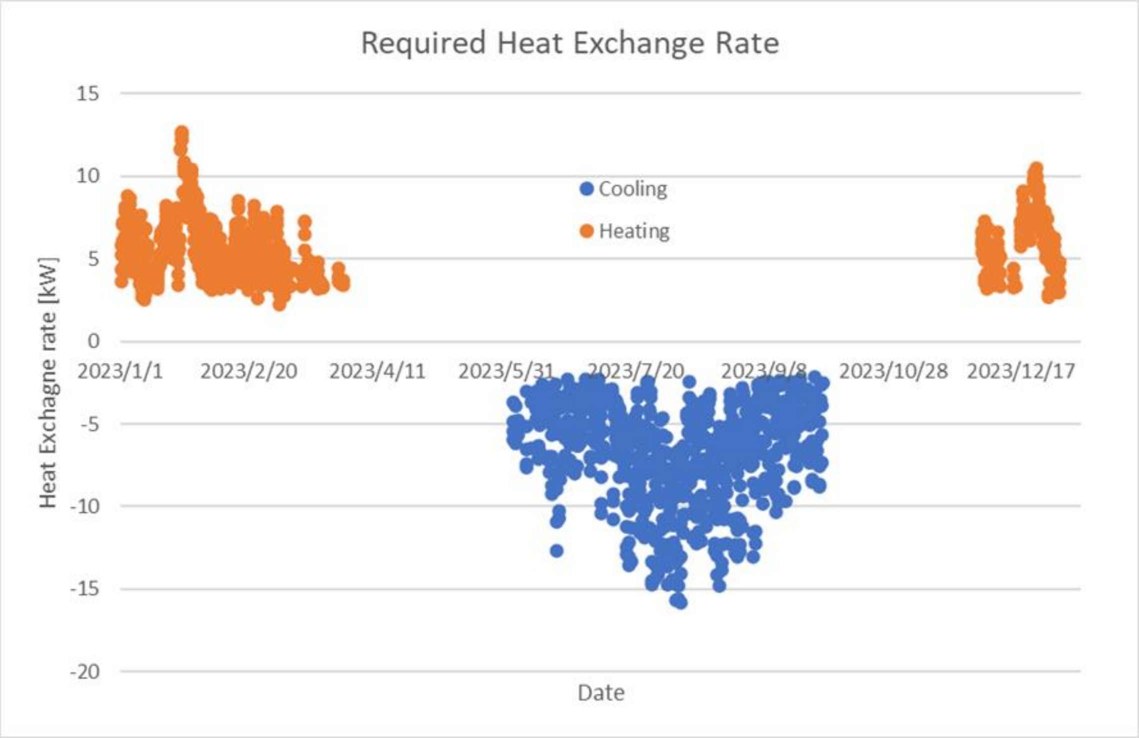


Fig. 8 Required heat exchange rate

Table 1 Operation Conditions for the Heat Exchange Rate Calculations

	Heating	Cooling
Period	Dezember to March	June to September
Operation Time	15:00 to 21:00	15:00 to 21:00
Target Room Temperature	20°C	24°C
Boundary Temperature	14°C	26°C
COP	3.5	5.5

To better showcase the results, the coefficient of performance (COP) will be calculated. These calculations will be based on the approximation formula of the performance curve of the Sunpot GSHP-1001 heat pump. The approximation formulas for heating and cooling are shown in Equation 6 and 7. The inverter frequenzy and secondary heat pump inlet temperature were chosen at 35 Hz, 12°C and 35 Hz, 28°C for heating and cooling respectively.

$$COP_{Heating} = 0.14 * T_{out} + 4.6 \tag{6}$$

$$COP_{cooling} = -0.23 * T_{out} + 14 \tag{7}$$

With Tout being the outlet temperature of the GHE.

3. Well Path Optimization

In the previous research conducted by Lein et al. (2024)results showed a strong influence of the permeability of the underground on the performance, and the installation in permeable layers as beneficial. The first part of this work aims to investigate the optimal placement of the well to improve the performance for water injection into the borehole of an HDD HGHE. For this the following parameters have been investigated:

Percentage of the well in the impermeable layer
Drilling Angle of the well
Influence of a shallower well
Vertical Distance of the borehole heat exchangers

For each of these case studies, the following operation conditions have been set. A constant heat load of 5 kW has been applied over the course of 30 Days. The injected water had a temperature of 25°C and was injected at a rate of 1 L/min.

3.1 Percentage of the well in the impermeable layer

The first parameter investigated to optimize the placement of the well is the amount of the well that is located in the impermeable layer. While previous results have shown that placing the well in an impermeable layer benefits the performance of the system, it is also important to show in which way this parameter influences performance. The results of the simulation can be seen in Figure 9.

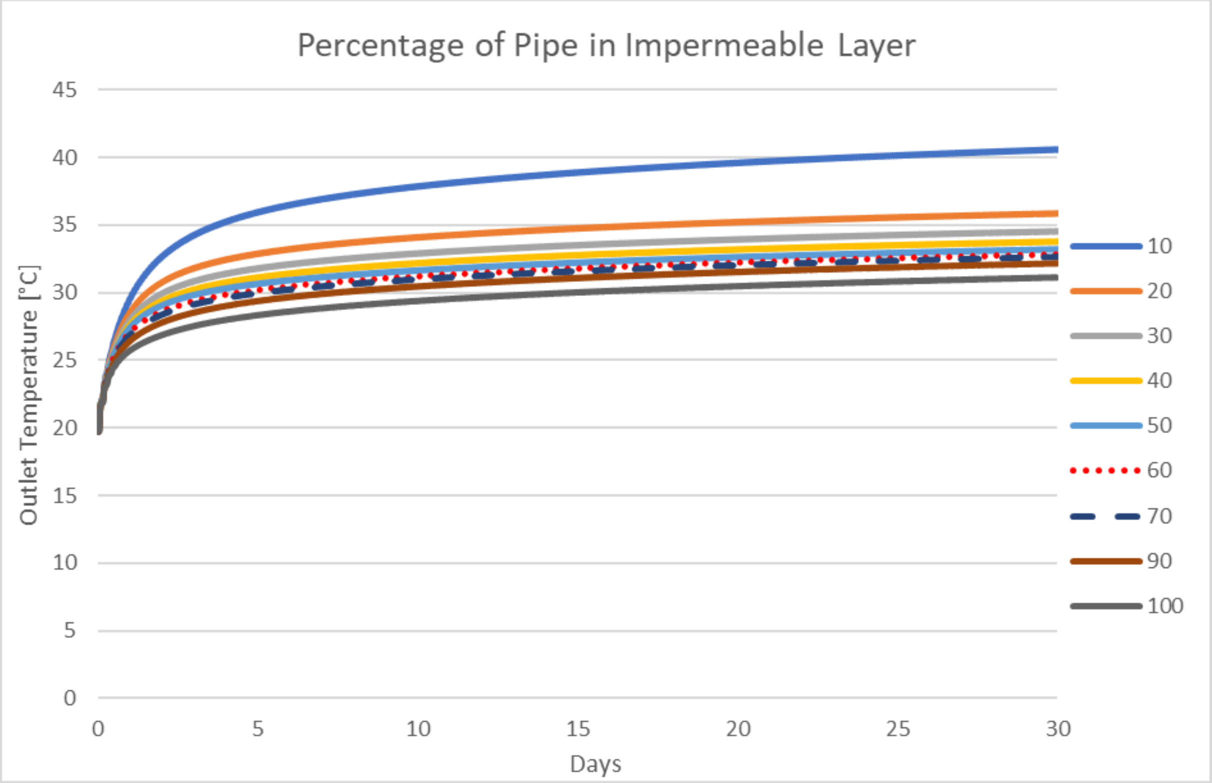


Fig. 9: Influence of the Percentage of the Pipe in the Impermeable Layer

The first thing to notice in these results is that they confirm previous findings of better performance if the GHE is mainly installed in the impermeable layer. When comparing each result, it is noticeable that initially larger differences in the outlet temperature after 30 Days, gets smaller the more of the pipe is buried in the impermeable layer. After burying more than 30% of the pipe in the impermeable layer the difference becomes much smaller compared to the differences before. A reason for this behavior can be found in the shape of the GHE. When increasing the percentage at the beginning, a larger section a larger vertical section of the model will be covered by the impermeable layer. Due to the horizontal design of the installation, in the higher percentages, the vertical area covered will become smaller. This behavior can also be seen in Figure 10, which showcases the difference between the impermeable layer covering 20%, 40% and 60% of the pipe. The increase in volume covered between 20% and 40% is noticeable larger than the increase between 40% and 60%. This behavior also showcases the effect of a casing inserted into the borehole, showing that in a permeable underground a casing can be used to improve performance. Concluding it was shown again, that impermeable layers are better suitable for water injection, and if possible, should at least cover up to 40% of the pipe to achieve good performance.

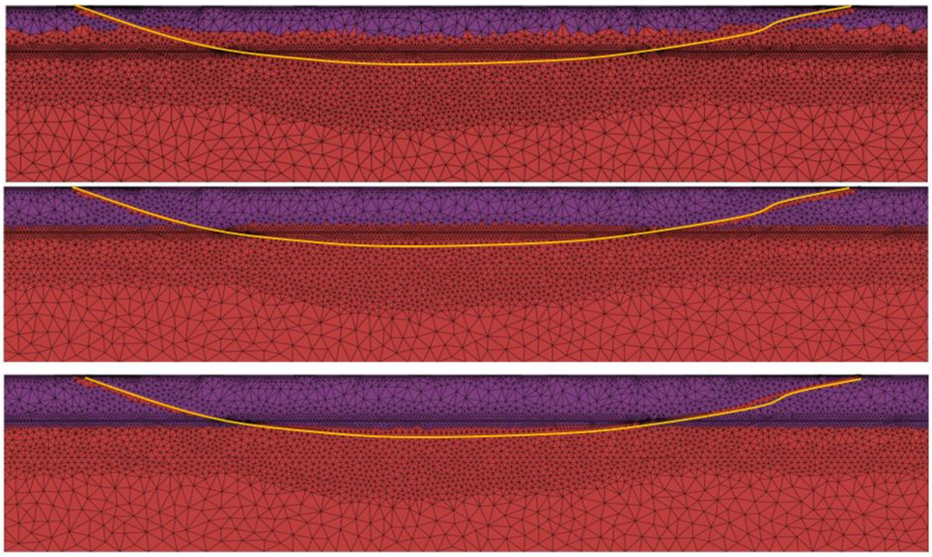


Fig. 10: 20%, 40% and 60% coverage of the BHE (yellow) visualized

3.2 Angle of the well

One of the biggest advantages of using HDD is the flexibility of the system. Due to this flexibility, HDD is able to drill wells at many different angels. Therefore, it is necessary to investigate the influence of the well angle on the effect of water injection into the system. For this reason, drilling angles of 10° to 70° have been investigated, with stepper angles not being feasible for being actually drilled. The simulations have been carried out in two geological settings, one resembling the geology of the location of the field test in Saga City, Japan, to determine the optimal angle for this setting. The second setting was carried out with a uniform impermeable geology, to eliminate the influence of the geology on the setting and determine the sole influence of the drilling angle. These two settings have been visualized in Figure 11.

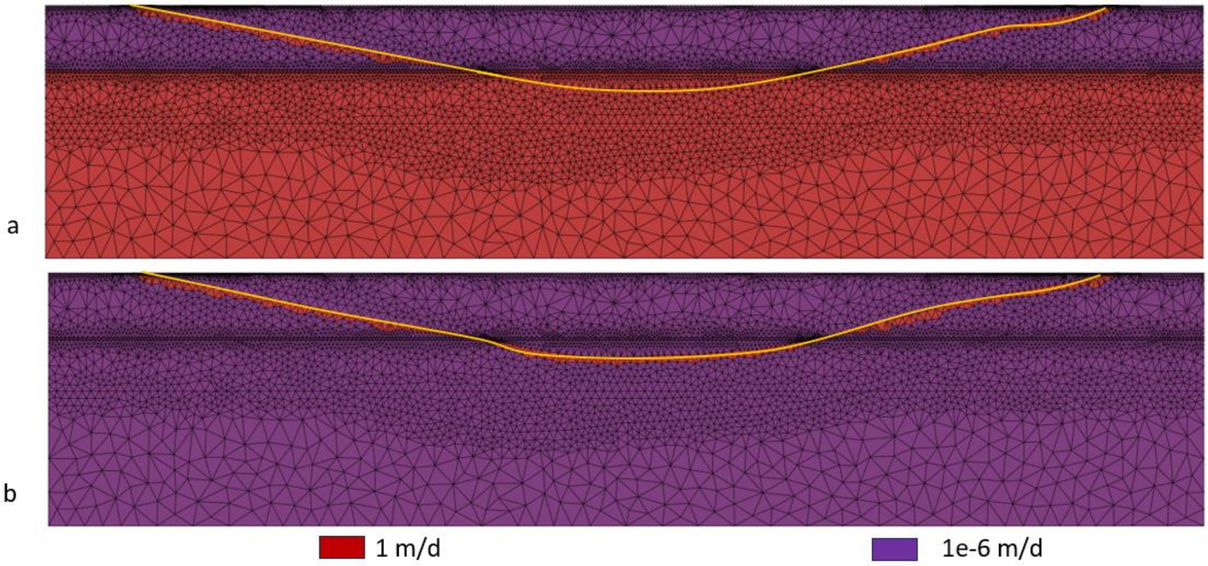


Fig. 11: (a) Permeability setting resembling the original location, (b) uniform impermeable setting

The results for setting (a) can be seen in Figure 12.

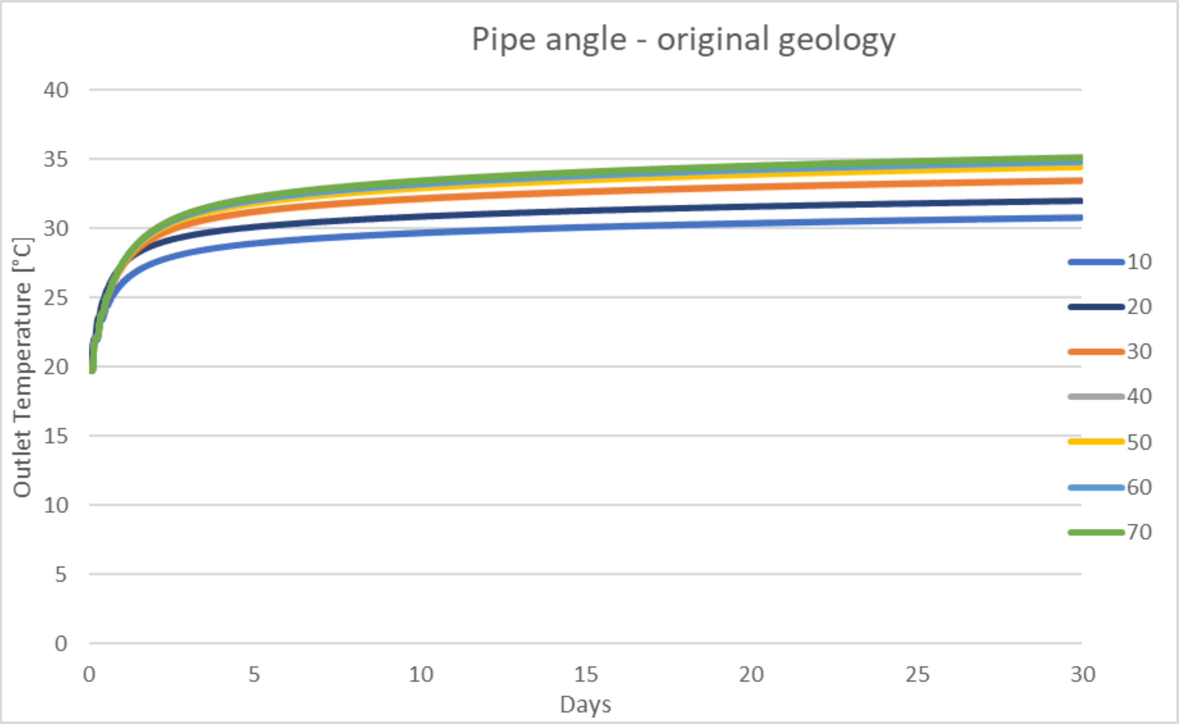


Fig. 12: Results of the Pipe angle on the original geology

In the original geological setting in Saga, increasing the drilling angle of the pipe leads to increasing outlet temperatures and therefore a worse performance. This behavior is explained by the shallower angle having a larger percentage of the pipe crossing through the impermeable layer, which was shown previously to improve performance. Due to having a difference in outlet temperature of about 5°C, for the location in Saga City, it was concluded that shallower angles are the optimal choice for the location.

To eliminate the influence of the location the results of the same case study with setting (b) are shown in Figure 13.

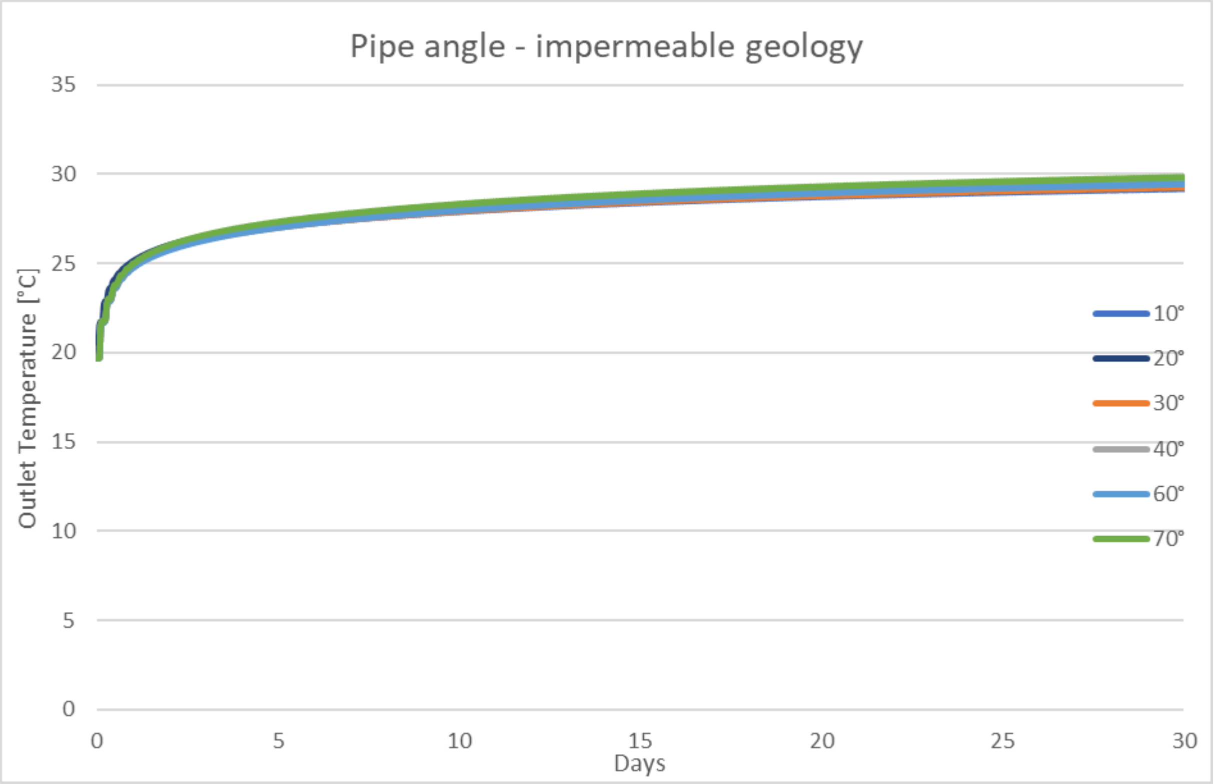


Fig. 13: Results of the Pipe angle with a uniform impermeable geology

When comparing the results of each angle in this setting, the difference in outlet temperature observed is much smaller, being only 0.63°C when comparing an angle of 10° and an angle of 70°. Considering this small difference, it can be concluded that for the performance of water injection the well angle only plays a minor role when designing a well. In uniform geologies, this parameter can therefore be neglected when planning a well path.

3.3 Shallower Well

With the previous results showing that water injection is more beneficial in impermeable layers, the question arises if a shallower well located in the impermeable layer at the location in Saga, would have a better performance. This well would have a depth of around 3 m compared to the original upper well with a depth of 5 m. Shallower wells usually have a worse performance than deeper wells due to the stronger influence of atmospheric conditions. The results of the comparison are shown in Figure 14.

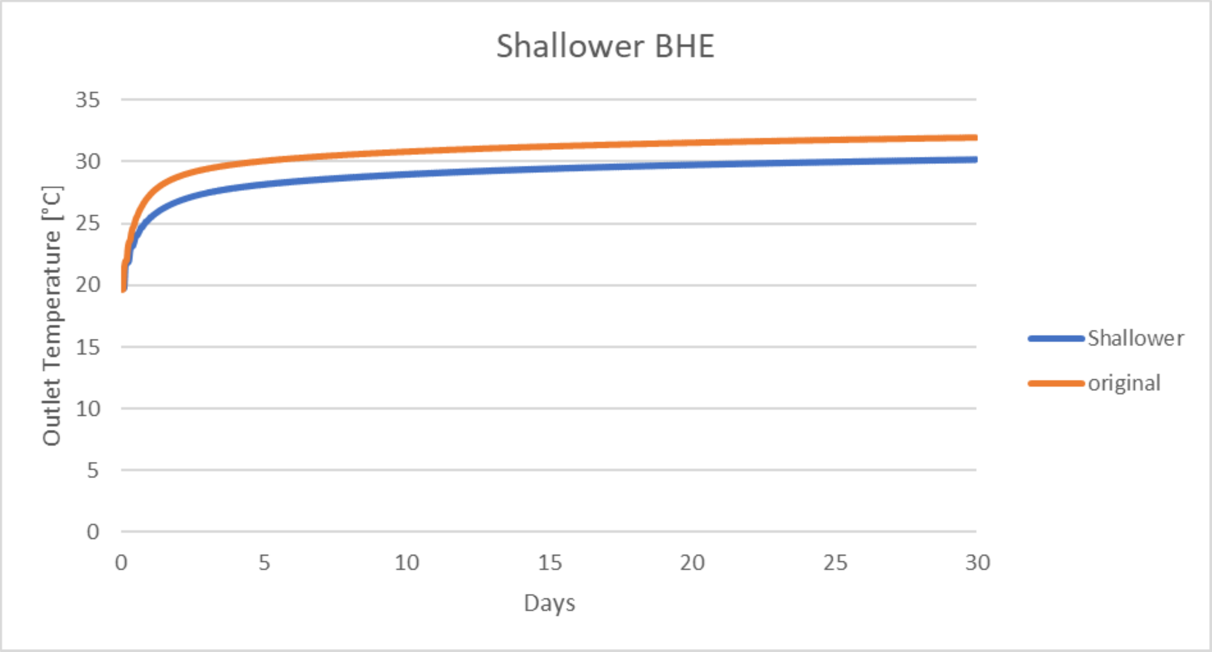


Fig. 14: Performance of a shallower well

The shallower well in this case shows a higher outlet temperature and therefore a better performance than the original well. This shows that at the location in Saga, the benefits of installing the well in the impermeable layer, outweigh the drawbacks of a shallower installation when injecting water.

3.4 Vertical Distance between wells

In the system used during the field test, the two boreholes have a vertical distance of about 4.5 m between them. This distance prevents most thermal interference between the two BHE and guarantees good performance. As water injection was proven to improve the performance of these kind of systems, it is necessary to investigate the effect of water performance on the thermal interference between the pipes. Figure 15 shows the outlet temperatures of systems with varying vertical distance between two BHEs when injecting water into the borehole.

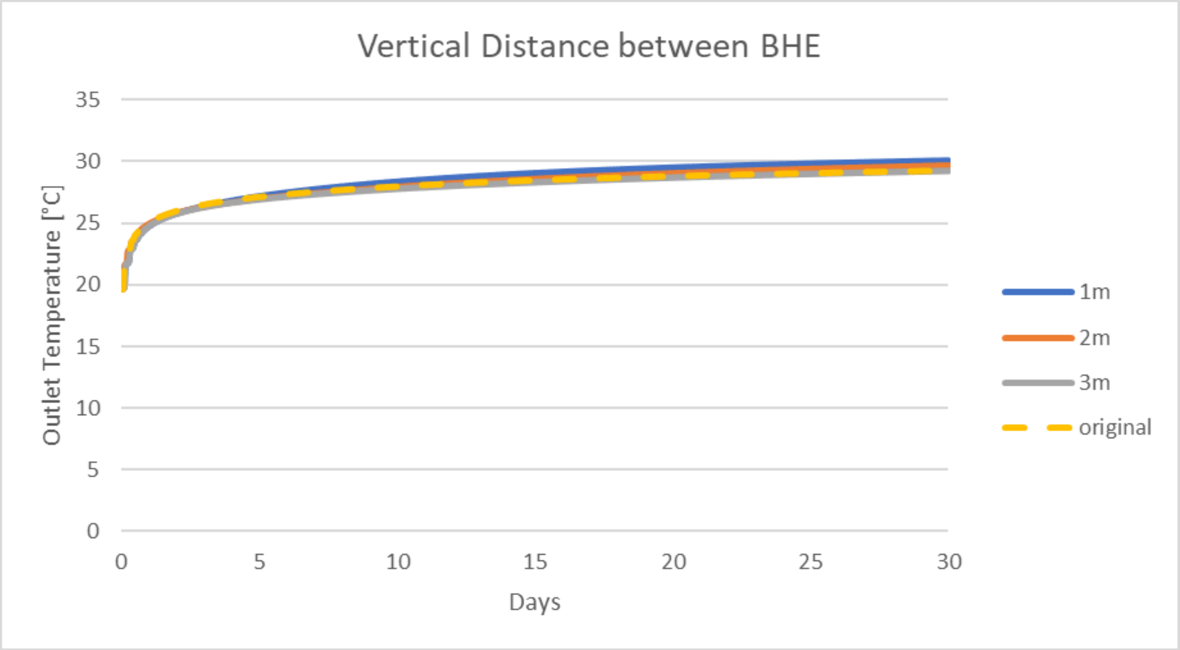


Fig. 15: Influence of the vertical distance between wells

When introducing water injection to the system, the influence of the vertical distance between pipes is overall small. Between the spacings of 1 m and 3 m a temperature difference of 0.8°C can be observed. This shows that water injection can almost completely negate the effects of thermal interference between the wells, even at the distance of only 1 m apart. As a small effect can still be observed, the recommended minimum distance between pipes should be set to 3 m to eliminate all influences of thermal interference.

4. Long-Term Simulation

Given that water injection has been demonstrated to enhance GHE performance, further research is necessary to determine its long-term impacts. To do this, the heat load will be simulated at the gym adjacent to the field test location in Saga, Japan. One year and ten years will be the simulated time periods. The comparison of one year of water injection and one year of no water injection can be seen in Figure 16.

For cooling operations, the outlet temperature could be lowered by roughly 2°C when water was introduced into the system at a rate of 2 L/min. This results in an increased average COP of roughly 0.4. The average outlet temperature was raised by 1.4°C for heating operations, which also resulted in a 0.4 improvement in the average COP.

When compared with the results from the previous study by Lein et al. (2024), the improvements are only small and can be explained by the short operating hours every day. The impact of the water injection was lessened because the system only ran from 15:00 to 21:00 every day. Nonetheless, the improvement was still readily apparent, particularly during the summer when a greater impact was apparent. The system's performance over the summer can be used to explain why the heating period in December started off with inferior performance. At the end of summer, the outlet temperature was lower when water was injected than when no injection was used. This difference is also reflected in the ground temperature surrounding the GHE, which is higher when no water injection is used. The system's initial performance was impacted since the ground temperatures did not reach the same level at the start of the heating phase due to the brief recovery interval.

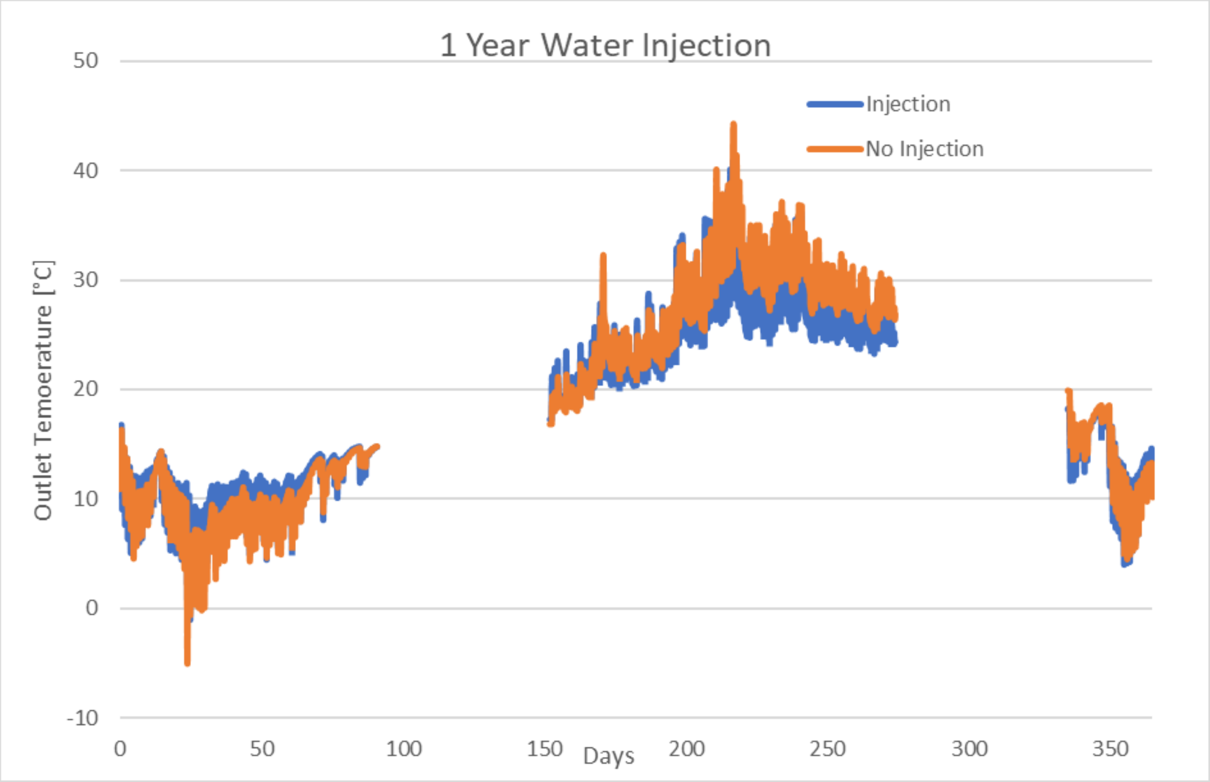


Fig. 16 Comparison of 1 year of water injection and 1 year of no water injection

The results of the 10-year simulation can be seen in Figure 17. The outcomes clearly show, that especially in summer during the cooling operations, water injection can constantly lower the average outlet temperature of the system. Compared to the simulation with no water injection, the results showed a more stable behavior, increasing by a lower degree. Over the course of the 10 years a slow but steady increase of the outlet temperature can be observed, which is caused by the thermal imbalance imposed by the heat loads calculated for the gym. For cooling a required heat load of 4.73 MW and for heating a heat load of 3.84 MW was calculated. These results show that Saga is located in a cooling dominant region. Even though water injection could improve the performance of the system, it can not prevent a slight increase in outlet temperatures causes by this thermal imbalance.

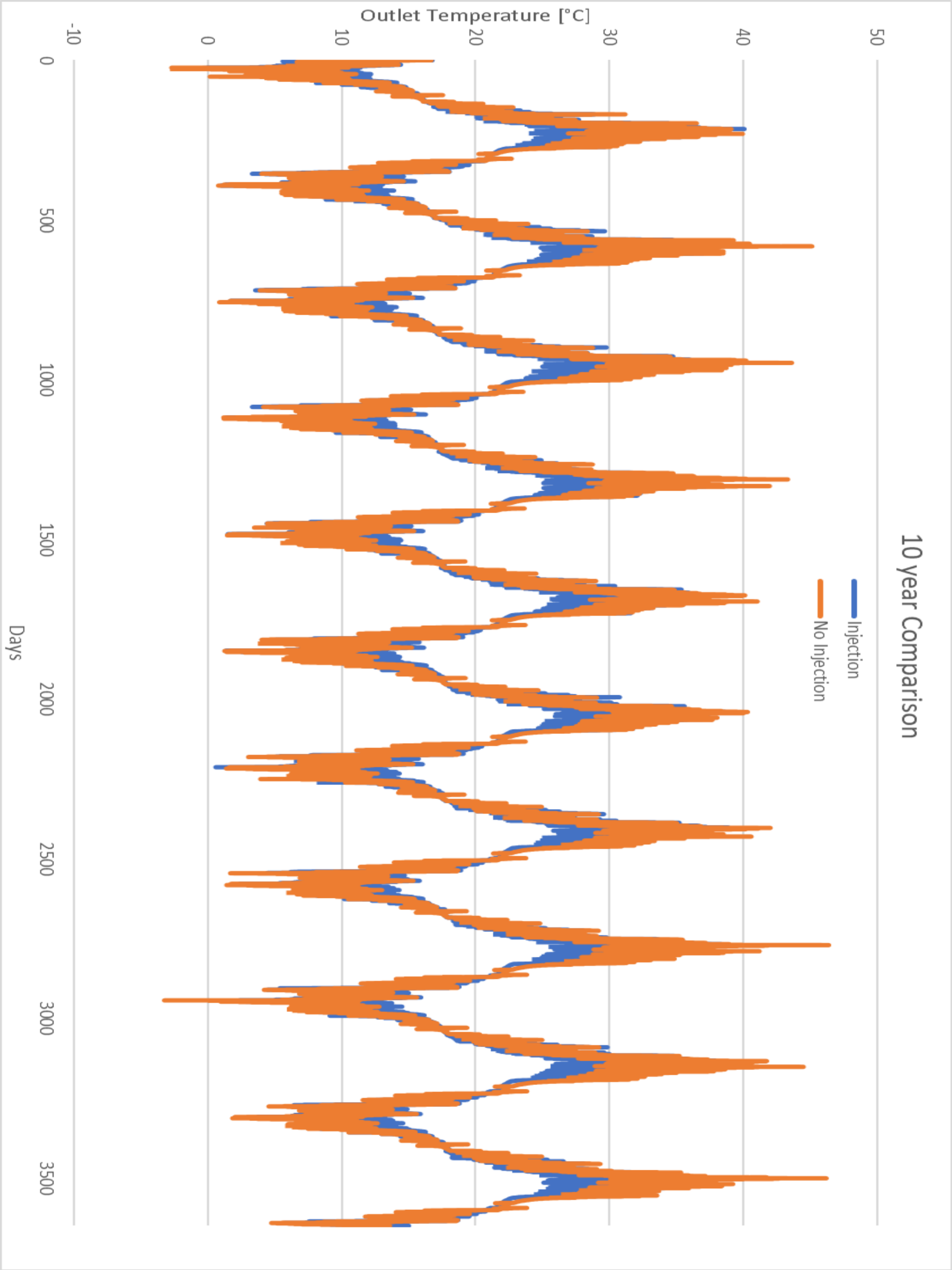


Fig. 17 Results of the 10-year simulation

5. Conclusions

In this study, a field test and numerical simulations were conducted to determine the best well path for injecting water into HDD drilled HGHE and show the long-term effect of water injection into the borehole. In Saga City, Japan a HGHE with two boreholes, each with a diameter of 114.3 mm and a depth of 5 m and 9.5 m respectively, was installed. To investigate the performance, in March 2022 a TRT was conducted, during which rain occurred decreasing the outlet temperature of the system.

Based on this field test, a numerical model was developed in FEFLOW and validated using history matching of the turning point temperature and the outlet temperature measured during the TRT. The model was then used to evaluate the optimum properties of the well to improve the performance of water injection into the borehole and to investigate the long-term performance of the system, when injecting water.

It was found that placing at least 30 to 40% of the pipe in the impermeable layer can greatly improve the performance. While lower percentages still show an improvement, it was significantly less. The best performance of the system can be achieved when the well is completely placed in the impermeable layer. Furthermore, it was shown that the well angle should be chosen in a way, that more of the pipe will be placed in the impermeable layer. In the case of the location in Saga City, this means choosing a shallower angle. In a uniform geology however, the well angle was shown to have only a small influence and can be neglected in the planning when water injection is desired. This behavior also reflects when comparing with a shallower well completely installed in the impermeable layer. While shallower wells tend to have a worse performance, the benefits of the installation in the impermeable layer outweigh this drawback of a shallower installation. It was also shown that the thermal interference between the two layers, even at a distance of only 1 m between pipes, can nearly completely be eliminated when injecting water. At a distance of 3 m, it was completely eliminated.

Lastly long-term simulations with a duration of 1 year and 10 years have been conducted. It was shown that during a year, the average outlet temperature for cooling could be reduced by 2°C and increased by 1.4°C for heating. This reflected in a COP improvement of about 0.4 for both cases. Over the span of 10 years, it was shown that water injection could constantly improve the outlet temperature of the system. However, a slight increase in overall average outlet temperature can still be overserved over 10 years, caused by a heat load imbalance imposed from heat loads of the gym which was used as a reference.

The results of this research showed the influence of several parameters of the well on the performance of water injection into the borehole of HDD drilled HGHE and the long-term performance of the system. This helps with further easing design choices for this kind of application and improve the use of GSHP. Future research should focus on investigating more geological settings and the applicability of water injection in other climates.

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