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Analysis of Operation Behavior and Numerical Simulation of a Large-Scale Borehole Field

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Ground source heat pump, borehole heat exchanger, thermal response test, numerical simulation

ABSTRACT

Air-condition systems with Ground Source Heat Pumps (GSHP) system is known to be energy efficient and is well distributed in American and European countries. On the other hand, the number of the systems is still limited in Japan due to the lack of the knowledge of the optimum design for the system. For the further promotion of the GSHP system, the high efficiency of the GSHP system for air-conditioning needs to be proved by improving the performance of heat exchange.

The objective of this study is to evaluate the performance of GSHP system installed in a large public facility in Akita, Japan. This facility has 36 boreholes with single U-tubes for heating and cooling purposes. The area for air condition in this facility is around 1530 m^2. Thermal Response Test (TRT) showed that the ground thermal conductivity in this site is 1.70 W/m/K. The geological column shows the existence of a gravel layer at around 80 m. The inlet temperatures, the outlet temperatures and the flow rate during operation of GSHP system have been recorded since April, 2015. Based on the analysis of operation behavior for 1 year, the cumulative heat extracted and heat injected were calculated as 93.95 MWh and 25.68 MWh, respectively, indicating the poor balance in the heat exchange rates in summer and winter.

A numerical model of the single ground heat exchanger was then developed using FEFLOW ver.7.0 software. The validity of this model was confirmed by conducting history matching with TRT data. Next, a numerical model of the borehole field was developed based on the parameters of the single well model. To confirm the validity of borehole filed model, history matching with operation data was conducted with reasonably good agreement. The long-term simulations with the borehole field model showed that the operation behavior would be stable for 10 years under current operation condition and the ground temperature around Boreholes Heat Exchangers (BHEs) would be affected by the direction of groundwater flow and the position of BHEs.

Introduction

The advantages of Ground Source Heat Pump (GSHP) system are considered to be the small environmental load and the high energy performance. Since the heat source is in the ground, not in the atmosphere, heat island phenomenon in urban areas could also be mitigated. In Japan, however, the expensive drilling cost and the low awareness of GSHP system impede the further increase of the system. As for the initial cost, Thermal Response Test (TRT) could prevent the overdesign of the well length. Sanner, et al. (2005) showed the importance, procedure and interpretation method of TRT.

The installation of GSHP systems in the public facilities could improve the public recognition of the system. The studies in the past show how to optimize the design of GSHP systems with a numerical model. Fujii, et al. (2005) developed a large borehole field model which simulates the performance of 75 Boreholes Heat Exchangers (BHEs) to optimize the positioning of the BHEs. Also Nam, et al. (2008) constructed a numerical model of borehole field and predicted the balance of heat exchange with the borehole field model in the commercial buildings. Fujimoto, et al. (2011) developed a borehole field model which consists of 78 boreholes in Hokkaido, Japan. The target area of the study belongs to a cold region of Japan, indicating that the annual heat extraction rate significantly exceed the heat disposal rate.

When a poor balance in the heat exchange rate is expected, we should carefully design the GSHP system because the area of influence on ground temperature in a large-scale borehole field is larger than that of the small-scale. In this study, the operation behavior of GSHP system in a large public facility is analyzed and the numerical model of the borehole field is developed for investigating an operation strategy applicable to systems of poor heat balance.

Information of GSHP in this study

The research field is located in a public facility in Akita prefecture, northern Japan. The region has deep snowfalls (440cm/year) and heavy heating load. The area for air condition in this facility is around 1530 m^2. In winter, floor heating is used in some part of the building. There are 12 heat pumps which have 360 kW heating and cooling capacity in total.

Figure 1 shows the location of 36 single U-tubes BHEs. The length and the diameter of borehole are 101m and 0.137m, respectively. The spacing of BHEs is 4m for avoiding the thermal interference. These boreholes are connected to the heat pumps using reverse return pattern. In one of the BHEs (show in with circle in Figure 1), the temperature sensors were set at -40 m, -60 m, -80 m, -100 m. Figure 2 shows the geological column in this site and the well completion design. In this site, the ground is composed of sand and gravel and the ground water level is -9.60 m. The BHEs were grouted with mixture of gravel and sand to allow the flow of groundwater through the GHE and hence to enhance the heat exchange capacity. The use of permeable materials is not restricted in the research area since surface water is used for the local water supply. The heat medium is the water solution of propylene glycol (40 %).

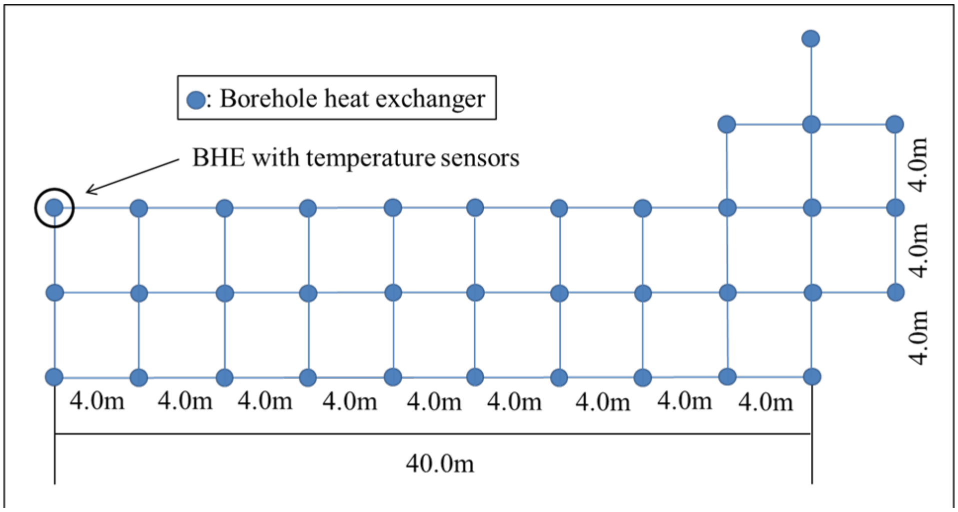

Figure 1. Position of wells

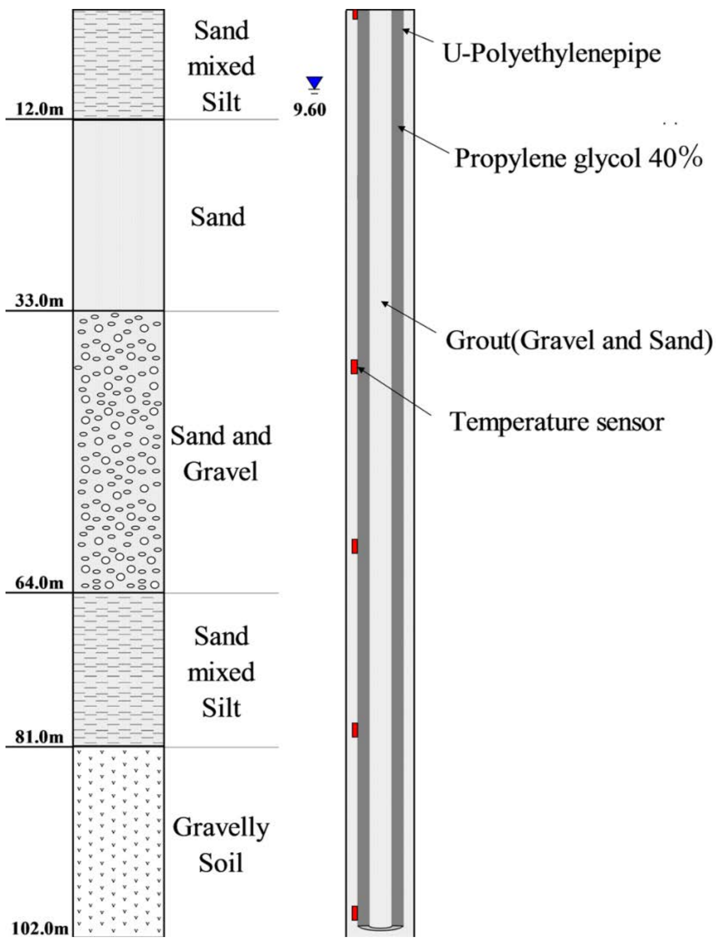

Figure 2. Geological column and well completion

Analysis of operation behavior

The operation behavior was analyzed for 1 year from April 2015 to March 2016. The heating periods are from 1 April 2015 to 19 June 2015 and from 4 October 2015 to 31 March 2016 and the cooling periods are from 26 June 2015 to 24 September 2015. The inlet and outlet temperatures and the circulation rate of heat medium the ground temperatures have been recorded for every 1 minute.

Figure 3 shows the change of inlet and outlet temperatures. The average temperature differences of inlet and outlet of BHEs in the heating and in cooling periods were as calculated 1.4℃ and 0.87℃, respectively. In heating and cooling operations, the cumulative heat exchange rates were -93.95 MWh, 25.68 MWh from April 2015 to March 2016, respectively. Since the balance of the exchanged heat was -68.27 MWh, the ground temperatures is expected to decrease gradually to cause a temperature drop in the formation.

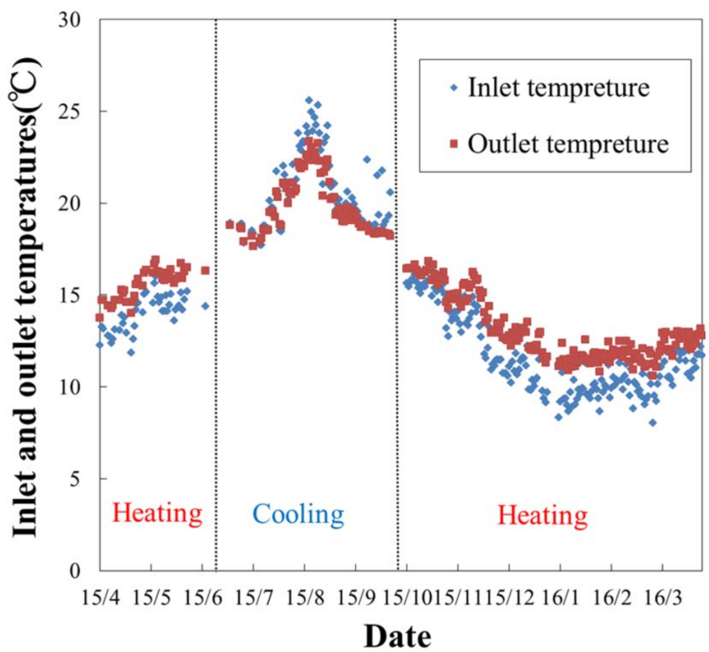

Figure 3. Change of inlet temperature and outlet temperature during operation

Figure 4 shows changes of ground temperatures at -40 m, -60 m, -80 m, -100 m. In June 2015 and September 2015, the ground temperatures showed a recovery to the initial temperature because the operation hours were short in the periods. Among them, the change of ground temperature at -80 m was the smallest, indicating the possible existence of groundwater flow.

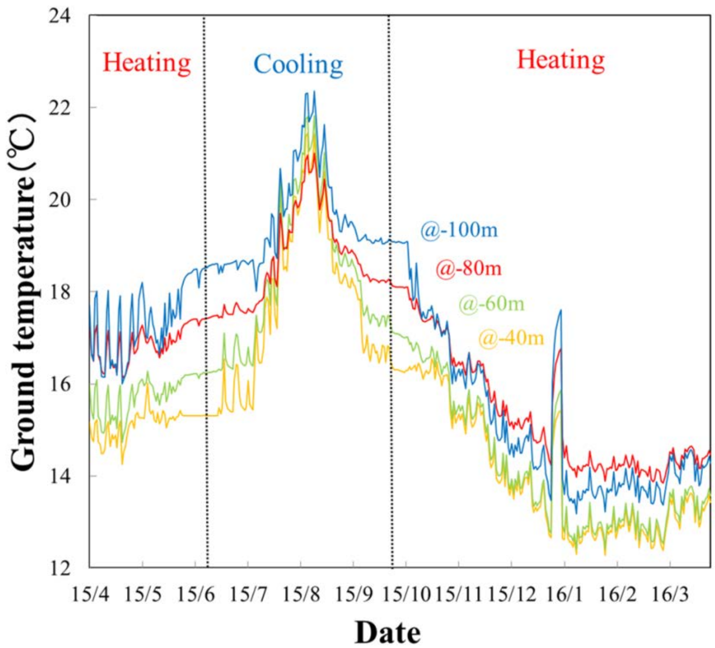

Figure 4. Change of ground temperature at -40 m, -60 m, -80 m, -100 m

Thermal response test and estimation of heat property

The thermal properties of the ground need to be estimate accurately in order to improve the accuracy of numerical models. In this site, TRT was carried out from 21 November 2014 to 28 November 2014 for around 6.8 days. The thermal conductivity of the ground was estimated with graphical method. Figure 5 shows the inlet and outlet temperatures, the heat exchange rate and the flow rate. Figure 6 shows the graphical interpretation of the TRT, which yield a thermal conductivity of as 1.70 W/m/K.

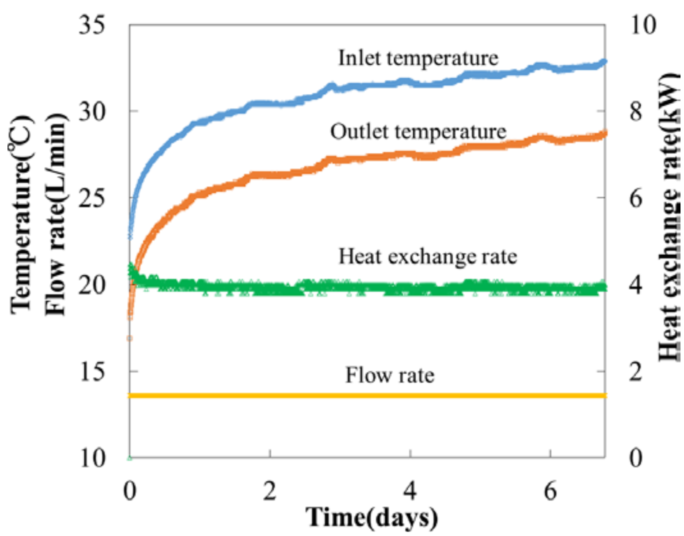

Figure 5. Result of TRT

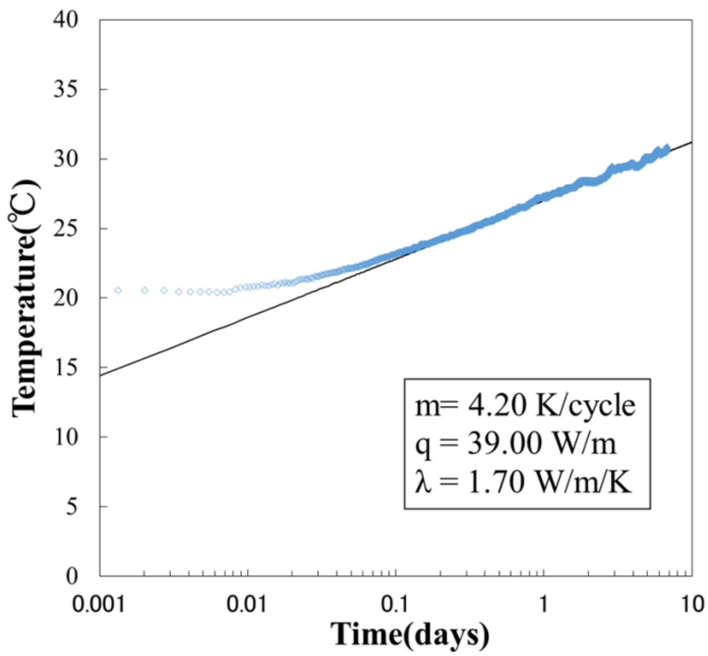

Figure 6. Result of graphical method

Development of numerical model for single U-tubes BHEs and history matching

In the next step of the study, a numerical model of single U-tube BHEs was developed with FEFLOW ver.7.0 which can simulate groundwater flow and heat transport in three dimensions. Figure 7 shows 3D view and plan view of the developed numerical model with single U-tubes BHEs.

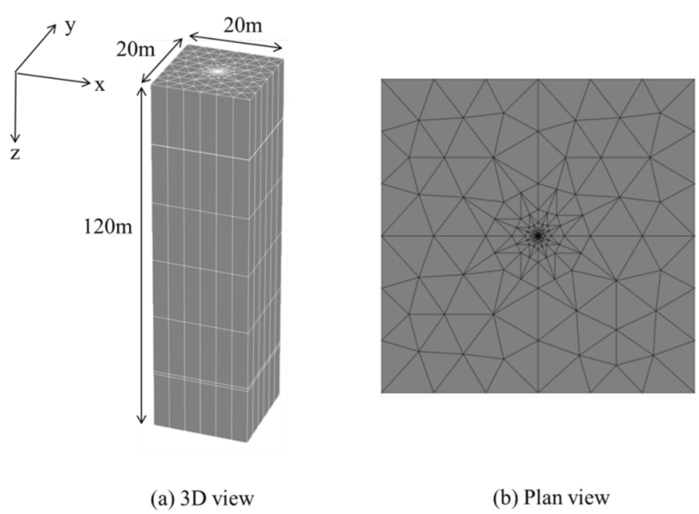

Figure 7. Numerical model of single U-tube BHE

The size of the model is 20 m by 20 m (in X and in Y directions) and 120 m (in Z direction). The grid in the model is defined as approaching the BHE to accurately reproduce the temperature behavior. The number of layers is defined as seven. The peripheral boundaries of the model were set as adiabatic, while the top and bottom boundaries were set as constant temperature (top: 14.5℃, bottom:19.5℃). The temperature measured in June 2015 was used as the initial temperature distribution. The same physical properties of ground were input in the all layers since the type of ground was relatively uniform from land surface to -100 m. The estimated thermal conductivity of the ground was 1.70 W/m/K, but the thermal conductivity of 1.45W/m/K was used in the numerical model considering the TRT result is affected by the groundwater flow. The hydraulic conductivity of layer 4 was set larger than other layers to model the fast groundwater flow at -80m. The hydraulic conductivity and the hydraulic head were adjusted to reproduce ground temperature at -80m with a trial and error. Table 1 shows the physical properties of the model. The hydraulic head at the east and west were set as -9.5855 m and -9.6115 m, respectively. The hydraulic gradient is set as 1.15×10^{-3} to generate a groundwater flow of 0.1m/day. Table 2 shows the physical properties of BHE in this model.

Table 1. Physical properties of the model

Depth(m)	0-40，80-120	60-80
Thermal conductivity(W/m/K)	1.45	
Hydraulic conductivity(x, y directions)(m/s)	1×10^{-6}	1×10^{-3}
Hydraulic conductivity(z direction)(m/s)	1×10^{-7}	1×10^{-4}

Table 2. Physical properties of single U-tube BHEs

Name		Value	Unit
Borehole Diameter		0.137	(m)
Pipe	Distance	0.069	(m)
	Diameter	0.034	(m)
	Wall Thickness	0.0029	(m)
Heat medium	Heat capacity	4.0	(10^6 J/m^3/K)
	Thermal conductivity	0.48	(J/m/s/K)
	Dynamic viscosity	3.0	(10^{-3} kg/m/s)
	Density	1.052	(10^3 kg/m^3)

After the numerical model of the single U-tube BHEs was developed, the history matching was conducted to confirm the validity of this model with TRT data. Figure 8 shows the result of the history matching for 6.8 days. The calculated and measured temperatures showed good agreement except for the small difference in the first day, demonstrating the validity of the numerical model of the single U-tube.

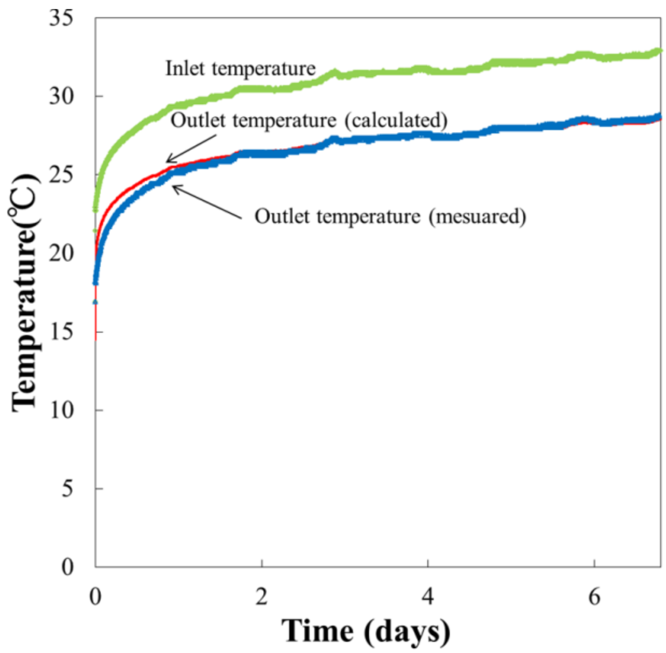

Figure 8. Result of history matching for single U-tube BHEs

Development of numerical model for the borehole field

The numerical model of the borehole field is developed in this section. Figure 9 shows the developed numerical model of the borehole field. This model was based on the parameter of the model of single U-tube. The model is 56 m by 80 m (in X and in Y directions) and 120 m (in Z direction) and the model consists of 7 layers from top to bottom. The hydraulic gradient is set as 1.16×10^{-3} to generate a groundwater flow of 0.1m/day.

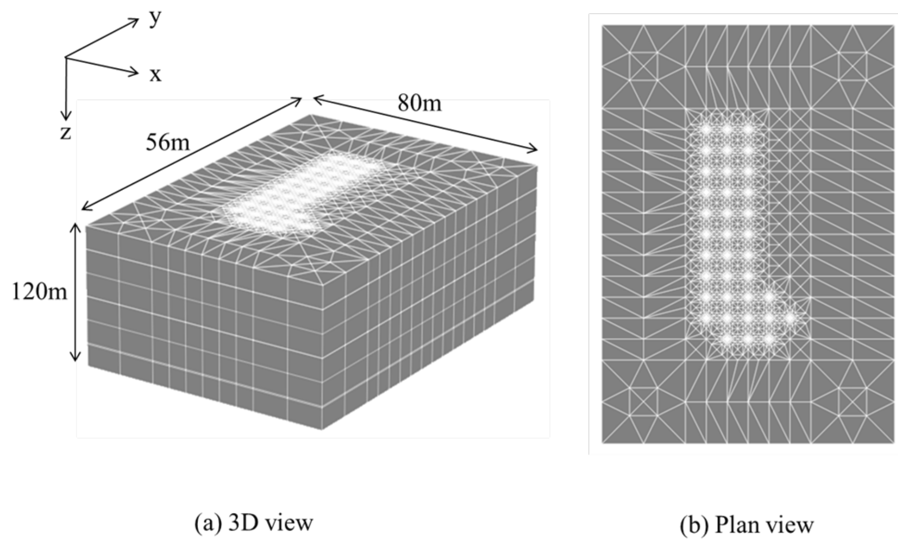

Figure 9. Numerical model of the borehole field

The history matching was conducted to confirm validity of the borehole field model with the measured operation data and ground temperatures. The operation data were averaged from every 1 minute to every 1 day to reduce computation time. Figures 10 and 11 show the result of the history matching. The calculated and the measured outlet temperatures showed good agreement. The measured and simulated ground temperatures matched reasonably at all depth. Though the ground temperature at -80m showed smaller change than others depth, the trend was well reproduced by the fast groundwater flow.

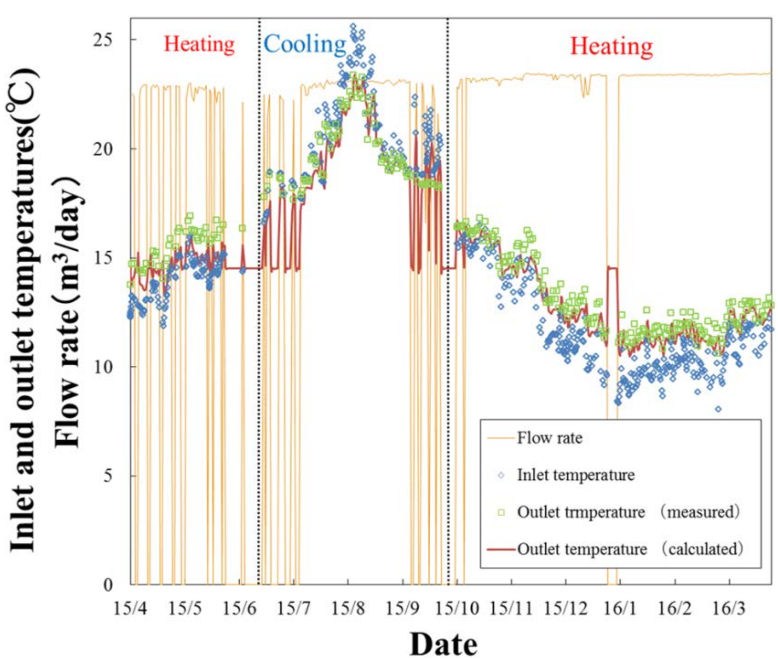

Figure 10. Result of history matching of outlet temperatures for the borehole field

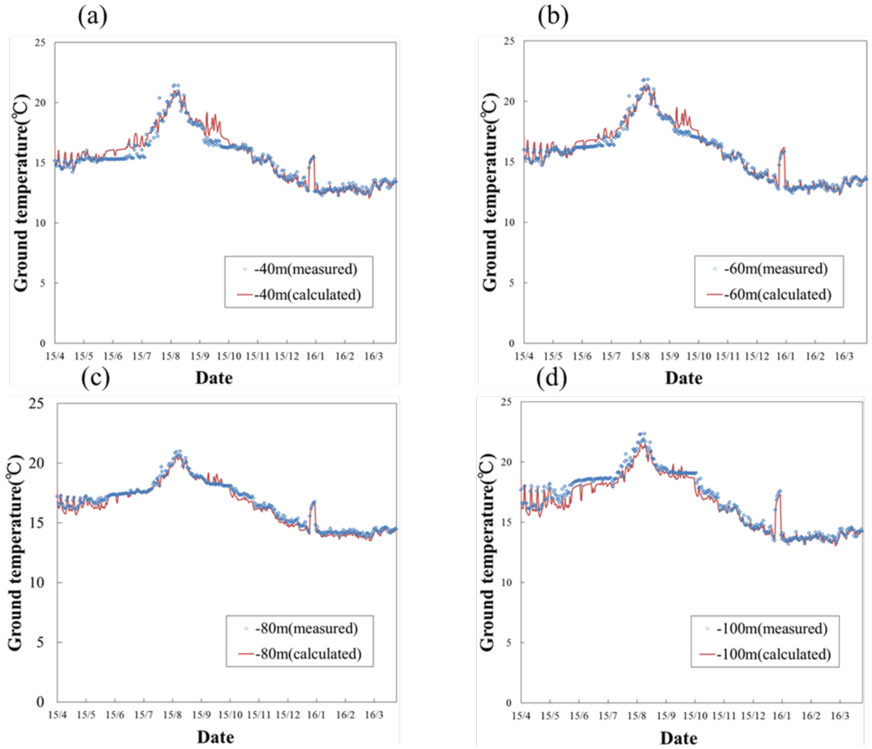

Figure 11. Result of history matching of ground temperatures, (a) -40 m, (b) -60 m, (c) -80 m, (d) -100 m

Long-term simulation

As mentioned above, the poor balance of heat exchange could worsen the performance of GSHP system in the long-term operation.

The ground temperature for 10 years was simulated with the borehole field model. In the condition of long-term simulations, the inlet temperatures in heating and in cooling operations were set as 0℃ and 30℃, respectively. The heating periods are defined from 1 April to 19 June and from 4 October to 31 March and the cooling periods are from 26 June to 24 September considering the current operation periods.

Figure 12 shows the predicted ground temperature at each depth. After the ground temperature at each depth declined for first 2 years, the ground temperature got stabilized and the behavior of ground temperature at -80 m was the most stable among other depths. This indicates that the long-term stability of the system can be maintained even under poor heat balance. The reasons why the ground temperatures were early stabilized are the interval of the wells is long enough to avoid the thermal interference and the extracted heat per the well length was very small (about 7W/m). Figure 13 shows the temperature distribution at -80 m after 10 years. The direction of groundwater flow was determined on the basis of topography. The figure shows that the distribution of ground temperature was strongly affected by the direction of groundwater flow.

The ground temperatures around BHEs at the east side and west were calculated 8.1℃ and 5.3℃, respectively. Compared with the temperature in the west side, the temperature in the east side rapidly recovered to the original temperature, which will give a higher COP (Coefficient Of Performance) in the east side BHEs due to the groundwater flow. The simulation results demonstrate the importance of the appropriate positioning of BHEs in a large-scale ground source heat pump system.

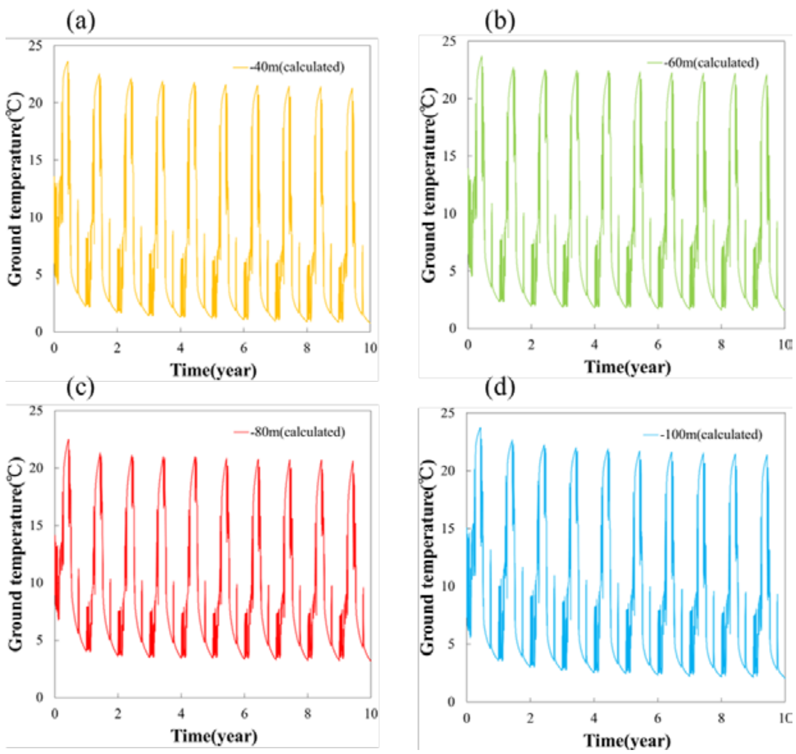

Figure 12. Result of future prediction of ground temperature (a) -40 m, (b) -60 m, (c) -80 m, (d) -100 m

Conclusions

In this research, the operation behavior of a large scale GSHP system in Akita, Japan was analyzed and the numerical model of the borehole field was developed. Then the validity of the model was confirmed with the operation data. Finally long-term simulation was conducted with the numerical model of the borehole field.

The operation data showed that the extracted heat was much larger than the injected heat. The ground temperature is expected to decrease gradually to cause a poor performance of the GSHP system.

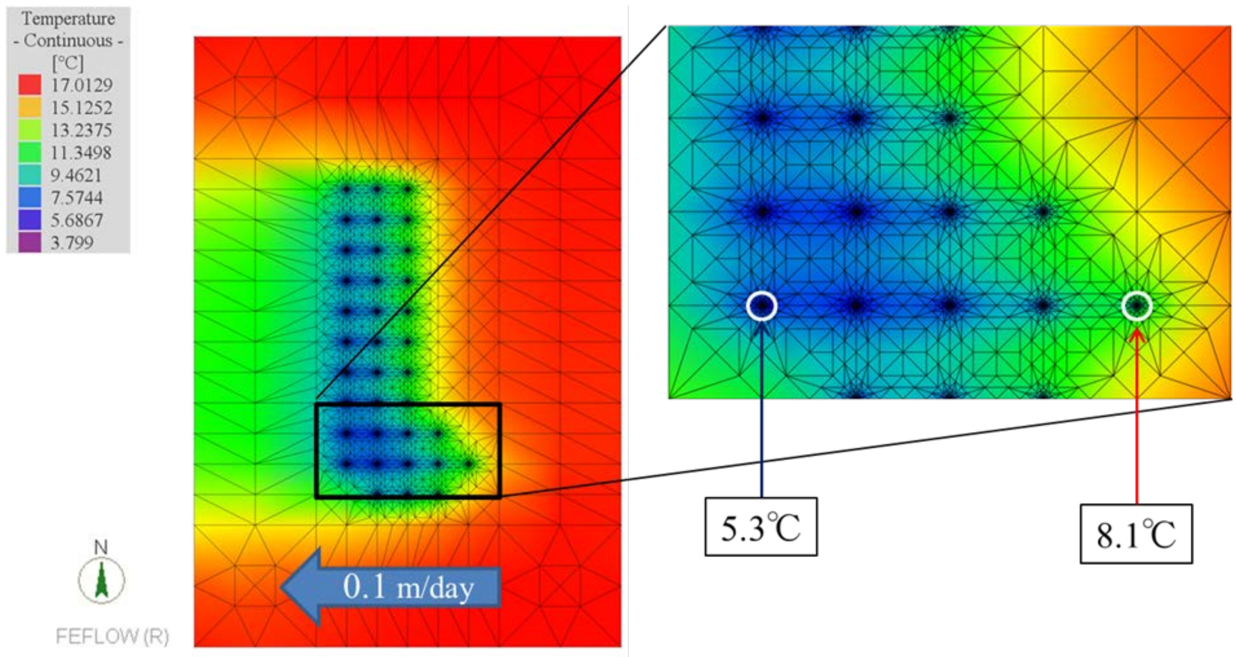

Figure 13. Distribution of ground temperature at -80 m at 10 years later

A numerical model of single U-tube BHE was developed and the validity of the model was confirmed with TRT data. Then, the numerical model of the borehole field was developed based on the model of single U-tube BHE and the validity of the model was confirmed with the operation data and measured ground temperature date at four depths.

The long-term simulation of ground temperature was conducted with the validated numerical model of borehole filed. The result of long-term simulation showed that the ground temperatures at each depth declined in the first 2 years, while they stabilized after 2years. The ground temperature around BHEs was affected by the direction of groundwater flow and the arrangement of BHEs

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