光ファイバー温度計を用いた多層の地下水流れの推定と地中熱ヒートポンプシステムの長期性能評価

Estimation of groundwater flow in multilayer using the distributed temperature sensors and the long-term GSHP performance evaluation

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This study proposes an improved analytical method for the thermal response test on utilizing distributed temperature sensors to determine groundwater velocity in the multi-layer. For the validation of the method, the temperature of the circulating fluid applied to estimated parameters in each sub-layer was calculated and compared with the thermal response test results and the measurement data of the building. The estimated groundwater velocities were 2750 m/y in 40 m of the depth, 58 m/y in 28 m of the depth and 0 m/y in 32 m of the depth. Based on the parameters, the performance of the GSHP system was analyzed according to the number of borehole heat exchanger. As a result, when the number of boreholes was applied to be 4, 3 and 2, the seasonal performance factors in the heating period were 7.5, 7.4 and 7.2, and the seasonal performance factors in the cooling period were 4.3, 4.2 and 4.2, respectively.

1. Introduction

Ground source heat pump (GSHP) system has been used to supply heating and cooling to buildings, using the ground as a heat source or a heat sink. The GSHP system can be improved in some areas with the groundwater flow. The effect of groundwater flow results in decreasing the length of the borehole heat exchanger (BHE) and the initial cost of the system.

Japan has consisted of a high slope of the mountains. The topographic conditions bring about active groundwater flow. Therefore, it is necessary to design the GSHP system, considering the groundwater flow for better system performance. However, many design tools only have considered effective thermal conductivity, and the GSHP system as a result of their results might be over/under-designed.

In the previous work of our research team, the effective thermal conductivity and the groundwater velocity were determined by the result of the minimum RMSE between the calculated results and the TRT data[1]. The approach method was efficient to determine the thickness-weighted average of the thermal conductivity and the groundwater velocity under the condition when the temperature data at the inlet and outlet from the Pt100 sensors can only be obtained. However, if the heat flux was injected during a long-term period, the temperature of the circulating fluid was expected to increase in practice. Whereas, the calculated temperature result is converged by the effect of the groundwater flow in the single-layer ground.

This study proposes an improved analytical method for the thermal response test on utilizing distributed temperature sensors to determine groundwater velocity in the multi-layer. This method can present better results for the long-term period. For the validation of the method, the temperature of the circulating fluid applied to estimated parameters in each sub-layer was calculated according to the building the load for one year. The calculated results were then compared with the measured data. Besides, the parameter study was conducted by the number of borehole heat exchangers, and each temperature results of the circulating fluid and coefficient of performance (COP) were compared. The result indicated the effect of the groundwater flow for the performance of the GSHP system.

2. Thermal response test

2.1 Test site description

The test site was in Kazuno City, the Akita prefecture (40°19’N and 140°78’E). The soil of the test site mainly consisted of gravel and gravelly sand and the thickness-weight average of the effective thermal conductivity was 2.4 W/(m·K). The GSHP system has been operated for cooling and heating to the three-story building with four BHEs installed at intervals of 4 m. The TRT was conducted from Jan. 9th to Jan. 30th for 400 h in 2017. During TRT, the heat injection period was 198 h, and the after heat injection period was 202 h. The temperature variation of the circulating fluid was measured according to the building load for one year in 2019.

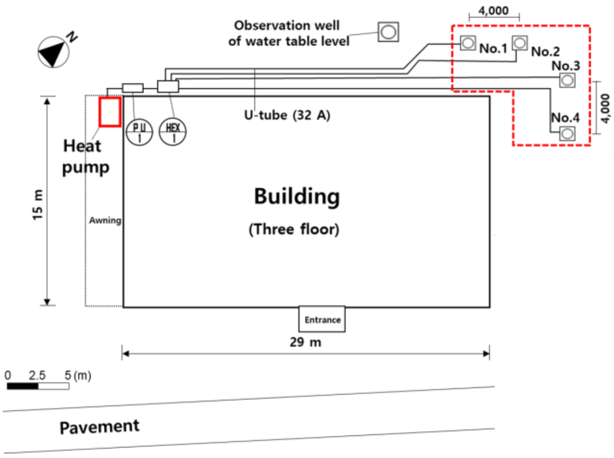

Figure 1. Ground plan of the test site

2.2 The thermal response test

The BHE was a double U-tube and high-density polyethylene (HDPE). Internal and external diameters of the U-tube were 25 mm and 32 mm. The length and diameter of BHE were 100 m and 146 mm. The borehole backfilled material was silica sand. The ethylene glycol (Concentration=41 %, freezing temperature= -23 °C) as the circulating fluid circulated in the BHE under 0.1 MPa of the pressure. The flow rate was almost constant in 20 L/min and the heat injection was calculated at 60.6 kW in Eq (1). The fiber optic-distributed temperature sensors (DTS) is inserted into the pipes to measure the temperature of the circulating fluid in each layer. Figure 2 shows the schematic the TRT machine units. Figure 3 indicates measurement data from TRT.

$$Q = \rho C_p m_f \bar{T} \tag{1}$$

$$\bar{T} = \frac{T_{in} + T_{out}}{2} \tag{2}$$

Here, Q is heat injection [kW], ρC_p is heat capacity [J/(K·m^3)], m_f is flow rate [L/min], $\bar{T}$ is mean temperature of the inlet and outlet temperature (T_{in}, T_{out}) of the pipe.

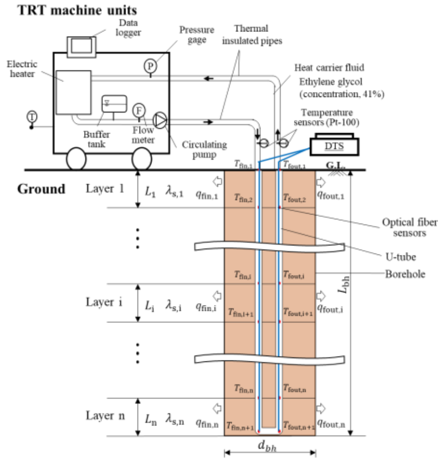

Figure 2. Schematic the TRT machine units

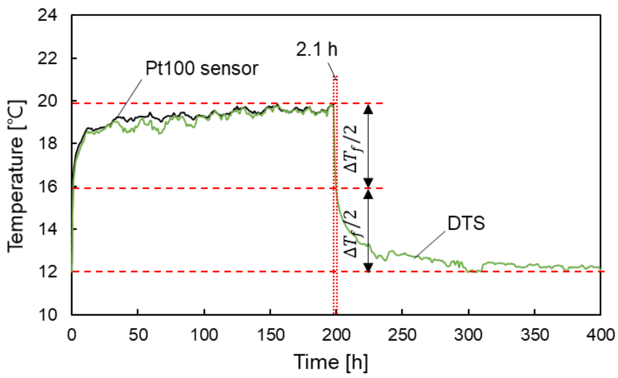

Figure 3. Measurement data of the Pt100 sensors and DTS

3. Estimation of thermal properties of sub-layers

3.1 Determination of the depth of sub-layers

The rate of the temperature increase of the circulating fluid each layer is mainly dominated by the heat injection for the TRT period and is similar, even though the heat transfer rate each layer is the difference. In other words, it is difficult to verify the thermal characteristics of each layer during the heat injection period. On the other hand, after heat injection, the rate of the temperature decrease of the circulating fluid in each layer is significantly different depending on the thermal properties of the soils. The rate of the temperature recovery that the heated temperature of the ground reaches the initial temperature of the ground can demonstrate both the heat transfer performance of the soil and the presence of the groundwater flow.

The rate of the temperature decrease calculated by the temporal superposition principle after the heat injection is determined by the thermal characteristic of the soil and the end time of the heat injection of the TRT, regardless of the heat flux. This study proposes a recovery time ($t_r = t - \tau$) when the rate of the temperature decrease becomes to be half of the temperature increase at the end of the heat injection of the TRT ($\Delta T_f(t) = 1/2\, \Delta T_f(\tau)$). When the thermal conductivity was 3 W/(m·K) and the end time of the heat injection was 198 h, the recovery time was 11.5h. As a result of the DTS, the recovery time was 2.1h. Based on those recovery times, the sub-layer was divided into three layers (the layer with the rapid groundwater flow, the layer with the moderate groundwater flow, the layer without the groundwater flow) Figures 4 shows the DTS data during the after heat injection.

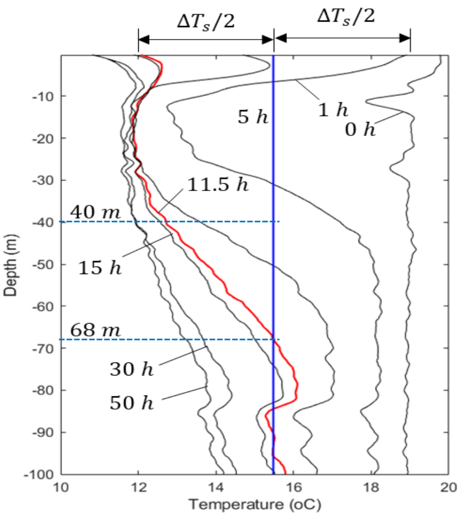

Figure 4. DTS data during the after heat injection

3.2 Estimation of the groundwater velocity and the effective thermal conductivity in the sub-layer

Based on the depth each the sub-layer, the heat exchange rate was calculated during the heat injection period by using Eq (3). The heat change rates in each layer were 92.8, 31.9 and 27.6 W/m. For the estimation of the groundwater velocity in sub-layers, the rate of the temperature increase was calculated by using the moving line source model that can consider the effect of the groundwater flow in Eq (4)[2]. The effective thermal conductivity of the soil was applied to the thickness-weight average of the thermal conductivity of the test site.

$$q_{L_i} = \frac{C\dot{m}}{L_i}\sum_{L_{i,start}}^{L_{i,end}} (\Delta T_{\mathrm{fin},i} + \Delta T_{\mathrm{fout},i}) \tag{3}$$

$$\Delta T_f(r_b, \varphi, t) = \frac{q}{4\pi\lambda}\int_0^{\pi}\int_0^{\frac{r^2}{4\alpha t}} \exp\left(\frac{U r_b}{2\alpha}\cos\varphi\right)\frac{1}{\beta}\exp\left(-\frac{1}{\beta} - \frac{U^2 r_b^2 \beta}{16\alpha^2}\right) d\beta + R_b q + T_0 \tag{4}$$

When the end time of the TRT during the heat injection period was 60 hours, the groundwater velocities of each layer were estimated to be 2750, 58, and 0 m/y. Figure 5 demonstrates the rate of the temperature increase according to the heat flux and the groundwater velocity. Figure 6 indicates the comparison of the TRT data and the calculated results. The calculated result is in agreement with TRT data.

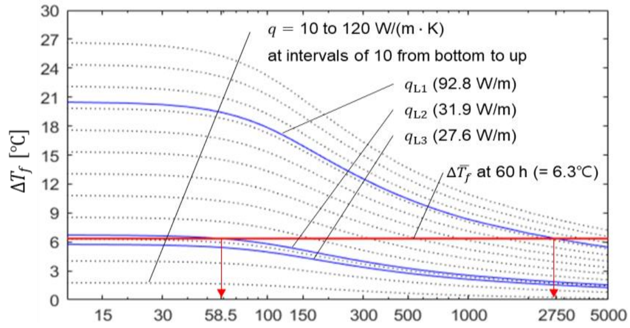

Figure 5. Rate of the temperature increase according to the heat flux and the groundwater velocity

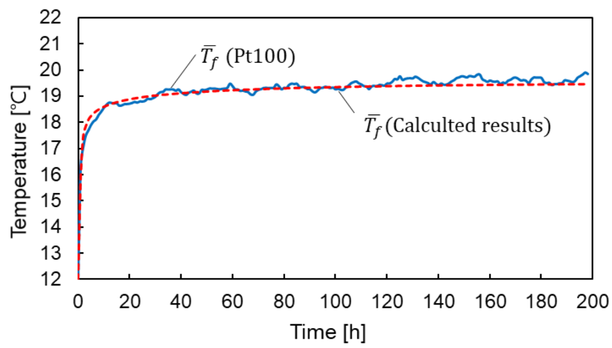

Figure 6. Comparison of the TRT data and the calculated results

4. Performance evaluation of the GSHP system during the long-term period.

4.1 Comparison of the measurement data and calculated results according to the building load

Figure 7 shows the heating and cooling loads of the building for one year and Figure 8 indicates the comparison of the measurement data and calculated results according to the building load. Figure 9 points out a comparison between the calculated data and measured data during the representative heating and cooling period for 10 days. The calculated result is in agreement with measurement data.

4.2 Performance evaluation of the GSHP system according the number of the borehole heat exchanger

The GSHP system has been operated for cooling and heating to the three-story building with four BHEs. Based on the estimated design parameters of the BHE, the circulating fluid and the COP was calculated according to the number of the BHE. Figure 10 shows the performance curve of heat pump. Figure 11 indicates the temperature variation according to the number of the BHE. Figure 12 points out the COP according to the number of the BHE. Figure 13 demonstrates the seasonal performance factor (SPF) of the heating and cooling period according to the number of the BHE. Although the number of the BHE was reduced, the SPF was not significantly different.

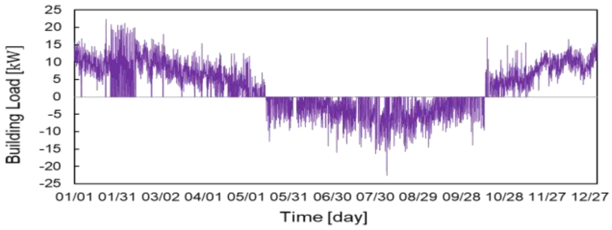

Figure 7. Heating and cooling loads of the building for one year

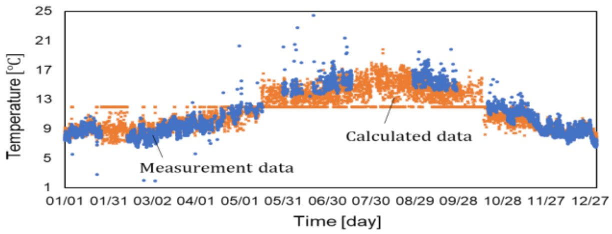

Figure 8. Comparison of the measurement data and calculated results according to the building load

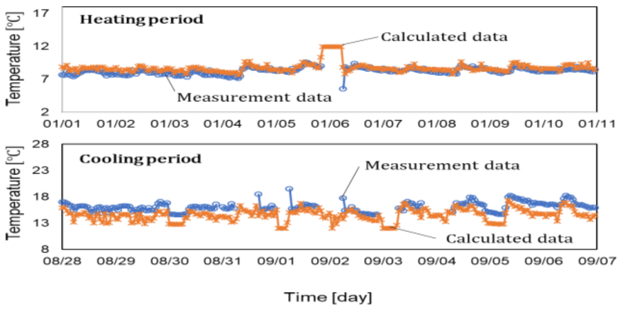

Figure 9. Comparison of the calculated data and measured data during the representative heating and cooling period for 10 days

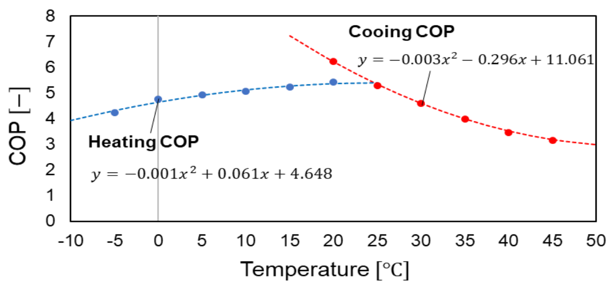

Figure 10. Performance curve of heat pump

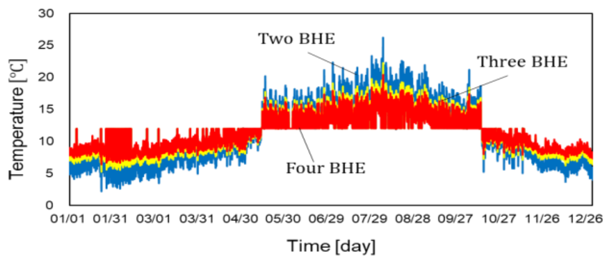

Figure 11. Temperature variation according to the number of the BHE

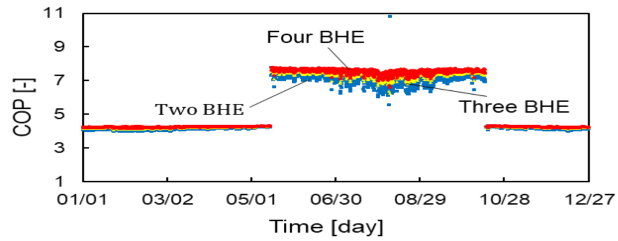

Figure 12. COP according to the number of the BHE

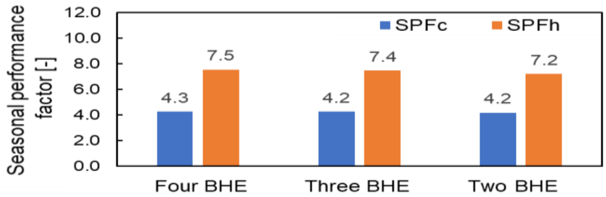

Figure 13. SPF of the heating and cooling period according to the number of the BHE

5. Conclusion

In this study, the depths in each sub-layer were estimated by using DTS data, and its thermal parameters estimated. Also, the calculated results of the circulating fluid were in agreement with the TRT data and the measurement data of the building. Based on the results, the performance of the GSHP system was analyzed according to the number of the BHE. Although the number of the BHE was reduced, the SPF was not significantly different.

References

1) H. Chae, K. Nagano, Y. Sakata, T. Katsura, T. Kondo , "Estimation of fast groundwater flow velocity from thermal response test results", Energy and Buildings, 2020

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Acknowledgement

Tohoku Electric Power Co., Inc. gave us a generous support to demonstrate the experiment.