HEAT TRANSFER MODEL OF A LINING BOREHOLE GROUND HEAT EXCHANGER UNDER GROUNDWATER FLOW

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ABSTRACT

Ground Source Heat Pump (GSHP) systems are a popular means to reduce energy consumption. However, in Japan, the spread of GSHP systems is hindered by drilling costs, which are much higher than those in western countries. Therefore, in order to reduce drilling costs, we previously developed a Lining Borehole Ground Heat Exchanger (LBHE). This study aims to determine the effect of groundwater flow on the heat exchange rate of an LBHE by constructing a heat transfer model of the LBHE under some assumptions and performing numerical simulation. First, a Thermal Response Test (TRT) was conducted to identify the effective thermal conductivity of the surrounding ground including the influence of groundwater flow. The accuracy of the model was confirmed by comparing the calculated outlet fluid temperature with that measured by the TRT. The results show that the calculated and measured temperatures are in good agreement. Finally, a numerical simulation was conducted under the condition that the inlet fluid temperature and the flow rate of the LBHE were constant. The results of the simulation predicted that the heat exchange rate per unit length would increase by 13 % when groundwater flow existed in the two gravel layers. This suggests that the effect of groundwater flow should be considered in order to precisely evaluate the thermal performance of LBHEs.

Keywords: ground heat, groundwater flow, lining borehole ground heat exchanger, thermal response test, effective thermal conductivity

1. INTRODUCTION

Ground Source Heat Pump (GSHP) systems have become popular worldwide since their efficiency is higher than those of conventional heat pump systems. It has been estimated that in 2014 GSHP systems saved an energy consumption equivalent to 52.5 million tonnes of oil (John et al., 2015). However, in Japan, the spread of GSHP systems is hindered by drilling costs, which are much higher than those in western countries due to the country's complex geology. In order to reduce drilling costs, we previously developed a new type of borehole heat exchanger, called a Lining Borehole Ground Heat Exchanger (LBHE; Terasaki et al., 2018), using a thermosetting resin-impregnated fabric. A schematic of the LBHE is shown in Figure 1. In the LBHE, the heat exchange area is wider than that of conventional borehole heat exchangers (e.g., the Double U-tube heat exchanger, DUT), and the heat storage capacity is larger than that of DUTs. Terasaki et al. (2018) examined the heat transfer characteristics of an LBHE, and Suzuki et al. (2019) proposed a flow rate control GSHP system with an LBHE from the view point of heat storage.

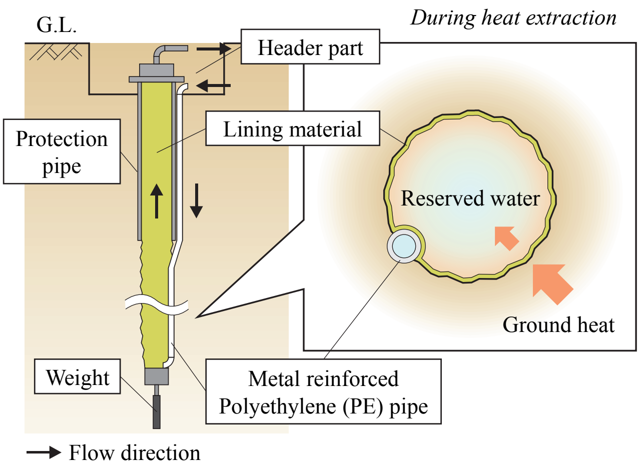

Figure 1. Schematic of a Lining Borehole Ground Heat Exchanger (LBHE).

On the other hand, some studies have considered the potential of groundwater flow to reduce the capacity of GSHP systems, as it is known that groundwater flow increases the heat exchange efficiency of such systems. For example, Uchida et al. (2010) constructed a potential map of a GSHP system and examined suitable areas for the application of such systems by using field survey data and a groundwater flow/heat transport model. Additionally, Sakata et al. (2018) analyzed the effects of groundwater flow on the required length of a borehole heat exchanger in a residential building. Therefore, it is important to evaluate the heat exchange rate of an LBHE under groundwater flow in order to further reduce its length.

Therefore, this study aimed to determine the effect of groundwater flow on the heat exchange rate of an LBHE using a heat transfer model of the LBHE and numerical simulation.

2. HEAT TRANSFER MODEL OF A LINING BOREHOLE GROUND HEAT EXCHANGER UNDER GROUNDWATER FLOW

2.1 Model assumptions

Figure 2 shows the spatial calculation range and element division of the proposed LBHE heat transfer model. The temperature of each element was calculated using a finite difference method (FDM) based on three-dimensional heat transfer analysis with the following assumptions:

1. The lining material expands uniformly in the z direction;
2. The temperature gradient of the fluid is uniform in the x and y directions;
3. The heat flux across the lining material and the metal reinforced PE pipe is proportional to the temperature difference between the fluid and the surrounding ground;
4. The effect of groundwater flow on the heat transfer can be expressed by the value of the effective thermal conductivity, λ_{eff} (W/m/K) including the influence of groundwater flow.

2.2 Fundamental equations

According to Fourier's law of heat conduction, the time rate of change of the internal energy of the ground elements which are not adjacent to the fluid elements is given by Equation (1):

$$(\rho c)_g \frac{\partial T_g}{\partial t} = \lambda_g \frac{\partial^2 T_g}{\partial x^2} + \lambda_g \frac{\partial^2 T_g}{\partial y^2} + \lambda_g \frac{\partial^2 T_g}{\partial z^2} \tag{1}$$

where $(\rho c)_g$ is the volumetric heat capacity of the ground (J/m^3/K); T_g is the ground temperature (°C); t is the time (s); and λ_g is the thermal conductivity of the ground (W/m/K), which is equal to λ_{eff} by Assumption 4.

The time rate of change of the internal energy of the fluid elements which are adjacent to ground elements is prescribed by the conductive heat, the sensible heat due to the movement of the fluid, and the extracted heat flux, i.e.:

$$(\rho c)_w \frac{\partial T_{w(m)}}{\partial t} = \lambda_w \frac{\partial^2 T_{w(m)}}{\partial z^2} - (\rho c)_w U_w \frac{\partial T_{w(m)}}{\partial z} + E_{(m)}\eta \tag{2}$$

where $(\rho c)_w$ is the volumetric heat capacity of the fluid (J/m^3/K), $T_{w(m)}$ (m [number] = 1: lining part, m = 2: pipe part) is the fluid temperature (°C), λ_w is the thermal conductivity of the fluid (W/m/K), U_w is the velocity of the fluid (m/s), $E_{(m)}$ is the extracted heat flux per unit contact area of the fluid (W/m^2), and η is the ratio of the contact area with the ground to the volume of the fluid element (1/m).

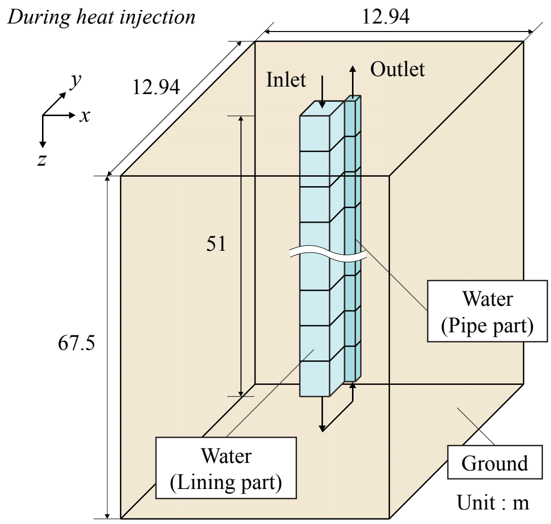

Figure 2. Three-dimensional view of the heat transfer model of the LBHE.

Table 1. Thermal properties of the heat transfer model.

		Thermal conductivity (W/m/K)	Volumetric heat capacity ($J/m^3/K$)
Water (30 °C)		0.62	4,163,280
Ground	z = 0.0–7.5 m	1.24	2,352,000
	z = 7.5–12.5 m	1.24	
	z = 12.5–17.5 m	1.33	
	z = 17.5–22.5 m	1.42	
	z = 22.5–27.5 m	1.44	
	z = 27.5–32.5 m	1.45	
	z = 32.5–37.5 m	1.41	
	z = 37.5–42.5 m	1.37	
	z = 42.5–47.5 m	2.08	
	z = 47.5–52.5 m	2.78	
	z = 53.5–57.5 m	1.45	
	z = 58.5–62.5 m	1.45	
	z = 62.5–67.5 m	1.45	

In Equation (2), $E_{(m)}$ is given by Equation (3) based on Assumption 3:

$$E_{(m)} = \alpha_{(m)}\left(T_g - T_{w(m)}\right) \tag{3}$$

where $\alpha_{(m)}$ is the heat transfer coefficient between the fluid and the surrounding ground ($W/m^2/K$).

2.3 Analytical conditions

The initial T_g was linearly interpolated from the measured data from the TRT. The inlet fluid temperature data obtained in the TRT (see Section 3) and meteorological data at the site where the TRT was conducted were used as boundary conditions. The parameter $\alpha_{(m)}$ was determined to the value which reproduced the outlet fluid temperature in the TRT. Table 1 shows the thermal properties of the model. The λ_{eff} at each depth was calculated from the TRT and the other parameters were derived from handbooks (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, 1995; The Japan Society of Mechanical Engineers, 2009).

3. THERMAL RESPONSE TEST

A Thermal Response Test (TRT) was conducted in Fukui, Japan, from 07 to 10 September 2017 using an LBHE which was constructed at a borehole (diameter: 160 mm; length: 51 m). A TRT is a test used to estimate the thermal properties of the ground and a borehole heat exchanger, and was standardized by Sanner et al. (2005). Details of the TRT are shown in Figures 3 and 4. During the TRT, the temperatures of the inlet and outlet fluid and the flow rate were measured using Pt100 sensors (manufactured by CHINO) and a flow meter (manufactured by KEYENCE) during heating, respectively. Additionally, the ground temperatures near the LBHE were measured by thermocouples placed every 10 m at depths of 0–50 m. These data were recorded at 1 minute intervals by data loggers.

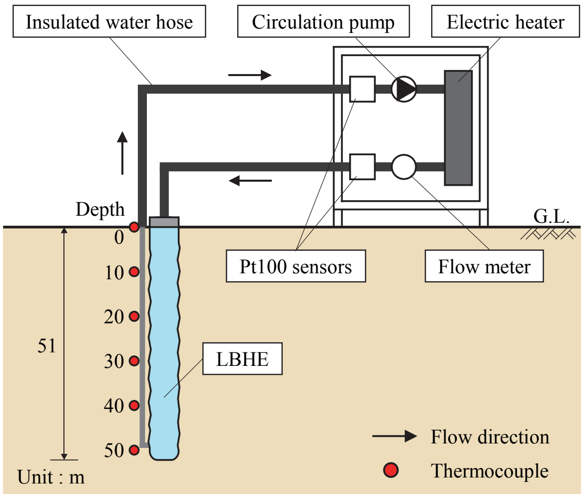

Figure 3. Schematic view of the Thermal Response Test (TRT). LBHE: Lining Borehole Ground Heat Exchanger. G.L.: Ground level.

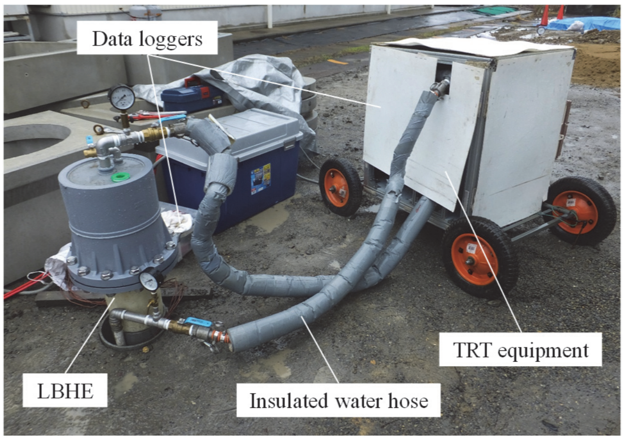

Figure 4. Equipment used to conduct the TRT.

The TRT procedure is as follows (after Sanner et al., 2005):

1. Connect the LBHE with the insulated water hoses and pass water into the hoses to remove the air;
2. Circulate the fluid in the LBHE at a flow rate of 20 L/min for about 30 minutes to measure the initial fluid temperature;
3. Heat the circulating fluid using a heater at a power of 4 kW for more than 60 hours (in this paper, this procedure is referred to as the circulation test);
4. Monitor the profiles of the temperature of the surrounding ground using the thermocouples for about 72 hours after circulation and heating (in this paper, this procedure is referred to as the recovery test).

The data obtained from the TRT were analyzed based on line source theory (Ingersoll and Plass, 1948). Assuming that the heat exchange rate is constant along the borehole, T_w during the circulation test and T_g during the recovery test are expressed by Equation (4) and Equation (5), respectively.

$$T_w = \frac{q}{4\pi\lambda_{eff}}\left(\ln\left(\frac{4\alpha_g t}{r_b^2}\right) - \gamma\right) + qR_b + T_o \tag{4}$$

$$T_g = \frac{q}{4\pi\lambda_{eff}}\ln\frac{t_a + t_p}{t_a} + T_o \tag{5}$$

where q is the heat exchange rate of the LBHE (W/m) per unit length, α_g is the thermal diffusivity of the ground (m^2/s), t is the elapsed time during heating (s), r_b is the borehole radius (m), γ is Euler's constant (= 0.5772), R_b is the thermal resistance of the LBHE (K/(W/m)), T_o is the initial fluid temperature in the LBHE (°C), t_a is the elapsed time after heating (s), t_p is the heating time (s), and $(t_a + t_p)/t_a$ is the Horner time (-). In the analysis, T_w is the average of the inlet and outlet fluid temperatures of the LBHE. The average λ_{eff} and R_b were calculated using T_w via Equation (4), and the λ_{eff} at each depth was calculated using the T_g at each depth obtained from Equation (5).

4. RESULTS OF THE THERMAL RESPONSE TEST

The main results which are discussed in this paper are those of the recovery test. Figure 5 shows the temporal variations in the inlet fluid temperature (T_{wi}, °C) and outlet fluid temperature (T_{wo}, °C), as well as the temporal variation of q calculated using these temperatures and the flow rate. As shown in the figure, the values of T_{wi} and T_{wo} increased slowly, and the difference between these temperatures was approximately 3 °C. Meanwhile, q varied constantly, and its average value was 87.2 W/m.

As an example of the analysis results, Figure 6 shows a logarithmic plot of T_g during the recovery test at a depth of 30 m. As shown in the figure, T_g varied linearly when the Horner time was less than 10, and it was expressed by logarithmic equation in the figure at t_a = 10–72 hours. Figure 7 shows the estimated λ_{eff} profile and the geological column at the site. At depths of 10–40 m, the geology mainly consists of silt and sandy silt and λ_{eff} ranges from 1.24–1.45 W/m/K. On the other hand, at a depth of 50 m, λ_{eff} is 2.78 W/m/K, around two times larger than the average value at depths of 10–40 m (1.37 W/m/K). It is expected that groundwater flow exists in the layer at 50 m since the layer consists of gravel and the value of λ_{eff} is higher than the thermal conductivity of saturated gravel (Laboratory of Ground Thermal Energy Systems, Hokkaido University, 2007).

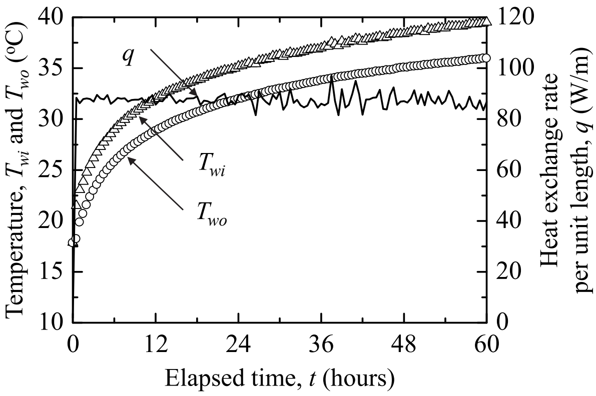

Figure 5. Temporal variations in inlet and outlet fluid temperatures (T_{wi} and T_{wo}, respectively) and heat exchange rate per unit length.

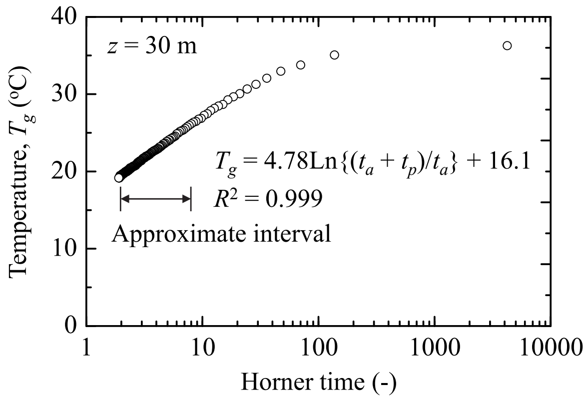

Figure 6. Logarithmic plot of ground temperature (T_g) against Horner time during the recovery test (depth = 30 m).

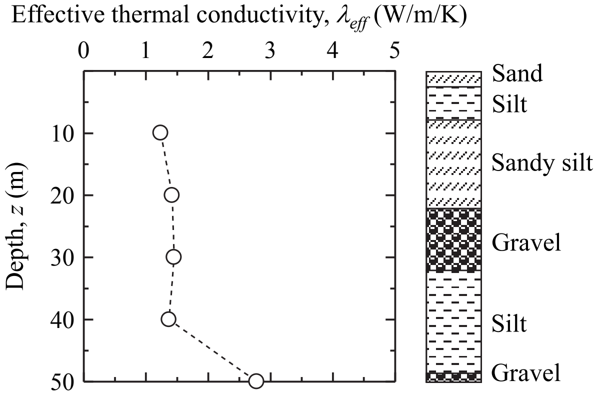

Figure 7. Estimated effective thermal conductivity profile and geological column.

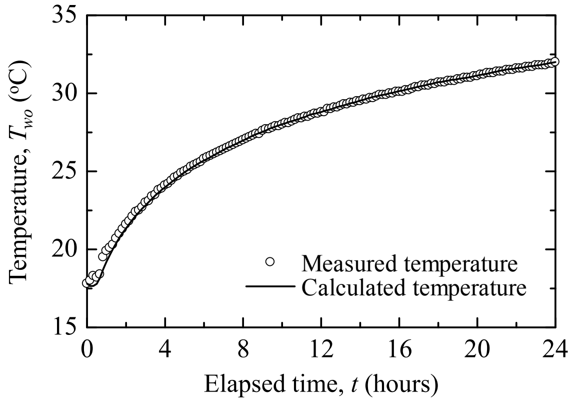

Figure 8. Temporal variation of the measured outlet fluid temperature of the LBHE and the calculated outlet fluid temperature of the LBHE.

Table 2. Conditions of the simulations.

Simulation	Duration (hours)	Inlet water temp. (°C)	Flow rate (L/min)	Thermal conductivity (W/m/K) z = 23.5–33.5 m	Thermal conductivity (W/m/K) z = 48.5–53.5 m	Presence of groundwater flow
1				1.37	1.37	None
2	24	30	20	1.37	2.78	Layer 2
3				2.78	2.78	Layers 1 and 2

Figure 8 shows the temporal variations in the measured and calculated values of T_{wo}. The calculated values are lower than the measured values until t = 3 hours; however, beyond 3 hours, the calculated values are in good agreement with the measured values, and the average difference between the two is lower than 0.1 °C.

5. SIMULATION WITH DIFFERENT GROUND CONDITIONS

A numerical simulation was conducted to examine the effect of groundwater flow on the heat exchange of the LBHE. The conditions of the simulation are shown in Table 2. In the simulation, the inlet fluid temperature and flow rate were 30 °C and 20 L/min, respectively, based on the results of the heat injection test of Fujii and Akibayashi (2002). In this model, the layer at depths of between 23.5 and 33.5 m (Layer 1) and the layer at depths of between 48.5 and 53.5 m (Layer 2) were expressed by gravel layers. Additionally, it was regarded that the value of λ_{eff} was 1.37 W/m/K when no groundwater flow exists and 2.78 W/m/K when groundwater flow exists. Three simulations were conducted, termed Case 1, Case 2, and Case 3. Groundwater flow does not exist in any layer in Case 1 and exists in Layer 2 in Case 2 and in layers 1 and 2 in Case 3.

Figure 9 shows the temporal variation of T_{wo} in each simulation. In each simulation, T_{wo} rapidly decreased from 20.5 to 17.9 °C between 0 and 30 minutes due to the fact that the low-temperature fluid in the LBHE flowed out from its outlet. Between 30 minutes and 2 hours, the T_{wo} increased to about 26 °C, and beyond 2 hours the increase rate of T_{wo} decreased gradually. This may be due to the increase in the temperature of the surrounding ground. In Case 3, the T_{wo} was about 0.3 °C and 0.2 °C lower than that of Case 1 and Case 2, respectively.

Figure 10 shows q at t = 24 hours in each simulation. In each simulation, q was more than 40 W/m, which is a standard value of conventional borehole heat exchangers (Laboratory of Ground Thermal Energy Systems,

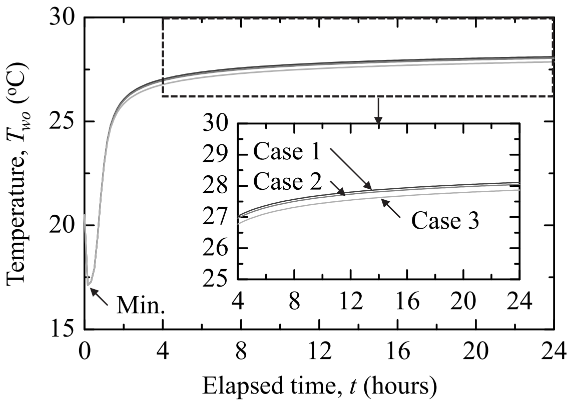

Figure 9. Temporal variations of outlet temperature in each simulation.

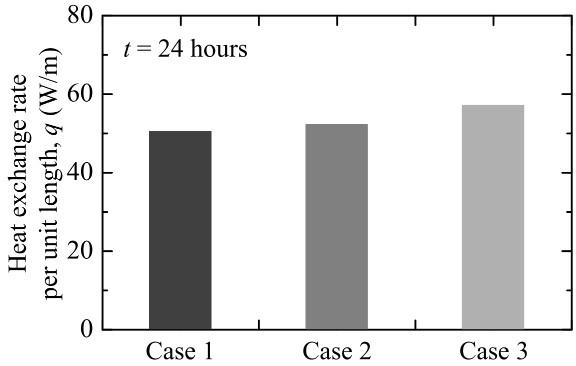

Figure 10. Comparison of the heat exchange rate per unit length at t = 24 hours in each simulation.

Hokkaido University, 2007). The value of q was 4 % and 13 % larger in Case 3 than in Case 1 and Case 2, respectively.

6. CONCLUSIONS

In order to determine the effect of groundwater flow on the heat exchange rate of an LBHE, a heat transfer model of the LBHE was constructed. First, a TRT was conducted to identify the effective thermal conductivity of the surrounding ground. Then, a numerical simulation was conducted under the condition that the inlet fluid temperature in the LBHE and the flow rate were constant. The main results are as follows:

1. Based on the results of the TRT, it is expected that groundwater flow exists at a depth of 50 m;
2. The temporal variation of the calculated outlet temperature is in good agreement with the measured temporal variation;
3. The results of the simulations suggest that the effect of groundwater flow should be considered in order to precisely evaluate the thermal performance of LBHEs.

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