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Multi-heat Injection Rate Thermal Response Test and Corresponding Parameter Estimation Method to Determine Performance Dependence in Saturated Porous Formation

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Abstract

The effective ground thermal conductivity and borehole thermal resistance, which are key parameters in the design of borehole heat exchangers (BHEs), are often determined using an in-situ *thermal response test (TRT). The results of TRTs in saturated porous formations have been reported to depend on the heat injection rate. If this dependence is examined using multiple thermal response tests at a single heat injection rate, the ground takes a long time to return to the initial temperature between tests and the ground conditions have changed. Therefore, the results of multiple TRTs will not depend solely on the heat injection rate, and many uncertainties can be included. In this work, a new practical method is proposed to minimize the effect of temporal changes in the ground condition. The method combines a multi-heat injection rate TRT with a parameter estimation method using the infinite line source model and the quasi-Newton method. TRTs were conducted with two different borehole heat exchangers installed in a saturated sandy formation to verify the effectiveness of the proposed method. The proposed estimation and experimental methods are relatively simple; however, the magnitude of the natural convection can be determined without detailed analysis of the subsurface condition.*

Keywords - Thermal response test; Parameter estimation; Ground source heat pump; Borehole heat exchanger; Inverse problem

1. Introduction

The design of a borehole heat exchanger (BHE), which is the most important component in a ground source heat pump (GSHP), requires two parameters: the ground effective thermal conductivity λ_{eff} and the borehole thermal resistance R_b. These parameters are estimated using an *in-situ* thermal response test (TRT) because of the site-specific characteristics. When interpreting TRT data, the approximated infinite line source (ILS) model [1,2] is frequently used. However, the ILS model (and many other models) assumes that the heat is dissipated only by conduction. However, if the BHE is installed in a saturated porous formation or has a groundwater-filled configuration, the advection effect, which is due to the density difference, will affect the results. Of course, the heat injection rate setting of the TRT has a significant impact on the strength of natural convection.

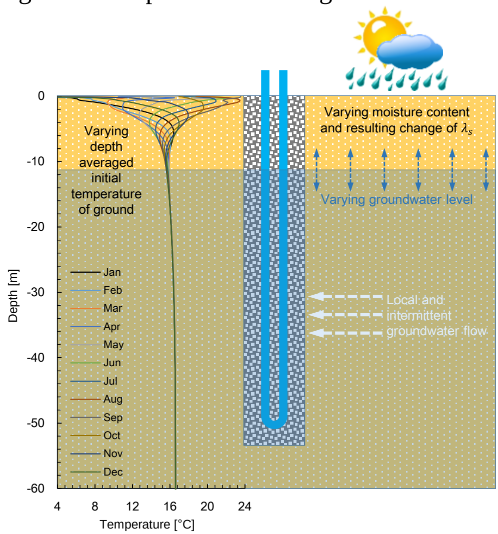

Fig. 1 Schematic illustration of temporal change in ground conditions

When conducting TRTs several times in the same BHE using different constant heat injection rates to examine the heat rate dependence, the experimenter should wait a long time, i.e., until the ground temperature returns to its original temperature. During the waiting period, the ground conditions are changed, as shown in Fig. 1; the results of the TRT will include the undesirable effect of the ground conditions having changed in addition to the effect of the heat injection rate.

To overcome the above problems, a new method is suggested to practically examine the heat rate dependence of TRTs of a BHE while avoiding the long recovery times required by the previous approach. The proposed method uses a multi-heat injection rate TRT and corresponding parameter estimation based on combining the ILS model with temporal superposition and the quasi-Newton method. The effectiveness of the proposed estimation method was validated using numerically generated TRT data. After validation, two multi-heat injection rate TRTs were conducted and parameters were estimated using the proposed method.

2. Setup of Thermal Response Test

The experimental system was constructed at Chiba Experimental Station at the University of Tokyo (Inage Ward, Chiba, Japan) in 2014. The details of the experimental system can be found in Ref. [3]. The site was stratigraphically divided into a top layer of loam and clay (depth: 0–8 m), followed by fine sand (depth: 8–25 m), silt (depth: 25–31 m), and fine sand (depth: 31–60 m) ((Fig. 2 (a)). The groundwater level fluctuated around a depth of 10–12 m. The soil sampling and pumping test estimated the porosity and hydraulic conductivity of sand to be 35% and 2.1e-04 m/s, respectively. The effective depth and diameter of the boreholes were 50 m and 165 mm, respectively. After drilling, a single high-density polyethylene (HDPE) U-tube was inserted in each borehole, with spacers to maintain a shank spacing of 50 mm. In Fig. 2 (b), the BHE on the right-hand side of the observation well was grouted with Portland cement mixed with 20% silica sand (GR-BHE), whereas the BHE located on the left was backfilled with gravel (BF-BHE) with a grain size of 8–15 mm and a porosity of 38%. Water was used as the working fluid. The flow rate was measured using an electromagnetic flowmeter. The inlet and outlet fluid temperatures were measured using a Pt-100 thermometer. All of the data were recorded at intervals of 5 s.

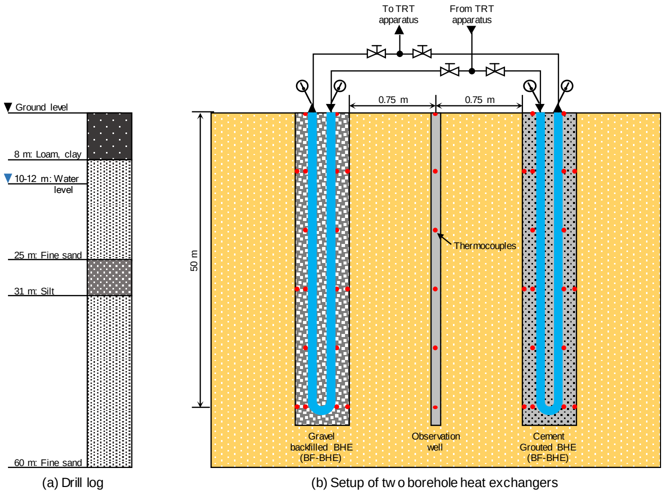

Fig. 2 Schematic illustration of experiment: (a) drill log of experiment site and (b) representation of experimental setup

3. Multi-heat Injection Rate TRT

The multi-heat injection rate TRT method has already been reported in papers on groundwater-filled BHEs [4,5]. The method used in this study was similar to several of those already reported but the first heat injection rate should be lower than 50 W/m so as to minimize the effect of natural convection. The experimental procedure is as follows:

(1) Start the first injection period t_{p1} using a relatively low heat rate of less than 50 W/m. If the experimenter has *a priori* information regarding the test site, the estimation can be performed with good initial guess values of

λ_{eff} and R_b. In this case, the duration of t_{p1} can be less than 2 days. However, if no information about the test site is available, the first injection period should be more than 60 h so as to obtain reliable initial guess values for the parameter estimation using a regressive estimation method based on the ILS model.

(2) After t_{p1}, the second injection period t_{p2}, with a higher heat injection rate, begins. The duration of the second period should be more than 1 day.

(3) If the TRT apparatus can generate a higher heat rate, a third injection period t_{p3} can be used. The duration of the third period should also be more than 1 day. During this period, the fluid temperature should be less than the temperature tolerance specified by the U-tube manufacturer.

4. Parameter Estimation Method and Validation

In this study, a parameter estimation method that combines the ILS model with temporal superposition and the quasi-Newton method was used for interpretation. The details can be found in Ref. [3]. This method can consider the disturbances that produce the TRT results fluctuating [6,7], and yield the estimation behavior. The ILS model, with temporal superposition applied, is an expression for the average fluid temperature as follows:

$$\bar{T}_{cf,cal}(t) = \sum_{n=1}^{N} \frac{q_n - q_{n-1}}{4\pi\lambda_{eff}} \mathrm{Ei}\left(\frac{C_s r_b^2}{4\lambda_{eff}(t_N - t_{n-1})}\right) + R_b \cdot q_N + T_0 \tag{1}$$

where $\bar{T}_{cf,cal}$ is the calculated average fluid temperature, q_n is the *n*-th heat pulse ($q_0 = 0$ W/m), C_s is the volumetric thermal capacity of the soil, r_b is the radius of the borehole, t_n is the discrete elapsed time ($t_0 = 0$), T_0 is the initial ground temperature, and N is the number of time steps.

The volumetric heat capacity of soil C_s was assumed to be 2.8 MJ/(m^3·K). The depth-averaged T_0 value varied in the range of 16.5–17.5 °C. The heat rate per unit length of the BHE for a given time step q_n is time-variant; its value can be obtained from the actual heat injection rate Q_{BHE}. The heat rate q was modelled using piecewise-averaged 6-min-long square pulses. The actual heat injection rate per unit BHE length q (W/m) can be obtained using the following formula.

$$q = Q_{BHE}/H = \rho_{cf} c_{cf} \dot{V}_{cf}\left(T_{cf,in} - T_{cf,out}\right)/H \tag{2}$$

where H is the depth of the BHE, ρ_{cf} is the density of the fluid, c_{cf} is the specific heat of the fluid, $\dot{V}_{cf}$ is the volumetric flow rate of the fluid, $T_{cf,in}$ is the BHE inlet fluid temperature, and $T_{cf,out}$ is the BHE outlet fluid temperature.

$\bar{T}_{cf,cal}$ is a function of two unknown variables, i.e., λ_{eff} and R_b. The two parameters λ_{eff} and R_b can be estimated by minimizing the objective function to less than 10^{-5} for every 6-min interval of the time step described in Eq. (3). Starting from the second injection period, λ_{eff} is fixed to the final estimated value of the first injection period, which is less affected by natural convection. Therefore, the objective function in Eq. (3) becomes Eq. (4), which is a function of R_b alone.

$$\min f_{obj}(\lambda_{eff}, R_b) = \left(\bar{T}_{cf,exp} - \bar{T}_{cf,cal}(\lambda_{eff}, R_b)\right)^2 \leq 10^{-5} \tag{3}$$

$$\min f_{obj}(R_b) = \left(\bar{T}_{cf,exp} - \bar{T}_{cf,cal}(R_b)\right)^2 \leq 10^{-5} \tag{4}$$

This objective function is minimized using the quasi-Newton method. Because of the ill-posedness of the inverse problem, there are multiple combinations of solutions. To alleviate this problem and enhance the estimation speed, two measures were introduced: (1) from the second time step onward, the initial guess values were updated using the solution determined in the previous time step; and (2) the search range was restricted to [$\lambda_{eff,ini}$ ± 0.5 W/(m·K)] and [$R_{b,ini}$ ± 0.05 m·K/W].

To verify the effectiveness of the proposed method, numerical TRT data were generated using the finite element method. The BHE geometry was fully discretized in a 3-D numerical model. The details of the numerical model can be found in Ref. [7]. The entire domain had an initial temperature of 17 °C. The thermal conductivity of the soil was set to 1.8 W/(m·K). The top, bottom, and lateral boundary conditions were adiabatic. The boundary condition of the BHE was defined using time-varying Dirichlet conditions. The flow rate $\dot{V}_{cf}$ was set to 15 L/min. The first, second, and third injection periods (t_{p1}, t_{p2}, and t_{p3}) were 48, 24, and 48 h, respectively. The heaters used in each period (Q_{p1}, Q_{p2}, and Q_{p3}) were 2, 3, and 4 kW (40, 60, and 80 W/m), respectively. Fig. 3 shows the temperature response and heat injection rate of the numerical model. Fig. 4 shows the estimated values and relative error ε_{rel} of R_b based on the final estimated value of t_{p1} (48 h).

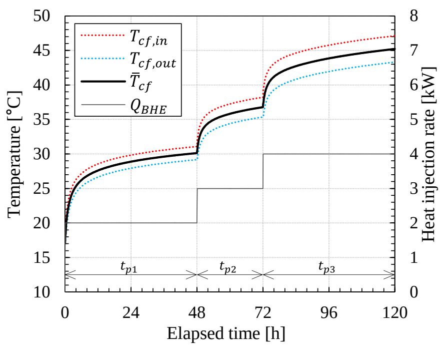

Fig. 3 Temperature response curve and the heat injection rate from the numerical thermal response test.

Table 1. Initial guess values and estimated values using numerical TRT data

Initial of λ_{eff} and R_b [W/(m·K)], (m·K/W)	Final λ_{eff} in t_{p1} [W/(m·K)]	Final R_b of each period (m·K/W)		
		t_{p1}	t_{p2}	t_{p3}
1.78, 0.17	1.79	0.167	0.167	0.167

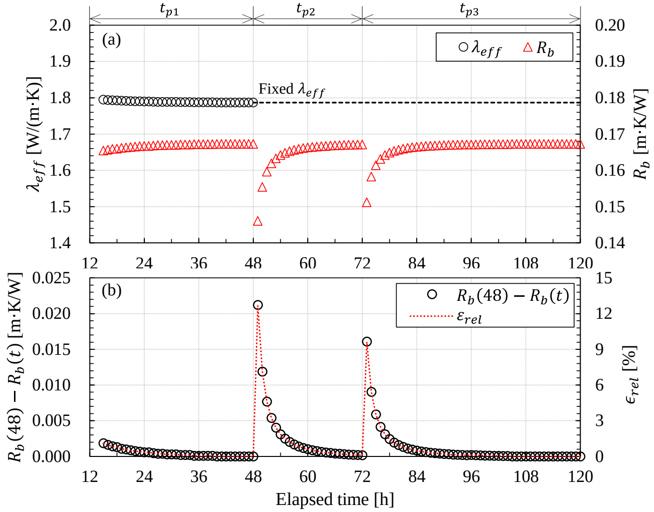

Fig. 4 Estimated results: (a) effective thermal conductivity and borehole thermal resistance, and (b) absolute error and relative error in borehole thermal resistance based on the final estimated value from the first injection period

The final estimated value of λ_{eff} in t_{p1} was 1.79 W/(m·K), which was very close to the set value of 1.8 W/(m·K). When the heat injection rate changed (at 48 and 72 h), the estimated value of R_b abruptly decreased and then gradually increased over time. This phenomenon was caused by the limitations of the ILS model, which cannot accurately consider the transient temperature response when temperature response is dominated by the BHE itself. For ε_{rel} to become less than 1%, t_{p2} and t_{p3} were be 9 and 8 h, respectively. Although unstable behavior was observed when the heat rate changed, the final estimated values of R_b in t_{p2} and t_{p3} were almost the same as that in t_{p1} (Table 1). This result indicates that if the heat transfer in the ground is dominated by conduction, the λ_{eff} and R_b values estimated using the proposed method are independent of the heat injection rate. Therefore, if the multi-heat injection rate TRT is conducted in a saturated porous formation in which the advection effect from the groundwater flow is negligible, and the estimated value of R_b is changed by the higher heat rate, natural convection causes the change in R_b. Because λ_{eff} is fixed in t_{p2} and remains the same in t_{p3}, the effect of natural convection is fully reflected by R_b. Therefore, the effectiveness and reliability of the proposed method were verified by this demonstration using numerical TRT data.

5. Thermal Response Test and Estimation Results

For each BHE, TRT was conducted once. Table 2 summarizes the test conditions. By combining the three different heaters (1, 2, and 3 kW) equipped in the TRT rig, three different output powers could be generated for different heat injection periods. The heat injection rates listed in Table 2 were averaged over the duration of each injection period. The averaged flow rates of TRT1 and TRT2 were 20.7 L/min and 19.6 L/min, respectively. The initial temperature of the ground was measured by circulating fluid without heat injection; it was found to be 17 °C.

Fig. 5 shows the temperature response of TRT1 and TRT2. When the heat injection rate and duration are the same, the BHE with the lower temperature should provide better performance. It was difficult to ensure that the heat injection rates of different TRTs were identical because of fluctuations in the voltage and heat exchange with the outdoor environment. Fortunately, the heat injection rates for the TRTs in this study were very similar (Table 2). Therefore, the performance of each BHE could be guessed based on the temperature level. At the end of each injection period, BF-BHE showed a slightly lower temperature than GR-BHE within the range of 0.25–0.41 °C, which means that BF-BHE has better performance than GR-BHE.

Table 2. Duration of each injection period and heat injection rates of two TRTs

Case	Duration [h]			Heat injection rate [W/m]		
	t_{p1}	t_{p2}	t_{p3}	q_{p1}	q_{p2}	q_{p3}
TRT1 (BF)	96	48	48	44.7	67.4	90.0
TRT2 (GR)	96	48	48	44.0	67.0	90.3

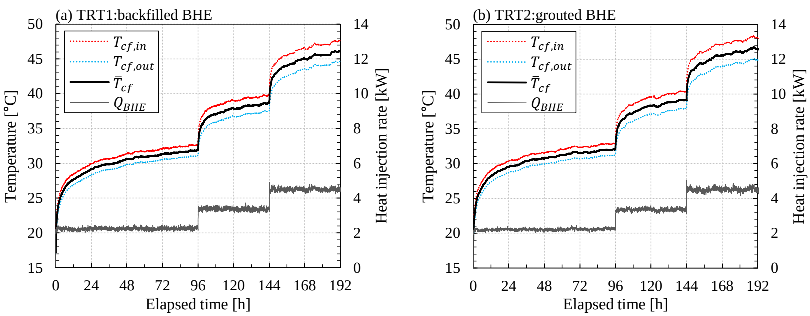

Fig. 5 Temperature response curve and heat injection rate: (a) TRT1 (backfilled BHE) and (b) TRT2 (grouted BHE)

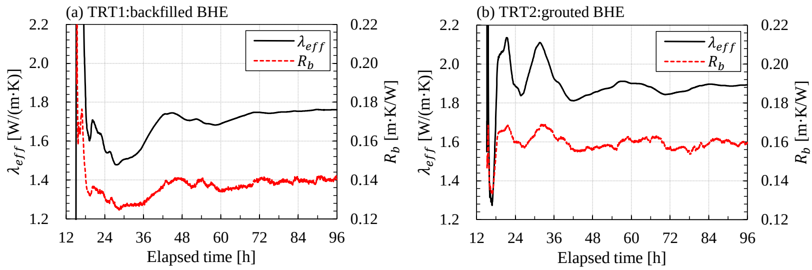

Fig. 6 Sequential estimation of first injection period using regression method: (a) TRT1 (backfilled BHE) and (b) TRT2 (grouted BHE)

Before parameter estimation, stepwise sequential estimation using the ILS model was performed to obtain good initial guess values for parameter estimation. Data from only the first injection period (96 h) were used. The averaged heat rates of the first injection period q_{p1} were used; they were 44.7 W/m for TRT1 and 44.0 W/m for TRT2. Stepwise estimation was performed at data intervals of 3 min. The first 15 h of temperature response data were not included in the estimation because of the limitations of the ILS model. The sequential estimation behavior of λ_{eff} and R_b are shown in Fig. 6. Because the above-ground TRT setup was covered by silver foil sheets to reduce the effects of disturbances [6,7], the estimation behavior was stable after 40 h, although a relatively low heat rate of roughly 44 W/m was used.

Although two BHEs were installed at the same site, the different filling materials produce different estimation results (Table 3). At the unsaturated ground layer above the groundwater level of 10–12 m, the BF-BHE might not be in close contact with the surrounding ground, unlike the GR-BHE. This difference results in a relatively lower value of λ_{eff}; in other TRTs, which are not included in this work, the estimated λ_{eff} values of BF-BHE were consistently lower than those of GR-BHE. However, the estimated value of R_b in the BF-BHE was 0.019 m·K/W lower than that of GR-BHE. This result indicates that BF-BHE has better performance than GR-BHE, although the estimated λ_{eff} of BF-BHE was lower than that of GR-BHE.

The estimated λ_{eff} and R_b values when using the regression method were used as the basis for deciding the initial guess values (Table 3) in the parameter estimation. The parameter estimation was conducted starting at an elapsed time of 12 h at 6-minute intervals. The estimated results are shown in Fig. 7 at 4-h intervals for clarity. Compared to estimation using the regression method (Fig. 6), the estimated behavior was very stable from early in the estimation because the variation in the heat rate due to disturbances can be considered using the temporal superposition of the variable heat rate and the estimation method is dependent on the number of data which is very important in the regressive estimation. The final estimated

λ_{eff} and R_b values in the first injection period were very close to those estimated using the regression method (Table 3).

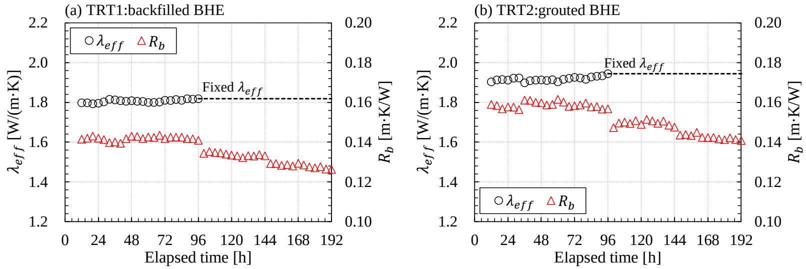

Fig. 7 Estimated effective thermal conductivity and borehole thermal resistance using developed estimation method: (a) TRT1 (backfilled BHE) and (b) TRT2 (grouted BHE)

Table 3. Initial guess values used for the estimations, estimated parameters and rate of change in borehole thermal resistance of each period based on the value of first injection period

Case	Estimated λ_{eff} and R_b using sequential estimation [W/(m·K)], [m·K/W]	Estimated λ_{eff} in t_{p1} [W/(m·K)]	Estimated R_b [m·K/W]			Rate of change in R_b [%]	
			t_{p1}	t_{p2}	t_{p3}	$t_{p1} \rightarrow t_{p2}$	$t_{p1} \rightarrow t_{p3}$
TRT1 (BF)	1.76, 0.140	1.82	0.141	0.133	0.126	5.5	10.4
TRT2 (GR)	1.89, 0.159	1.94	0.157	0.148	0.141	5.8	9.9

From the second injection period onward (i.e., 96 h), λ_{eff} was fixed at the final estimated value in the first injection period. For this reason, if there is a change in the BHE's performance, its effects will be reflected in the estimated value of R_b. For both BHEs, as the heat injection rate increased from q_{p1} to q_{p2} and from q_{p2} to q_{p3} (Table 2), the estimated value of R_b abruptly decreased, and then, gradually decreased over time (because the estimated values are shown at 4-h intervals, this behavior is not shown in Fig. 7). In BF-BHE, as the heat injection rate changed from 44.7 W/m to 67.4 W/m, and from 44.7 W/m to 90.0 W/m, R_b decreased by 5.5 % and 10.4 %, respectively (Table 3). In GR-BHE, the rates of change were very similar. As the heat injection rate changed from 44.0 W/m to 67.0 W/m, and from 44.0 W/m to 90.3 W/m, R_b decreased by 5.8 % and 9.9 %, respectively (Table 3).

Based on the results of this study, we can conclude that the performance dependency of BHE caused by the natural convection was dominated by the hydrothermal properties of the formation, rather than the filling material of the BHE. Although the heat injection rates used were close to ASHRAE's suggested range of 50–80 W/m [8], if a BHE is installed in a saturated porous formation, then the results can be changed by changing the heat injection rate. To draw more reliable conclusions, additional experiments and numerical studies should be conducted in the future.

6. Conclusion

This study proposed a method of combining a multi-heat injection rate TRT with a corresponding parameter estimation method to accurately and practically examine the effect of natural convection on the BHE performance installed in a saturated porous formation. The main results can be summarized as follows:

- The effectiveness and reliability of the proposed method were verified through an estimation using numerical TRT data.
- The rates of performance enhancement at higher heat injection rates were almost the same in both BHEs. When the heat injection rate was increased from approximately 44 W/m to 90 W/m, the reduction rate of R_b was approximately 10% for both BHEs.
- The filling material of the BHE seems to have a small impact on the performance dependence of BHE, caused by the change of the heat injection rate. Instead, the performance seems to be dominated by the hydrothermal properties of the formation. Additional experiments and numerical studies will be conducted to clarify the effect of natural convection on the saturated formation.

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