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Effect of natural convection on thermal response test conducted in saturated porous formation: Comparison of gravel-backfilled and cement-grouted borehole heat exchangers

Wonjun Choi*, Ryozo Ooka

Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

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ABSTRACT

Thermal response tests (TRTs) have been conducted to evaluate two design parameters of borehole heat exchangers (BHEs): effective thermal conductivity and borehole thermal resistance. The effect of natural convection on groundwater-filled BHE performance has been reported mainly from northern Europe. Even in a backfilled or grouted BHE, if the formation is saturated and composed of porous medium, the estimation may depend on the heat injection rate. In this study, we experimentally examined the effect of natural convection on TRTs conducted in saturated porous formation. TRTs were conducted with two BHEs having the same geometry but different backfill materials: one was cement-grouted and the other was gravel-backfilled. TRTs were conducted for each BHE at two different heat injection rates (approximately 45 W/m and 90 W/m). The TRT data were analyzed by a parameter estimation method using a temporal superposition-applied infinite line source model. The results show that when the heat rate was almost doubled, the borehole thermal resistances of the gravel-backfilled and cement-grouted BHEs decreased by 9.8% and 8.7%, respectively. Based on the results, discussions on existing design methods related to typical practices in TRTs and advantages of backfilled BHEs from the perspectives of performance and constructability are presented.

1. Introduction

Vertical closed-loop ground heat exchangers (GHEs), also known as borehole heat exchangers (BHEs), are the most frequently installed types of GHEs because they require less space than horizontal or slinky-type GHEs and are not strictly affected by regulations related to the use of groundwater. The effective thermal conductivity of the ground and the borehole thermal resistance must be known to select an appropriate size for a BHE. The former is a site-specific value, whereas the latter depends on the geometry of the BHE and the thermal properties of the pipes and materials (e.g., grout or backfill soil) that fill the annular space of the borehole. In the design of a ground-source heat pump (GSHP), these values have a significant impact [1], and therefore, many engineers conduct in situ thermal response tests (TRTs) to obtain those values.

The general practice in constructing a BHE is to fill the annular space with grout or a backfill material such as sand or gravel. This prevents collapse of the borehole and contamination of the groundwater and aquifer and enhances the thermal contact between the BHE and ground. A thermally enhanced backfill material is typically used to lower the borehole thermal resistance, as reported previously [2–8].

In northern Europe, groundwater-filled BHE installed on a strong bedrock is a commonly used BHE configuration. A schematic diagram of a groundwater-filled BHE is shown in Fig. 1(a). Several studies [9–15] on these BHEs have reported that natural convection occurring in the annular space considerably lowers borehole thermal resistance and that the results of a TRT depend on the heat injection rate.

Claesson and Hellström [15] conducted both in situ and laboratory experiments to examine the change of borehole thermal resistance in groundwater-filled BHEs. The results of in situ experiments showed 25% lower borehole thermal resistance than the results of simulated cases that only considered conduction of water. Their laboratory experiment [15] using a 3 m high cylinder that imitated a groundwater-filled BHE with a single U-tube also showed an approximately 20% lower borehole thermal resistance when the heat injection rates were changed in the range of

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* Corresponding author.
E-mail address: wonjun@iis.u-tokyo.ac.jp (W. Choi).

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Nomenclature

C	volumetric heat capacity ($\mathrm{J/(m^3 \cdot K)}$)
Ei	exponential integral
f_{obj}	objective function
H	length of BHE (m)
k	gradient of temperature response in the semi-log plot
n	timestep number
N	the number of timesteps or measured data
P_i	i-th parameter
q	heat injection rate per unit length of BHE (W/m)
Q_{BHE}	actual heat injection rate to the BHE (W)
r_b	radius of borehole (m)
R_b	borehole thermal resistance (m·K/W)
t	time, elapsed time after the heat injection (s)
t_j	timestep of the estimation
T	temperature (°C)
$\overline{T}$	average temperature (°C)
$\dot{V}$	volumetric flow rate ($\mathrm{m^3/s}$)

Subscripts

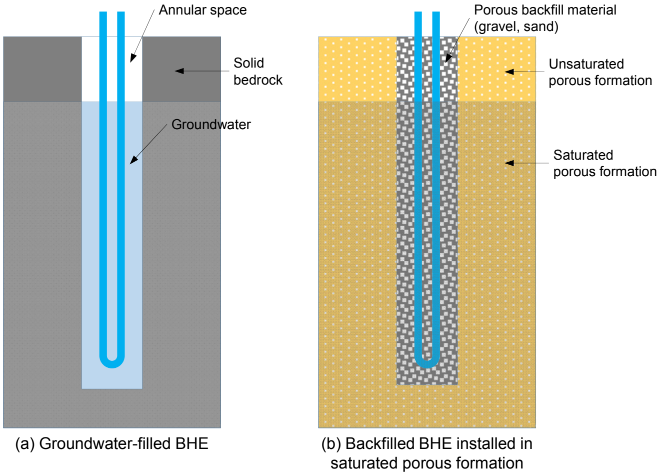
avg	average
cal	calculated
cf	circulating fluid
eff	effective
exp	experimental
ini	initial value of parameter estimation
s	soil
0	initial

Greek letters

α	thermal diffusivity ($\mathrm{m^2/s}$)
γ	the Euler–Mascheroni's constant, $\gamma \fallingdotseq 0.5772$
λ	thermal conductivity (W/(m·K))
ρ	density ($\mathrm{kg/m^3}$)

Abbreviations

BF	backfilled
GR	grouted
SC	sensitivity coefficient
RSC	relative sensitivity coefficient



(a) Groundwater-filled BHE

(b) Backfilled BHE installed in saturated porous formation

Fig. 1. Schematic diagrams of two borehole heat exchanger (BHE) configurations: (a) groundwater-filled BHE and (b) backfilled BHE installed in porous formation.

10–30 W/m. Kjellsson and Hellström [16] investigated the effect of heat injection rates and resulting temperature level by using the laboratory experimental facility used in Ref. [15]. Compared with the resistance obtained by considering only conduction, the borehole thermal resistances were lower by approximately 50%. Later, these experimental results were used in Ref. [14].

Gustafsson and Gehlin [9] reported that the borehole thermal resistance decreased by more than 10% when the heat injection rate increased from 40 W/m to 80 W/m. They used the infinite line source (ILS) model [17] for the interpretation of TRT data. Gustafsson and Westerlund [10] conducted multi-injection-rate TRTs of two BHEs with lengths of 75 m and 150 m. They varied the heat injection rate over the range of 21–83 W/m. The results showed that the borehole thermal resistance decreased from 0.12 m·K/W to 0.065 m·K/W. Comparing the results of these two studies [9,10], Javed et al. [12] reported that the borehole thermal resistance does not depend on the heat injection rate but that the effective thermal conductivity increases beyond 10% when the heat injection rate changes from 68 W/m to 140 W/m.

Spitler et al. [14] conducted several TRTs of groundwater-filled BHEs. With the heat injection rate over the range of 25–75 W/m and the heat extraction rate of −45 W/m, the borehole thermal resistance values varied over the range of 0.047–0.098 m·K/W, but the effective thermal conductivities stayed almost constant within the range of 3.3–3.4 W/(m·K). Additionally, they developed a borehole thermal resistance model for groundwater-filled BHEs based on in situ TRTs. The experimentally obtained TRT data were used to derive a correlation model for Nusselt and Rayleigh numbers, which are required to calculate the convective thermal resistances of the annulus part. Because the measurements inside BHE have inevitably high uncertainty, their model cannot be generalized yet. However, their work provides insight into new design and simulation methods for BHEs affected by natural convection.

Studies of groundwater-filled BHEs have also been conducted in Japan. Fujii et al. [18] conducted TRTs of a groundwater-filled BHE and interpreted the data using the Horner plot method and the infinite cylindrical source model [19]. They reported an enhancement of heat transfer by natural convection as revealed using the empirical formula for the Rayleigh and Nusselt numbers suggested by MacGregor and Emery [20]. Fujii et al. [21] estimated the vertical distribution of thermal conductivity by conducting TRTs with optical fiber sensors. The effective heat exchange length of the groundwater-filled BHE was approximately 30 m. Heat injection rates of 68, 118, and 168 W/m were used. The effective thermal conductivity increased slightly from 2.4 to 2.46 W/(m·K) and the borehole thermal resistance decreased from 0.1 to 0.089 m·K/W as the heat injection rate increased.

From the perspectives of performance, constructability, and maintenance, a groundwater-filled BHE is a promising type of BHE. However, the applicability of groundwater-filled BHEs is limited to certain subsurface conditions. In areas with strong bedrock, where a borehole is structurally stable and can maintain its shape against lateral pressure without the need for a backfill material, a groundwater-filled configuration can be used. However, in weak subsurface conditions, the most common BHE construction method