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A numerical and experimental approach to the estimation of borehole thermal resistance in ground heat exchangers

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ABSTRACT

This paper presents a numerical and experimental study on the evaluation of borehole thermal resistance with TRT (thermal response test) and TPT (thermal performance test) results observed in closed-loop vertical type boreholes with U and W type GHEs (ground heat exchangers). Field TRTs were carried out for 48 h on a closed-loop vertical type borehole, and an equivalent ground thermal conductivity was estimated using the infinite line source model. Closed-loop vertical type boreholes with U and W type GHEs and field ground conditions were numerically modeled using a three dimensional finite element method to estimate borehole thermal resistance and the TRT results were compared. Field TPTs were also conducted for 100 h continuously to calculate the heat exchange rate and borehole thermal resistance. The borehole thermal resistance values were compared with various analytical solutions, and the multipole and EQD (equivalent diameter) method produced results closer to those of the experimental and numerical analysis than the SF (shape factor) method.

1. Introduction

Among various renewable energy resources, the use of geothermal energy has been regarded as energy efficient way of space heating and cooling [1–3]. Geothermal energy has a great potential as a directly usable type of energy, especially in connection with GSHP (ground source heat pump) systems. Hence, GSHP systems combined with various types of GHEs (ground heat exchangers) have been widely used since the early 20th century [4–6]. Geothermal energy is often called ubiquitous energy because it can be used anytime and anywhere.

The GSHP system is largely composed of a geothermal heat pump and a ground heat exchanger. The ground heat exchanger is a system that extracts or emits heat using a circulation fluid such as flowing water or an anti-freezing solution through the heat exchanger installed in the ground. The system uses the heat source of the ground, which maintains a relatively uniform temperature to release heat energy in the summer and absorb heat energy in the winter. The ground heat exchanger is an important element that determines the performance and initial installation fee of the entire system and generally 150–200 m depth closed-loop vertical types are used most widely. The closed-loop vertical type ground heat exchanger is composed of a heat exchange pipe, the ground and grout that fill the empty space between the pipes inside the borehole.

Considering the high initial construction cost, researchers are conducting numerous studies on closed-loop vertical type ground heat exchangers in order to obtain higher thermal efficiencies [7–11]. The heat transfer between the surrounding ground through the ground heat exchanger has a close relationship with the heat transfer between the fluid that circulates within the heat exchanger pipe and the complex medium (grout/ground) surrounding the pipe [12–14]. Therefore, the ground thermal conductivity and borehole thermal resistance are important design parameters that determine the heat performance of GSHP systems [15,16]. The ground thermal conductivity is almost accurately measured through an in-situ TRT and the obtained value is used as a design parameter in GSHP systems. However, there is no clear guideline on a method to determine the borehole thermal resistance and not many studies are being conducted in comparison with ground thermal conductivity measurement.

This paper presents a numerical and experimental study to derive the borehole thermal resistance. U type and W type GHEs were installed in a landfill area at Incheon International Airport in South Korea, and then in-situ TRTs and TPTs were conducted to verify the suitability of the borehole thermal resistance analytical models. Furthermore, the TRT test and on-site ground conditions

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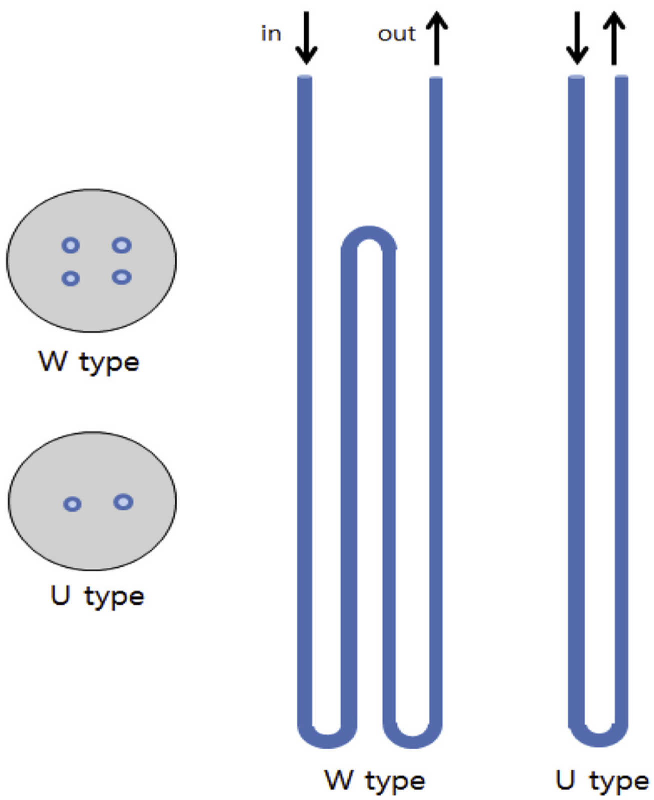

Fig. 1. Diagram of ground heat exchanger.

were numerically modeled using the finite element method coupled with a CFD (computational fluid dynamics) analysis. The borehole thermal resistance values were calculated by a numerical analysis of the TRT and TPT (thermal performance test) results and compared with analytical solutions.

2. Experimental setup

2.1. Setup of GHE

U and W type GHEs (Fig. 1) were installed in a partially saturated landfilled runway area of Incheon International Airport. The borehole depth was 50 m, and the diameter was 15 cm. The distance between each borehole was 6 m to avoid thermal inference. Polybutylene pipes (inner/outer diameter of pipe = 0.016/0.02 m) were used as GHEs, and bentonite grout was poured into the borehole. The total pipe length of U and W type GHE was 100 m and 200 m, respectively. Fig. 2 shows the construction process of the vertical GHEs.

The ground was composed of silt, clay, weathered granite soil and weathered rock. The ground water level was 3.5 m below the top of the embedded borehole, and no noticeable flow of ground water was observed. The SPT (Standard Penetration Test) *N* value was 9/30–33/30 in the partially saturated landfill ground, and weathered rock appeared 30 m below the ground level. The average void ratio was 0.95 and the water content was 30–35%.

2.2. Theory of TRT analysis

The heat transfer mechanism of the ground heat exchanger involves the process of absorbing and releasing heat to and from the grout material and the surrounding ground as the heat transfer fluid flows through the pipe within the borehole, whereas the heat transfer behavior between the ground heat exchanger and the surrounding ground involves a complex mechanism, and the heat transfer to the ground is through conduction [3]. The heat transfer governing equation from conduction in the ground is as follows:

$$-\lambda_i\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}+\frac{\partial^2 T}{\partial^2 z}\right)+\rho_i c_i\frac{\partial T}{\partial t}+q_{\mathrm{internal}}=0 \quad (1)$$

where T is the temperature, λ is the thermal conductivity, ρ is the density, c is the specific heat capacity, q_{internal} is the internal heat generation. The subscript i denote each region of the GHE such that g and s indicate the grout and soil, respectively.

Heat transfer in the GHE involves pipe convection, pipe conduction, grout conduction in the borehole and ground conduction. In order to measure the ground thermal conductivity in the GHE system outside the borehole, some analytical equations such as line source, cylindrical source, and numerical analysis models have been used. Among these, the infinite line source model is the most widely employed to measure the ground thermal conductivity due to its simplicity and convenience in analysis, and the analytical solution for the heat transfer between the buried pipe and the ground can be obtained by the Kelvin theory. As shown in Fig. 3, the vertical closed-loop ground heat exchanger has a borehole radius (r_b) that is much smaller than the borehole length (L), and hence it can be assumed to be a line source, and the ground is regarded as an infinite and isotropic medium. When the heat transfer medium surrounding the line source is a different material, such as that of grout and soil, the following solution of the heat conduction equation can be obtained when considering the thermal resistance between the borehole and soil about the line source [17–19].

(a) Drilling of borehole (b) Installation of GHE (c) Bentonite grouting

Fig. 2. Construction process of GHE.