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An equivalent diameter in calculating borehole thermal resistance for spiral coil type GHE

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ABSTRACT

Ground-coupled heat pump (GCHP) systems have been applied to obtain shallow-depth geothermal energy with satisfactory energy efficiency. Recently, the geothermal energy pile has been developed as efficient means of reducing the installation cost. With its incorporation, however, the heat exchange behavior of the energy pile becomes more complex than typical GCHP systems buried in the ground, owing to the incorporation of the pile and grout surrounding the ground heat exchanger (GHE). Differences in thermal properties of the grout, the pile and soil have to be considered because those affect the borehole thermal resistance. The borehole thermal resistance is an important factor to design the GCHP systems such as ground heat exchangers and geothermal energy piles. Recently, coil type heat exchangers are being used because the spiral coil configuration has an advantage, even though the coil type heat exchanger has more complex geometry than the U-tube. Numerical simulation assuming a constant heat rate from the pipe legs was conducted for the spiral coil type GHE. The equivalent diameter was suggested by the results obtained from the numerical simulation. The results were compared with those obtained by the multipole method based on the equivalent diameter.

1. INTRODUCTION

The use of geothermal energy and GCHP systems has significantly increased in recent years (Lund, 2003). Geothermal energy used to be called ubiquitous energy because it can be used at any time at any place. The GCHP system uses a constant

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ground temperature to transfer heat during the summer and winter for cooling and heating buildings. The geothermal energy pile has been developed as efficient means of reducing the installation cost. However, the heat exchange behavior of the energy pile becomes more complex than typical GCHP systems buried in the ground, owing to the incorporation of the pile and grout surrounding the ground heat exchanger. Differences in thermal properties of the grout, the pile and soil have to be considered because those affect the borehole thermal resistance.

The borehole thermal resistance is an important factor to design the GCHP systems such as ground heat exchangers and geothermal energy piles. The influence of the borehole thermal resistance on the overall heat transfer properties of the ground loop array may become relatively large in conventional designs. (Claesson and Hellstrom, 2011).

Recently, coil type heat exchangers are being used because the spiral coil configuration has the advantage of more heat transfer area and better flow pattern without air chocking in the pipes compared with the serial of parallel U-tubes in the pile (Cui et al, 2011). The coil type heat exchanger has more complex geometry than the U-tube. This paper describes a method, adopting the equivalent diameter method, to calculate the borehole thermal resistance for a borehole ground heat exchanger of spiral coil type. Numerical simulation assuming a constant heat rate from the pipe legs was conducted for spiral coil type GHE. The equivalent diameter method was suggested by the results obtained from the numerical simulation. The results were compared with those obtained by the multipole method based on the equivalent diameter.

2. THEORETICAL BACKGROUND

This paper relies on the conventional series sum method and the multipole method.

2.1. Conventional series sum method

Thermal resistance of fluid convection is defined as:

$$R_{conv} = \frac{1}{2\pi d_i h_i} \tag{1}$$

The convection coefficient, h_i, is determined by Dittus-Boelter correlation:

$$h_i = \frac{0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}\,\lambda_f}{d_i} \tag{2}$$

For the U-tube GHE, the thermal resistance of pipe is equivalent to the thermal resistance of two individual pipe thermal resistances in parallel. Assuming that the fluid temperatures in each pipe are the same, the equation to calculate the equivalent thermal resistance of two pipes in parallel follows (Remund, 1999):

$$R_p = \frac{R_{p1} R_{p2}}{R_{p1} + R_{p2}} \tag{3}$$

Since the two pipe resistances are equal (R_{p1}=R_{p2}=R_{pipe}), Eq. (3) reduces to

$$R_p = \frac{R_{pipe}}{2} = \frac{\ln(d_o / d_i)}{4\pi\lambda_p} \tag{4}$$

where outside diameter of pipe is d_o and inner diameter of pipe is d_i.

Thermal resistance of grout can be computed by shape factor method and equivalent diameter method. Shape factor method is used to describe the heat conduction characteristics of a complicated geometry (Liu et al., 2009).

$$R_g = \frac{1}{\lambda_g \beta_0 (d_g / d_o)^{\beta_1}} \tag{5}$$

where outside diameter of grout is d_g and inner diameter of grout is d_o. β_0 and β_1 are the shape factors of R_g, whose values depend on the relative location of U-tube pipes in the borehole. Remund (1999) studied three configurations.

Equivalent diameter method means that the two legs in the U-tube are replaced by a single concentric cylindrical heat sink. The equivalent diameter given by Gu and O'Neal (1998) is as follow:

$$d_e = \sqrt{2 d_o L_s} \quad (d_o < L_s < r_g) \tag{6}$$

where outside diameter of grout is d_o and leg spacing between inlet pipe and outlet pipe is L_s and radius of grout is r_g.

When the equivalent diameter method is used for computing the thermal resistance inside the borehole, thermal resistance of fluid and pipe should remain constant and the mass flow rate and heat capacity of the fluid should also be constant. Therefore, thermal resistance of grout can be computed as follow:

$$R_g = \frac{\ln(d_g / d_e)}{2\pi\lambda_g} \tag{7}$$

where outside diameter of grout is d_g and equivalent inner diameter of grout is d_e.

Thermal resistance of PHC pile is defined as:

$$R_{PHC} = \frac{\ln(d_b / d_g)}{2\pi\lambda_{PHC}} \quad (8)$$

where outside diameter of borehole is d_b and inner diameter of borehole is d_g.
Then, thermal resistance of borehole can be found by adding the thermal resistances as follow:

$$R_b = R_{conv} + R_p + R_g + R_{PHC} \quad (9)$$

2.2. Multipole method

The multipole method was first derived in 1987 and was described in two internal reports (Claesson and Hellstrom, 2011). In the multipole method, the pipes are located inside a homogenous circular region that is inside another homogeneous circular region. The multipole method is not constrained to calculating the steady state borehole thermal resistance for a borehole with only one pipe. Furthermore, the pipes do not need to be symmetrical about any axis. This is advantageous since some boreholes contain more than two pipes. The method is also able to calculate borehole thermal resistance for pipes that are not equidistant from the center of the borehole.

Fig. 1 shows the most common case of two pipes, a U-tube in a borehole. The thermal conductivity in the ground outside the borehole is λ and it is λ_b for the grout in the borehole outside the pipes. The borehole radius is r_b. The outer radius of pipe n is r_{pn} and R_{pn} is the thermal resistance from pipe fluid to the grout adjacent to the pipe. The resistances in the first sum give the solution at multipole order J=0 as expressed in Eq. (10). The detailed multipole method is given in the paper of Claesson and Hellstrom (2011).

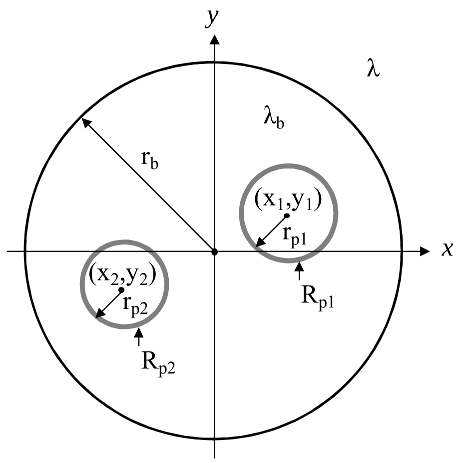

Fig. 1. Multipole method for two pipes in a borehole.

$$\hat{R}^0_{m,n} = \frac{1}{2\pi\lambda_b} \times \begin{cases} \ln\left[\frac{r_b}{r_{pm}}\right] + \beta_m + \sigma \cdot \ln\left[\frac{r_b^2}{r_b^2 - r_n^2}\right] & m = n \\ \ln\left[\frac{r_b}{r_{m,n}}\right] + \sigma \cdot \ln\left[\frac{r_b^2}{\left|r_b^2 - \bar{z}_m \cdot z_n\right|}\right] & m \neq n \end{cases} \tag{10}$$

3. NUMERICAL SIMULATION

Numerical simulation assuming constant heat rate from the pipe legs was performed for the spiral coil type GHE. 2-dimentional finite element model was applied in ABAQUS/Standard (ABAQUS Inc., 2004). As shown in Fig. 2, radii of pile, grout and coil are 0.2m, 0.12m and 0.11m, respectively. Diameter of pipe is 0.02m and thickness of pipe is 0.002m. Thermal conductivities of pipe, grout, PHC pile and soil ground are 0.38W/mK, 2.02W/mK, 1.62W/mK and 2.06W/mK, respectively. Pitches of spiral coil are 6.8cm, 10.3cm and 19cm (spacing of spiral coil are 4.8cm, 8.3cm and 17cm), respectively, and depth of borehole is 14m.

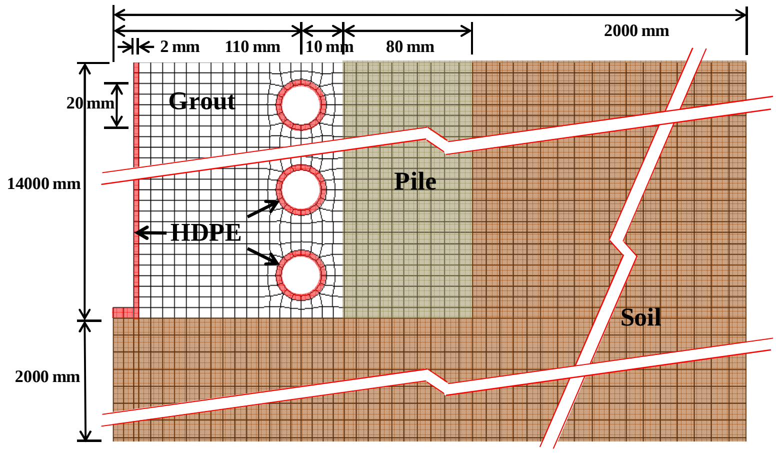

Fig. 2. Schematic view of numerical simulation.

4. PROPOSED METHOD

4.1. Conventional series sum method

To compute a borehole thermal resistance, two points were modified. First, pipe thermal resistance was modified to consider a spiral coil pipe. Length of spiral coil pipe is defined as follow:

$$L = h\sqrt{\omega^2 r_o^2 + 1} \tag{11}$$

Then, the total length of spiral coil GHE including outlet pipe can be computed as follow:

$$L_{tot} = h + h\sqrt{\omega^2 r_o^2 + 1} \tag{12}$$

If we assume that the n (=L_{tot}/h) pipes are parallel, R_p can be obtained from Eq. (3), (4) and (12) as follow:

$$R_p = \frac{R_{pipe}}{n} = \frac{\ln(d_o / d_i)}{2\pi\lambda_p}\frac{1}{n} = \frac{\ln(d_o / d_i)}{2\pi\lambda_p}\frac{1}{1+\sqrt{\omega^2 r_o^2 + 1}} \tag{13}$$

Next, the equivalent diameter for the spiral coil GHE was suggested by defining a shape factor β based on the results obtained from numerical simulations to calculate the grout thermal resistance. The equivalent diameter is defined using related spiral coil radius r_o as follow:

$$d_e = \beta \cdot 2r_o \tag{14}$$

4.2. Multipole method

Let r_o, d, N and h be the radius of coil, diameter of pipe, number of coil turns and depth of borehole, respectively (Fig. 3). The wave number is ω=2Nπ/h. When we cut the face at any depth of spiral coil GHE, the cutting face is the combination of two parts as shown in Fig. 4 (left). If we assume that the thermal resistance of borehole at the cutting face A-A' has the same value at any depth z, then, by changing the left part to an equivalent circle divided by 24 as shown in Fig. 4 (right), the thermal resistance of borehole can be calculated by the multipole method.

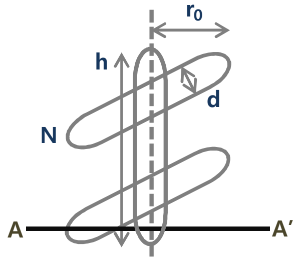

Fig. 3. Side view of spiral coil GHE.

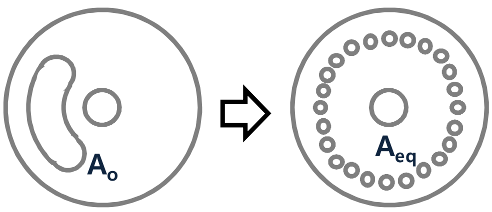

Fig. 4. Cutting face A-A' of spiral coil GHE.

The area of left part of the cutting face A_o is:

$$A_o = \frac{\pi d^2}{4}\sqrt{r_0^2\omega^2 + 1} \quad (15)$$

Because the area of A_o equals A_{eq}:

$$A_o = A_{eq} = \frac{\pi d^2}{4}\sqrt{r_0^2\omega^2 + 1} = \pi r_{eq}^2 * 24 \quad (16)$$

Eq. (17) can be obtained from Eq. (16):

$$r_{eq} = \frac{\sqrt[4]{r_0^2\omega^2 + 1}}{48} d \quad (17)$$

where r_{eq} is a radius of small circle.

Table 1 shows the radius of small circles with spiral coil pitches 6.8cm, 10.3cm and 19cm (spiral coil spacing 4.8cm, 8.3cm and 17cm).

Table 1. Radius of small circles

Pitch (cm)	r_{eq} (cm)
6.8	0.817
10.3	0.667
19.0	0.495

5. DISCUSSION

Fig. 5 plots thermal resistances of borehole for the spiral coil GHE. The conventional series sum thermal resistance was fit for the results of numerical simulation to each of the three spiral coil GHE configurations. Table 2 summaries the shape factor of different configurations of spiral coil GHE (spiral coil pitches 6.8cm, 10.3cm and 19cm) obtained from the numerical simulation (Fig. 5). Besides, the multipole method calculations with assumed small circles was conducted the obtained equivalent diameter ($d_e = \beta * 2r_o$). As a result, the difference in the borehole thermal resistances obtained by the numerical simulation and multipole method becomes larger as the coil pitch increases.

6. CONCLUSION

In this study, an equivalent diameter method defining a shape factor in calculating a borehole thermal resistance for a borehole ground heat exchanger of spiral coil type was suggested based on the numerical simulation results. The equivalent diameter including a shape factor can be used to calculate the borehole thermal resistance with three configurations of spiral coil GHE. It is necessary to conduct more researches to verify the method for more general configurations of spiral coil GHE.

The results were also compared with those obtained by the multipole method based on the obtained equivalent diameter. It just shows the tendency, yet, more modifications are needed.

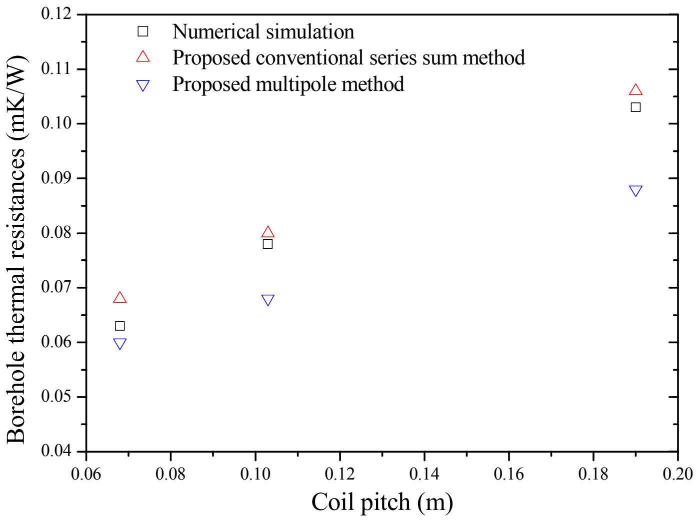

Fig. 5. Thermal resistances of borehole for spiral coil GHE.

Table 2. Shape factor for different configurations of spiral coil GHE

Pitch (cm)	β
6.8	1
10.3	0.909
19.0	0.727

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