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Prediction of Thermal Properties from a Thermal Response Test in Energy Piles

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ABSTRACT

The use of geothermal energy has been increased for economically and environmentally friendly utilization, and a geothermal heat pump (GSHP) system for space heating and cooling is being widely used. As ground thermal properties such as ground thermal conductivity and ground thermal diffusivity are essential parameters in the design of a geothermal heat pump system, the ground thermal conductivity should be obtained from an in-situ thermal response test (TRT). This paper presents an experimental study of the ground thermal properties of W type ground heat exchanger (GHE) measured by TRT in energy pile. The W type GHE was installed in a partially saturated weathered granite soil, and a TRT was conducted for 30 hours. A method to derive the thermal diffusivity and thermal conductivity was proposed based on a non-linear regression analysis.

1. Introduction

Recently, the use of renewable energy sources is constantly increasing with the advent of global warming and the depletion of fossil energy. Geothermal energy has a great potential as a directly usable type of energy, especially in connection with ground sources and GSHP systems, to achieve energy-efficient spaces for cooling and heating. GSHP systems use the ground as a heat source since it provides a relatively constant temperature. The GSHP systems are largely divided into open and closed systems. The open system exchanges heat using aquifer water directly, while the closed system exchanges heat by a fluid circulating in GHEs. The closed vertical system is used most widely, and it is composed of GHE pipes, ground and grout that fills the empty space between the pipes inside the borehole (Bennazza *et al*. 2011, Johnston *et al*. 2011). However, it can involve high initial construction costs, as a borehole up to tens or

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hundreds of meters deep needs to be installed.

As an alternative, the application of energy piles under a raft foundation has recently become more common (Brandl 2006, Cui *et al.* 2011, Yoon and Lee. 2015a). It has the advantage of a relatively low initial investment cost with no additional construction costs during the construction process. Compared to a conventional closed vertical system, it has a larger diameter and a shorter length. In Korea, most of energy piles have relatively short lengths of less than 20m due to the shallow depth of the bedrock in many locations.

In the design of the GSHP system, ground thermal properties are one of the most important parameters. The ground thermal conductivity is almost accurately measured through an in-situ TRT and the value is inputted as a design parameter. However, there is no clear guide line for the method to determine the ground thermal diffusivity. In energy piles, ground thermal conductivity and thermal diffusivity should be obtained from the lab test with soil specimen. However, it may not be accurate to measure ground thermal properties with soil specimen disturbed from the ground.

Therefore, this paper presents an experimental study of ground thermal properties for a W type GHE in energy piles by TRT. A method to derive the ground thermal diffusivity as well as the ground thermal conductivity was proposed by a non-linear regression analysis.

2. Experimental setup

2.1 Thermal response test of an energy pile

Yoon *et al*. (2014) conducted a field TRT using a PHC pile at the construction site of the 154kV Substation in Suwon city. The energy pile was in the form of a polybutylene pipe (an inner/outer diameter of the pipe = 0.016/0.02m) grouted in a PHC pile. Cement grout with a cement-to-water ratio of 0.5 was poured and cured for more than 28 days. The heat exchanger configuration was shown in Fig. 1. The detailed description for the TRT was explained in the reference (Yoon *et al*. 2014)

2.2 TRT interpretation

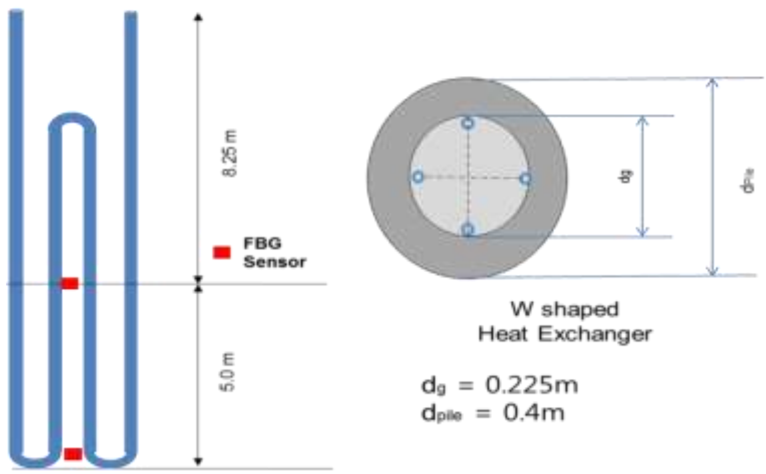


Fig. 2 Dimensions of the energy pile with the W shape (Yoon *et al*. 2014)

2.2 TRT interpretation

The heat transfer mechanism of the GHE involves the process of absorbing and releasing heat to and from the grout material and the surrounding ground, and the heat transfer to the ground is mainly through conduction (Brandl *et al*. 2006). The heat transfer governing equation for the conduction in the ground can be expressed by Eq. (1).

$$-\frac{d}{di}(\lambda\frac{dT}{di})+\rho c\frac{dT}{dt}+q_i=0 \quad (i=x,y,z) \tag{1}$$

where T is the temperature, λ is the thermal conductivity, ρ is the density, c is the specific heat capacity, and q_i is the internal heat generation. The methods to solve this heat transfer equation include line source, cylindrical source, and numerical analysis models. Among them, the infinite line source model is the most widely employed to measure the ground thermal conductivity due to its simplicity and convenience. The vertical closed-loop ground heat exchanger has a borehole radius (r_b) that is much smaller than the borehole length (L), and then it can be assumed to be a line source. The change in the ground temperature at distance (r) from the line source after a time duration (t) can be described by Eq. (2).

$$T(r,t)-T_o=\frac{Q}{4\pi L\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du \tag{2}$$

Here, T_o is the initial ground temperature and α is the ground thermal diffusivity. In Eq. (2), ($r^2/4\alpha t$) is the integral variable, and the integral can be expressed as an infinite series in Eq. (3).

$$\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du=-\gamma-\ln(\frac{r^2}{4\alpha t})+\frac{r^2}{4\alpha t}-\frac{1}{4}(\frac{r^2}{4\alpha t})^2\cdots \tag{3}$$

In Eq. (3), γ is the Euler constant with a value of 0.5772. When the integral variable ($r^2/4\alpha t$) in Eq. (3) is very small, Eq. (3) can be expressed in the following manner.

$$T(r,t)=\frac{Q}{4\pi\lambda L}\{\ln(\frac{r^2}{4\alpha t})-\gamma+\frac{r^2}{4\alpha t}(1-\frac{r^2}{16\alpha t})\} \tag{4}$$

When the heat is transferred from the fluid temperature (T_f) to the ground, Eq. (5) is applied with the thermal resistance (R_b) inside the borehole.

$$\frac{Q}{L}=\frac{T_f-T_b}{R_b} \tag{5}$$

Here, the circulating fluid temperature (T_f) is the average temperature of the circulating fluid between inlet and outlet in the GHE. The borehole wall surface temperature (T_b) is calculated as shown below by substituting $r=r_b$ into Eq. (4), which becomes $T_b=T(r_b, t)$.

$$T_b - T_o = \frac{Q}{4\pi\lambda L}\{\ln(\frac{r_b^2}{4\alpha t}) - \gamma + \frac{r_b^2}{4\alpha t}(1-\frac{r_b^2}{16\alpha t})\} \tag{6}$$

Combining Eqs. (5) and (6) and reorganizing for T_f gives Eq. (7)

$$T_f = \frac{Q}{4\pi\lambda L}\ln t + \frac{Q}{4\pi\lambda L}(\ln\frac{4\alpha}{r_b^2} - \gamma) + \frac{Q}{L}R_b + T_o \tag{7}$$

T_f in Eq. (7) can be expressed as a linear equation about $\ln t$ as given in Eq. (8).

$$T_f = Ax + B \tag{8}$$

with $A = \frac{Q/L}{4\pi\lambda}$, $x=\ln t$, and $B = A(\frac{4at}{r_b^2} - \gamma) + \frac{Q}{L}R_b + T_g$ Therefore, once A can be solved, the thermal conductivity (λ) can be obtained by

$$\lambda = \frac{Q/L}{4\pi A} \tag{9}$$

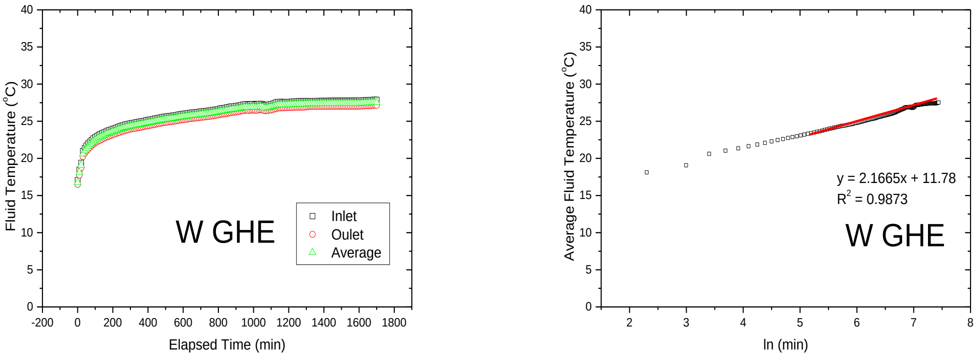
Based on the Eq. (8), once B is solved, the ground thermal diffusivity (α) can be obtained by Eq. (10).

$$\alpha = \frac{e^{\frac{B-\frac{Q}{L}R_b - T_o}{A}}}{4} r_b^2 \tag{10}$$

3. Result and discussion

3.1 Experimental result

The TRT in the energy pile was performed for 30 hours. The temperature of the circulating water in the inlet and outlet of the GHE was measured at 10-minutes interval. Generally, for the closed vertical type GHE, the thermal response test must continue for more than 48 hours. However, in this experiment, the temperature of the circulating water mostly reached a steady state within 30 hours. Heat-free water circulation was performed for 30 min to equalize soil and circulating fluid temperature. The initial temperature of the ground was 16.8 °C, the average flow rate was 16 *lpm*, and the temperature difference between the inlet and the outlet was 0.75 °C. Also, the average fluid temperature distribution of the inlet and the outlet was between 16.80 and 27.52 °C during the TRT. Fig. 2 plots the temperature distribution at the inlet and the outlet of the GHE pipe, and the average fluid temperature during the TRT. The ground thermal conductivity was evaluated as 2.32 W/(m·K) from Eq. (9), and ground thermal diffusivity was 0.899 mm^2/s from Eq. (10).



(a) Temperature distribution vs. time (b) Temperature distribution vs. ln*t*
Fig. 2 Fluid temperature distribution during the TRT

3.2 Non-linear regression analysis

A non-linear regression analysis was conducted using TRT results with Fig. 2. Surface tool box in MATLAB program was used to derive the non-linear model expressed by Eq. (8). Table 1 shows the results of the regression analysis. From the *t* statistical analysis, p-value of coefficient of independent variable was lower than 0.05, which means that independent variable can be used significantly to estimate dependent variable (Yoon *et al*. 2015b). The coefficient of determination (R^2) was 0.9873, which reveals very high accuracy for the non-linear regression model. The analysis of variance that is called ANOVA can be also constructed for the regression analysis. Table 2 shows the results of the ANOVA. Since the p value was less than 0.01, the significance between an independent and dependent variable is very high, which means that the empirical equation from the regression analysis can be used (Anthony 2007, Yoon *et al*. 2015 b).

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Table 1 Results of multiple regression analysis

	B	Standard error	*t*	P-value
Constant (B)	2.886	0.4390	6.574	<.01
A	2.168	0.0398	54.462	<.01
R^2	.9697			
$_{adj}R^2$	.9693			
SSE	1.007			

B: non-standardized coefficient, *t*: *B*/standard error

Table 2 Results of ANOVA analysis

	DF	SS	*MS*	F	P-value
Regression	1	3.2201E+01	3.2201E+01	2904.948	<.001
Residual	91	1.0087E+00	1.1085E-02		
Total	92	3.3210E+01			

4. Summary and conclusion

This paper presented an experimental study to measure the ground thermal conductivity and ground thermal diffusivity. A PHC energy pile with W type GHE was installed and an in-situ TRT was conducted for 30 hours. Up to now, only the ground thermal conductivity was measured from the in-situ TRT using the approximate infinite line source model. However, this paper proposed a method to determine the ground thermal diffusivity since the ground thermal diffusivity is as important as the ground thermal conductivity in the design for the GSHP system. A non-linear regression analysis was conducted to suggest a method to derive the ground thermal diffusivity, and statistical significance was validated from the *t*-analysis and ANOVA analysis. In conclusion, according to the results, it is thought that the ground thermal diffusivity can be also determined with statistical significance once an in-situ TRT is conducted.

Acknowledgements

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