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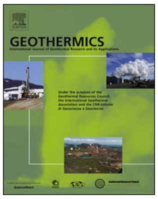

Multilayer-concept thermal response test: Measurement and analysis methodologies with a case study

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ABSTRACT

A multilayer-concept thermal response test is proposed by incorporating the standard test with a pair of fiber-optic distributed temperature sensors in the U-tube. The heating exchange rates in any vertical segment are estimated from the sequential temperature data. The ground thermal conductivity of each sub-layer is calculated using the line heat source model, in which the heating exchange rates and the temporal temperature slopes are determined at their convergence as the thickness increases. The convergence analysis continues downward until reaching the borehole bottom to obtain the stepwise conductivity. A case study of Sapporo, Japan, is shown with the sensitivity analysis of the convergence threshold.

Cs Specific heat (Jm − 3K − 1)
CV Coefficient of variation (%)
dz Vertical measurement interval (m)
kt Temporal slope of fluid temperatures (K)
kz Vertical slope of fluid temperatures (K)
L Thickness or length (m)
ME Average of a sample
MAE Absolute mean of relative errors (%)
N Total number of sub-layers
n Sample number for convergence determination
Q Heat exchange rate (W)
q Heat exchange rate per unit length (Wm − 1)
Rb Thermal resistance of borehole (mKW − 1)
r Radius of borehole (m)
REQ Relative error of total heat exchange rate (%)
REλ Relative error of ground thermal conductivity (%)
RMSE Root mean square of relative errors (%)
SD Standard deviation of a sample
TCV Threshold value for convergence (%)
t Elapsed time (h)
v Flow rate of circulation fluid (m3h − 1)
z Depth (m)
α Thermal diffusivity (m2h − 1)
λ Ground thermal conductivity (Wm − 1K − 1)
ρ Density (kgm − 3)
θ Temperature (K)
ω Weight coefficient for error estimators
* Equivalent value from convergence results
(in) Inlet flow
(out) Outlet flow
i Layer number
j Step number for increasing temporary thickness
0 Initial value
intersect Intersect of fitting line

1. Introduction

The thermal response test (TRT) is the most popular in situ method for determining effective thermal conductivity of the ground (ground thermal conductivity) for the design and planning of ground source heat pump systems (GSHPs). A variety of heat exchangers are used for heat extraction and injection from the ground at almost constant temperature. Among them, the borehole heat exchanger (BHE) is widely used, consisting of a high-density polyethylene U-tube in a vertical borehole of approximately 100 m in depth. The heat carrier fluid is contained in the U-tube, and the heat is exchanged between the fluid and the ground via the flow circulation. BHE has an advantage in terms of small areal extents for its installation, especially in development areas. The performance of the BHE is dependent on various natural and artificial factors, among which the ground thermal conductivity around the BHE is the most important. The ground thermal conductivity for the design of the BHE usually corresponds to the depth average of the ground thermal conductivity of each layer of different soil/rock types. In general, effective thermal conductivity of soil and rock ranges between $< 1\ \mathrm{Wm^{-1}K^{-1}}$ in unsaturated fine sediments and $> 3\ \mathrm{Wm^{-1}K^{-1}}$ in heavy consolidated rocks (Ingersoll et al., 1954;

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Nomenclature

Greek letters

α	Thermal diffusivity (m^2h^{-1})
λ	Ground thermal conductivity ($Wm^{-1}K^{-1}$)
ρ	Density (kgm^{-3})
θ	Temperature (K)
ω	Weight coefficient for error estimators

Superscripts

*	Equivalent value from convergence results
(in)	Inlet flow
(out)	Outlet flow

Subscripts

i	Layer number
j	Step number for increasing temporary thickness
0	Initial value
intersect	Intersect of fitting line

Farouki, 1981). On a smaller scale, the value is variable in relation to the thermal conductivity of solids and water and their volumetric fractions. The ground thermal conductivity might also increase in the aquifers due to heat advection by the groundwater flows (Chiasson et al., 2000; Signorelli et al., 2007). Moreover, detailed information regarding the geologic and hydrogeologic structures is rarely obtained in the deep zones for BHE installation. Thus, TRT is usually performed for in situ determination of the ground thermal conductivity at each construction site of GSHPs.

The methodology of TRT for the BHE originated in Sweden (Mogensen, 1983) and is referred to as "the standard TRT" in this study. The standard TRT performs the heat injection at a constant rate and measures the fluid temperature variations during heating on both shanks of the U-tube. The standard TRT analyzes the temperature data based on the line heat source model, in which the borehole is assumed to be a line heat source in the finite region of homogeneity. The assumption is that it is possible to derive the simple solution of the ground thermal conductivity and that the simplicity is valuable, especially for practical purposes. However, the standard TRT has a limitation in which it provides the averaged ground thermal conductivity which is almost insensitive to the geologic structure in each site (Lee, 2011). Obviously, there is room to reduce the initial costs of GSHPs by optimizing the lengths and arrangements of the BHE considering the depth-varying ground thermal conductivity at each site. It has long been desirable to develop TRT methodologies that improve upon this limitation due to the geologic complexities and uncertainties (Spitler and Bernier, 2011).

The present study proposes the multilayer-concept TRT to determine the stepwise ground thermal conductivity with the simplicity of the standard TRT for practical purposes. An additional modification to the standard TRT is the inclusion of a pair of fiber-optic distributed temperature sensors (DTS), which are temperature sensors that evaluate the laser back-scattering Raman effects (Grattan and Sun, 2000). The fiber-optic DTS is widely used for monitoring temperatures in the BHE system (e.g., Kallio et al., 2011) owing to a low signal loss along the U-tube and a small diameter to avoid disturbances of the flow circulation. An application of the fiber-optic DTS to measure the temperature for in situ determination of ground thermal conductivity is similar to those of several previous studies (e.x., Günzel and Wilhelm, 1999; Freifeld et al., 2008). Fujii et al. (2009) first utilized the fiber-optic DTS to measure the temperatures in the BHE and estimated the depth-varying effective thermal conductivity using the least squares method. The following study (Acuña et al., 2009) applied a pair of the fiber-optic DTSs in the U-tube and analyzed both ground thermal conductivity and borehole thermal resistance in each sub-layer 20 m thick. Sakata et al. (2017) also demonstrated the similar approach to determine the ground thermal conductivity per a depth of 10 m near the pumping well, indicating its apparent increase by the artificial flow of groundwater in the aquifer. Both studies revealed the profiles of the ground thermal conductivity by applying the line heat source analysis individually in each sub-layer, while the standard TRT calculates the averaged conductivity in the formation. The approach is straightforward without any numerical inversion, and the simplicity is expected to be acceptable for practical use. However, the assumption of a constant thickness of each sub-layer is not often valid in any geologic formation; the thickness of each sub layer is variable depending on the geologic structure at each site.

The present study also measures the temperature profiles of the entire U-tube by using a pair of the fiber-optic DTSs. One of the DTSs is installed in the inlet path of the U-tube and another in the outlet path; therefore, the transient temperature profiles of the fluid circulating through the entire U-tube are measured during the testing. The measurement approach is similar to the previous studies above, but the multilayer concept is different in terms of thickness of each sub-layer. The present study is based on the assumption that the thickness is variable in each layer, and the purpose of this TRT method is to determine not only ground thermal conductivity but also thickness individually. In the proposed method, the temperature measurement is performed with a small interval in the vertical direction. A fine sampling interval is possible to detect the geologic boundaries in complex situations such as fluvial and debris flow sediments. For example in Japan, there are various fluvial deposits such as clay, sand and gravel in most sedimentary basins, and the sediments are vertically variable, often within a thickness of one meter. This study also calculates the heat exchange rate directly in any vertical segment from the sequential temperature data, so that the measurement errors of the fiber-optic DTS are reduced in statistical sense. Thus, the approximated solution of the line heat source model is applicable to calculating the ground thermal conductivity in each sub-layer.

This study also assumes that such geologic information regarding the boundary depth of each sub-layer is rarely obtainable in the deep zone (about a depth of 100 m) for the BHE installation. To address the uncertainty of the geologic structure, this method proposes a convergence analysis of the line heat source model. The convergence analysis is based on two factors in the analytical solution, i.e., the heat exchange rate per unit depth and the temporal temperature slope. In this study, the thickness of each layer is determined when the two factors are converged by increasing the thickness gradually according to a measurement interval. The ground thermal conductivity in each sub-layer is also calculated using the the analytical solution with the converged values. The determination is performed downward step by step until the total thickness reaches the total borehole length. Finally, the stepwise profile of the ground thermal conductivity is obtained.

This study introduces the measurement and analysis methodologies and demonstrates the method applied to a study site in Sapporo City, Hokkaido Island, Japan. In the case study, the sensitivity analysis of the threshold for convergence is performed to assess the influence of the threshold on the convergence analysis and to specify the stepwise conductivity in terms of the least error with the standard TRT result.