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Interpretation of disturbed data in thermal response tests using the infinite line source model and numerical parameter estimation method

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HIGHLIGHTS

- The ILS model combined with the quasi-Newton method is proposed for TRT analyses.
- In-situ TRTs were conducted to verify the accuracy of estimation results.
- Disturbance factors can be accurately considered with the proposed method.
- The proposed method yielded at least four times lower standard deviations.
- Nearly four times faster convergence speeds were achieved with the proposed method.

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ABSTRACT

Effective ground thermal conductivity and borehole thermal resistance, which are key parameters in the design of borehole heat exchangers (BHEs), are often determined on the basis of in-situ thermal response tests (TRTs). However, many disturbance factors can affect the accuracy of a TRT, e.g., voltage fluctuations from the power grid and oscillating external environments where a TRT rig is installed. Interpretation of TRT data is often done using the infinite line source (ILS) model, combined with the sequential plot method, because it is not only simple but also provides additional information about the estimation behavior and convergence. However, estimation behavior using the sequential method tends to fluctuate over time because the constant heat flux assumption is always violated as a result of the disturbance factors. As an alternative, a temporal superposition applied analytical model can be used in a recursive curve fitting manner, but this method cannot provide the additional information that sequential method can. In this study, as a solution for interpreting disturbed TRT data and to utilize additional information from the sequential plot method, we proposed an alternative method using a temporal superposition applied ILS model combined with the quasi-Newton optimization method. To verify the effectiveness, the proposed method was applied to in-situ TRTs and the results were compared with those from the conventional method in terms of the estimation stability and convergence speed. The results showed that, compared to the conventional sequential method using the ILS model, the proposed method yielded standard deviations for the effective thermal conductivity and borehole thermal resistance that were at least six times and four times lower, respectively. Moreover, the proposed method was able to achieve about four times faster convergence speeds.

1. Introduction

In-situ thermal response tests (TRTs) are often conducted to obtain information on the thermal properties of the ground, which are necessary data to design a ground source heat pump (GSHP). This process is very important to the design of borehole heat exchangers (BHEs) because the performance and cost depends on the estimated values. To solve the inverse problem using TRT data obtained from a vertical closed loop BHE, many analytical and numerical response models have been used. Specifically, the infinite line source (ILS) model [1], the infinite cylindrical source model [2], the finite line source model [3], the composite model [4], and the numerical method with a parameter estimation technique [5–12] have been used to estimate the thermal properties of the ground and to predict the temperature response of the ground. Among all of the estimation methods available, one of the most frequently used methods is regression estimation using

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Nomenclature

c	specific heat capacity (J/(kg K))
C	volumetric heat capacity (J/(m^3 K))
Ei	exponential integral
f_{obj}	objective function
H	length of BHE (m)
k	gradient of temperature response in the semi-log plot
K	overall heat transfer coefficient per unit pipe length (W/(m K))
l	a certain location on the hydraulic circuit
L	length of hydraulic circuit above the ground surface (m)
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	heat exchange rate between the TRT system and the outdoor environment (W)
Q_{BHE}	actual heat injection rate to the BHE (W)
r	cylindrical coordinates (m)
r_b	radius of the borehole (m)
R_{tot}	overall thermal resistance (m K/W)
t	time, elapsed time after the heat injection (s)
t_j	timestep of the estimation
t_n	discrete elapsed time (s)
T	temperature (°C)
$\overline{T}_{cf}$	average temperature of the circulating fluid (°C)
$T_{sol,a}$	sol-air temperature (°C)
$\dot{V}$	volumetric flow rate (m^3/s)

Subscripts

a	outdoor air
amb	ambient air
avg	average
b	borehole
cf	circulating fluid
$dist$	disturbance
eff	effective
exp	experimental
f	final
in	inflow (from TRT rig to BHE inlet)
ini	initial value of parameter estimation
lat	latent heat
out	outflow (from BHE outlet to TRT rig)
r	radius of the borehole, location of the borehole wall
rad	radiation
rig	TRT rig
s	soil
cal	calculated
0	initial

Greek letters

α	thermal diffusivity (m^2/s)
γ	the Euler–Mascheroni's constant, γ=0.5772
κ	non-dimensional parameter
λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)
σ	standard deviation

Acronyms, abbreviations

GR	grouted
PE	parameter estimation method
Seq	sequential plot method

the exponential integral approximated ILS model [1,13]. This is primarily because of the ILS model's simplicity and wide applicability. For the boundary conditions, the ILS model assumes an adiabatic condition on the ground surface and a constant heat flux from the heat source. However, in practice, those boundary conditions are violated in most cases. First of all, the ground surface, which is assumed to be adiabatic in the ILS model, exchanges heat with the external environment. Additionally, the TRT rig, which includes the hydraulic circuit that connects the TRT rig and BHE loop, can also be affected by changes in the external environment. Moreover, voltage fluctuations from the power grid can affect the heat output from the TRT rig. Therefore, the constant heat rate assumption is also violated. These violations of the boundary conditions cause estimation errors when the ILS model is used for the inverse estimation. The above-mentioned disturbances have been recognized by many researchers [6,10,12,14–20], and the effects can even be found in some response curves from studies that did not account for the influence of the disturbances [21–26].

Florides and Kalogirou [17] stated that TRT data are affected by two factors. One is the heat flux from the ground surface, which changes the temperature of the top layer of the ground. This effect would be important only when the BHE is short, because effects of the surface ground temperature change are not typically apparent at depths of 10 m in our observations. The second factor is the change of the heat injection rate caused by voltage fluctuations from the power grid. In their study [17], the output of the heater increased by about 300 W at night time. The authors said that the disturbance effects from multiple factors can be neglected during 280–400 h of the TRT when the fluid temperature increment becomes stable. However, in practice, a TRT of such a long duration might not be conducted because of cost and time limitations. Accordingly, many researchers have been trying to determine the appropriate minimum test period to obtain reliable results [4,6,27–32]. Austin [10] also found that temperature changes in the heat carrier fluid can occur as a result of unstable power supplies and that the results of a TRT can be altered by diurnal temperature variations. Notably, Austin [10] observed disturbance effects even when the test period was long. Other researchers [14,33] have also pointed out this same problem.

Signorelli et al. [6] presented the relation between estimated thermal conductivity and the temperature difference between the outdoor air temperature and heat carrier fluid. The estimated ground thermal conductivity was oscillating within the range of 3.5–3.9 W/(m K) because of the heat exchange between the outdoor air and heat carrier fluid. The authors stated that insufficient insulation of the test device and piping above the ground can affect the test results considerably. Raymond et al. [34] showed that there was a strong influence of surface temperature variations, which varied between day and night, on a TRT conducted in a short BHE installed in a mine waste dump. This disturbance created different estimated thermal conductivities between the numerical analysis and ILS model results. Roth et al. [15] found that the fluid temperature was affected by the outdoor environment even when the hydraulic circuit was insulated. Bandos et al. [16] also pointed out effects from the varying external environment.

Power fluctuations of the heater caused by unstable supply voltage from the power grid were clearly captured in the TRT results conducted by Sharqawy et al. [18]. They observed increases in the heating power during the night time and decreases during the day time. The electrical power swing was directly connected to temperature fluctuations in the circulating fluid.