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Parameter estimation of in-situ thermal response test with unstable heat rate

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ABSTRACT

This paper proposed the history-independent algorithm based on CSM (cylindrical source model) in the TRT (thermal response test) with unstable heat rate. It achieved a faster computing speed and more accurate results than the usual superposition algorithms in processing variable heat rate problem. In order to alleviate ill-posed problem and improve the reliability of parameter estimation, a Matlab program was compiled to perform inversion calculation to obtain the ground thermal properties based on the SAA (simulated annealing algorithm) with preset lower and upper bounds for estimated parameters. The estimated ground thermal conductivity and volumetric heat capacity from in-situ TRT with unstable heat rate (case A) showed closest agreement with those (case B) evaluated by the LSM estimation method, and calculated water temperatures corresponding to estimated results agreed well with the measured water temperature. Based on SAA coupled with the history-independent mathematical algorithm in in-situ TRT with unstable heat rate, TRT can be performed continuously, independent of power fluctuation with both time and cost saved.

1. Introduction

GCHPs (ground-coupled heat pump system) is now well established to provide heating or cooling in commercial and residential buildings, and offers higher energy efficiency and lower environmental impact [1,2]. A GCHPs includes a conventional heat pump unit and a group of BHEs (borehole heat exchangers), which are connected with a circulating pump. The improvements in GCHPs are currently focused on the optimization of the system and the reduction of installation cost. The length of BHEs is crucial for achieving optimal design and low cost. Moreover, for the design of larger BHE systems, it is necessary to know some points such as the effective heat transfer capacity of the borehole, size, configurations and backfill materials of BHEs. Because the capacity of heat/cool exchange strongly depends on the thermal properties of the ground (thermal conductivity, borehole thermal resistance, heat capacity, undisturbed ground temperature, etc), it is very important to know these properties when designing and optimizing GCHPs. However, ground thermal properties are site-specific and cannot be influenced by engineering, so it needs to be obtained in time to best plan the layout of BHE systems (e.g. number and depth of boreholes).

There are several methods to determine the thermal properties of the ground, such as type identification, steady-state test, probe test and TRT (thermal response test) [3]. As a basic tool for in-situ determination of thermal properties, TRT is widely recognized as the most effective method, and has been widely applied in Europe, America, Oceania, Asia and Africa [4]. In the ideal TRT, heat is generated by an electric heater and rejected to the ground at nearly a constant rate aiming for a temperature development in the thermal carrier fluid as similar as possible to the real GCHPs. ASHARE [5] recommends acceptable power quality could be obtained when the standard deviation is no bigger than 1.5% of average power and the maximum variation (spikes) is no bigger than 10.0% of average power. When the deviations are larger, acceptable results could be obtained if the maximum deviation of average loop temperature is no bigger than 0.3 °C. The heat rate should be from 50 W to 80 W per meter of borehole. Actually, the heat rate is never absolutely constant but varies with voltage change in the electric heater. If the electric power is from a local

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utility line or a portable generator, the variations in electric power cause significant changes in the heat rate. Therefore, an acceptable constant supply of electricity is generally very difficult to achieve in the actual project. Although the regulator may be installed and the power stability could be improved, the effect would be limited. When the ideal TRT can't be guaranteed, ASHARE [5] recommends a 10- to 12-day waiting period before retesting a borehole after a completed 48-h test, and suggests the waiting period can be reduced in proportion to the reduced test time. So, how to determine ground thermal properties is vital for TRT with unstable heat rate, which has the potential of being cost and time effective.

The estimation of the unknown thermal properties is a well-known inverse heat conduction problem, and the identification of the unknown thermal properties is achieved through a comparison between the raw data of the time-based average fluid temperature, experimentally acquired directly from TRT, and the corresponding values predicted by related mathematical models for BHE [6]. In order to enable a more accurate estimation of the thermal properties, a number of mathematical models for BHE have been recently applied in TRT, such as LSM (line source mode) [7–11], CSM (cylindrical source model) [11–13], numerical model [14–16], and other models [17–19]. For parameter estimation of in-situ TRT with unstable heat rate, Sauer [8] developed a computer program to evaluate TRT data using the superposition method of LSM. Several calculations were also performed using test data, and showed a stable result in stepwise/sequential evaluation. By comparison of 21 tests, the deviation between standard method and superposition method is less than 3%. Hu et al. [19] used superposition principle to solve the variable heat input problem in TRT including the large power fluctuation and power failure, which was an unsteady method based on modified composite model considering the unsteady-state heat transfer in the borehole. Fleur et al. [20] applied power superposition method of G-function to data from a multi-stage TRT conducted on a small diameter test pile, and it was proved to be a useful approach for addressing medium term power variations and analysis of multiple test stages. In the study conducted by Raymond et al. [21], the well function, the superposition principle and the radius of influence were applied to temperature calculations using LSM, and to the analysis of variable heat injection rate tests and temperature recovery following heat injection. A sensitivity analysis of the mean water temperature increment was carried out for two levels of thermal properties variance during the heat injection and recovery phases. The conclusion showed that borehole thermal resistance should be estimated with the heat injection data, and the thermal conductivity estimation in recovery phase. Monzó et al. [22] analyzed the influence of heat rate variations in different phases of a DTRT (distributed thermal response test). The highest values of the thermal parameters were obtained when only the data during the heating phase was taken into account, and the lowest values were from the analysis of the recovery phase. Moreover, in the recovery phase, the duration of heat steps considered in the DTRT analysis did not seem to have any effect on the thermal conductivity result as long as the superposition principle was applied. In order to remove variable-rate effects for TRT, Austin et al. [15] used numerical parameter estimation methods to estimate ground thermal conductivity in variable-rate tests. Moreover, Beier and Smith [23] adapt the Laplace domain approach to take out the effect of variable heat rate during an in-situ test without forcing the user to choose the method of analysis beforehand. The deconvolution method serves as a preprocessing step before applying a mathematical BHE model to determine ground conductivity and thermal resistance, which gives the engineer more flexibility in analyzing a test. Gustafsson and Westerlund [24] conducted multi-injection rate TRT to detect the convective heat influence and to examine the effect of different heat injection rates. They found that an increase in heat injection rate results in a higher effective bedrock thermal conductivity.

In the previous studies on unstable heat rate in-situ TRT, the superposition principle based on BHE model was mainly used to process the variable heat rate, and the inversion calculation was conducted to obtain ground thermal conductivity, volumetric heat capacity and borehole thermal resistance with the experimental data. Different from the superposition of the unstable contributions of each time step, a history-independent mathematical algorithm based on CSM was used to predict the mean fluid temperature in in-situ TRT with unstable heat rate in this article. Next, SAA (simulated annealing algorithm) was applied in mathematical optimization processes in order to alleviate ill-posed problem and improve the reliability of parameter estimation. Finally, an in-situ field test was studied with the present method. The resulting estimates for ground thermal parameters were checked and compared with that from evaluating method based on LSM presented by Beier and Smith [7], which had been validated with data from a large-scale laboratory sandbox.

2. Heat transfer model of BHE in TRT

The modeling of BHE in TRT has undergone many improvements since it was first formulated. Compared with numerical model, it must be noted that analytical models, particularly the LSM and CSM, show the advantages that they are fast and easy to use and allow the estimation of ground thermal parameters by adopting the late regime temperature history. At the same time, the straightforward algorithm deduced from the analytical models can be readily integrated into parameter estimation program, which also makes the analytical models popular. Especially, for in-situ TRT with unstable heat rate, shortening computational time and improving accuracy of mean fluid temperature response to transient heat power in the pipes of BHE make model selection more important.

2.1. Line source model

Referring to the Kelvin line source model [25], a borehole can be considered a line source with a constant heat injection rate, the mean temperature of the circulating fluid in the ground loop under constant heat rate is approximated by

$$T_f(t) = T_0 + \frac{q_l}{4\cdot\lambda_s\cdot\pi}\cdot\left[Ei\left(\frac{r_b^2\cdot C_s}{4\cdot\lambda_s\cdot t}\right) + 4\cdot\pi\cdot\lambda_s\cdot R_b\right] = T_0 + \frac{q_l}{4\cdot\lambda_s\cdot\pi}\left[\ln\left(\frac{4\cdot\lambda_s\cdot t}{1.78\cdot r_b^2\cdot C_s}\right) + 4\cdot\pi\cdot\lambda_s\cdot R_b\right] \quad (1)$$

where $Ei(x) = \int_x^\infty \frac{e^{-s}}{s}\cdot ds$, which represents the exponential integral. The natural logarithm approximation on the right side of Eq. (1) is accurate to 5% when $\left(\frac{4\cdot\lambda_s\cdot t}{r_b^2\cdot C_s}\right) > 11$.

As shown in Eq. (1), it can be re-written in a linear form as:

$$T_f(t) = k\cdot\ln(t) + b \quad (2)$$

where $k = \frac{q_l}{4\cdot\pi\cdot\lambda_s}$, the thermal conductivity can be determined from the slope of the line resulting when plotting the fluid temperature against $\ln(t)$. For in-situ TRT with constant heat rate, Beier and Smith [7] recommended the borehole thermal resistance can be calculated as