Short-time thermal response test based on a 3-D numerical model

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Abstract. To assist the design of ground heat exchangers the thermal response test method is usually performed. In its traditional version the thermal response test data are compared with the line source model solution to restore the soil thermal conductivity and the borehole thermal resistance. This approach requires that a steady-state thermal condition is approached and, consequently, it may need up to about 50 hours to be carried out. Promising approaches can be found within parameter estimation procedures supported by 3-D numerical tools. They allow the reduction of the test duration, since they perform a more realistic description of the system’s behaviour especially in the early regime. In this paper, a versatile parameter estimation procedure based on a 3-D numerical model of a geothermal system is presented. The procedure is aimed to restore the value of both the soil thermal conductivity and the borehole thermal resistance, by using only the first few hours of the thermal response test data. The approach is validated by comparison with a medium-scale set of experimental laboratory data.

1. Introduction
Several studies, promoted by environmental and energy concerns [1], have shown the importance of ground coupled heat pumps based on borehole heat exchangers in reducing primary energy use in building heating and cooling, both in mild [2] and in harsh climates [3].

The traditional methodology used to assist the design of ground heat exchanger (GHE) installations is the thermal response test (TRT). Essentially it consists of providing constant heat power to a carrier fluid, usually water, which is circulated through an in-situ pilot GHE. The time-dependent behavior of the mean fluid temperature between the inlet and the outlet of the heat exchanger represents the experimental data which, when taking the test conditions into consideration, enables to estimate the soil’s and the GHE’s thermal properties. Usually the TRT data are compared with the line source model (LSM) solution [4] to restore two important properties for the GHE design: the soil thermal conductivity and the borehole thermal resistance.

Although the LSM has the advantage of being very simple, it requires steady-state data for good results and, consequently, it needs up to about 50 hours to be carried out. The long time requested increases the cost of the test and, as a consequence, ground heat exchangers are not usually optimized by TRT [5]. For this reason, TRT can be defined short-time when it takes much less than 50 hours, reducing noticeably its cost.

Beier and Smith [6] developed a method based on dimensional analysis to calculate the minimum testing time necessary to estimate soil thermal conductivity within 10% of the estimated value from a very long test. Due to its extreme sensitivity to some quantities which can not be accurately estimated before the TRT (e.g. borehole thermal resistance and volumetric heat capacities of grout and soil), the so calculated minimum test time is affected by huge uncertainty which limits the utility of this approach in the practical cases.

More promising approaches can be found within parameter estimation procedures supported by numerical tools [7]. They allow either the reduction of the test duration because they already converge in a transient thermal regime or the restoration of more information than the standard TRT data processing approach. An important advantage of the numerical simulation is that it can be easily
improved to include some aspects of the actual TRT, e.g., fluid flow rate fluctuations, non-uniform heat power supply and the non-homogeneity of the ground. On the other hand, this approach is more complex because it requires GHE numerical modeling and it requires the system's geometry to be accurately known.

This methodology was adopted by Shonder and Beck [8] first, to estimate both the grout and the soil thermal conductivities by coupling a parameter estimation method with a 1-D thermal model. Afterwards Austin et al. [9] and Spitler et al. [10] enlarged the estimation procedure to the consideration of a 2-D thermal model.

Austin et al. [9], in the discussion of their 2-D approach, suggested coupling parameter estimation procedures with numerical transient 3-D GHE models in order to improve the accuracy of TRT and to shorten the test time. Indeed, a 3-D numerical approach is fundamental to correctly predict the early regime of the temperature history, which is strongly dependent on the GHE geometrical and thermal details. Despite this, because the huge computational resources requested were not available at that time, Austin et al. [9] did not validate the 3-D modeling approach.

In the open scientific literature many GHE 3-D models are present but, to the authors’ knowledge, only in few cases a 3-D model has been coupled with parameter estimation procedures applied to experimental data under an inverse problem approach.

Bozzoli et al. [11] have processed TRT data in order to restore the grout and soil thermal conductivities and volumetric heat capacities. These Authors have shown that this procedure is successful with 48 hours TRT data while it fails on shorter time interval data.

In this paper a parameter estimation procedure (PEP), aimed to restore the value of both the soil thermal conductivity and the borehole thermal resistance by using only the first 12 hours of the TRT data, is discussed. The procedure, which is based on a 3-D numerical model of the geothermal system, is here applied to a medium-scale set of experimental laboratory data.

2. Physical model
The feasibility of a short-time TRT assisted by a 3-D numerical model is here validated by using experimental TRT data which are provided by the Oak Ridge National Laboratory. The data refer to a medium scale laboratory experiment [6,12], in which a 18 m long GHE installed vertically is immersed in a bentonite grout and surrounded by a homogeneous soil of known composition delimited by a thermally insulated parallelepiped box.

Based on the experimental setup specifications, the considered GHE with the coupled energy storage system is schematically shown in figure 1. It consists of a high-density polyethylene (HDPE) U-tube pipe immersed in the filling material (grout), where the heat carrier fluid (water) is circulated at a given flow rate. The system shows a symmetry plane, and it is considered practically unlimited in the radial direction. In the axial direction, instead, according to the test conditions it is limited by two adiabatic surfaces placed at z=0 (soil surface) and z=H (depth of the tested GHE).

3. 3-D numerical model
The simulation of the geothermal energy storage (GES) system behavior during the TRT is performed by a transient, 3-D numerical finite element model implemented within the Comsol Multiphysics® environment. The model couples the 3-D transient conduction heat transfer problem within the soil, the grout and the HDPE tube wall, with the 1-D convective problem within the heat carrier fluid which flows in the U-tube, by means of the weak boundary condition technique. Moreover, in order to simulate the actual heat power provided to the GHE, the experimentally acquired temperature at the inlet of the U-tube has been imposed in the model. A detailed description of the simulation procedure is available in [11].

The whole geometry has been discretised by means of 41,080 prism elements as shown in figure 2. The radial mesh is much finer than the axial one because the temperature gradients are expected to be much higher in magnitude in the radial than in the axial direction. Moreover, the radial mesh is finer in the central area, where the soil-GHE coupling is modeled, and becomes coarser in the surrounding
soil. The accuracy of the adopted mesh has proven by reaching the convergence of the system temperature within 0.5%.

![Figure 1. Geothermal energy storage system’s model.](image1)

![Figure 2. Finite element model.](image2)

4. Parameter estimation methodology
A general procedure, suitable to estimate unknown parameters through the comparison between experimental data and the corresponding model simulation, is based on least squares minimisation. By denoting with $Y_i$ (measured temperature at time $i$, $i=1,.., M$) the temperature data measured at the exit section of the GHE and with $T(P)$ the corresponding simulated temperature obtained from the solution of the direct problem by using the current estimate for the unknown parameters $P_j$ (unknown parameters, $j=1,.., N$), the parameter estimation problem is solved by minimising the following function:

$$S(P) = (Y - T(P))^T(Y - T(P))$$

The minimization of $S(P)$ is here achieved by an iterative procedure based on the Gauss linearization method [13]. At each iteration a new parameter set is estimated as:

$$P^{k+1} = P^k + \Delta P^k$$

where $\Delta P^k$ is the unknown parameters increments vector, obtained by minimising the function $S(P)$ at the $k^{th}$ iteration. This is done by approximating the temperature vector with a first-order Taylor series expansion.

The minimisation of function $S(P)$ can therefore be expressed as a system of $N$ linear algebraic equations where $\Delta P_j^k$ are the unknown increments. The solution of this equations system is given as:

$$\Delta P^k = J^k [T(P^k) - Y]$$

where $J^k$ is the sensitivity matrix, whose column vector $J_j^k$ quantifies the rate of change of $T$ in the parameter space:

$$J_j^k = \frac{\partial T}{\partial P_j}$$
The parameter estimation model is supported here by the transient 3-D numerical model of the vertical GHE described in the previous paragraph. The iterative procedure stops when the parameters show a relatively flat increment. When dealing with noisy data, a further stopping criterion based on the discrepancy principle [14] may also be considered, in which the iterative procedure stops when the residuals between noisy data and the estimated temperature are of the same order of magnitude of the measurement uncertainty. That is when:

\[
S(p^{k+1}) < M\sigma^2
\]  

where \(\sigma\) is the standard deviation of the measurement error.

The procedure described by equations (1)-(4) has been applied to TRT data to estimate both the soil thermal conductivity and the borehole thermal resistance.

The borehole thermal resistance is defined as follows:

\[
R_b = \frac{(T_f - T_b)}{q}
\]

where \(T_f\) and \(T_b\) are the averaged fluid and borehole wall temperatures, respectively, and \(q\) is the corresponding steady-state heat flow rate per borehole unit length.

The borehole thermal resistance is not included in the problem formulation, but it strictly depends on grout’s thermal conductivity [15]. Therefore, the grout’s and the soil’s thermal conductivities, \(\lambda_g\) and \(\lambda_s\), respectively, were considered as the unknown parameters of the inverse thermal problem.

5. Results
In a previous paper Bozzoli et al. [11] applied a two-step parameter estimation procedure to the same experimental data set provided by the Oak Ridge National Laboratory. By subdividing the 48 hours acquired temperature time interval in an early regime data and a late regime data, they estimated the thermal properties of both the grout and the soil as specified in table 1.

|                      | Soil  | Grout |
|----------------------|-------|-------|
| Thermal conductivity (W/m·K) | 2.40  | 0.76  |
| Volumetric heat capacity (kJ/m³·K) | 3110  | 4759  |

In their discussion about these estimates, Bozzoli et al. [11] point out that the above quoted heat capacity values are quite reasonable in relation to the previously published data [6,12], while the thermal conductivity values do not satisfactorily match both the target thermal conductivity values, i.e., 2.82 and 0.73 W/m·K for soil and grout, respectively.

In this paper only the first 12 hours of this data set are considered to simulate a short-time TRT. The heat capacity of both the soil and the grout are considered to be known and equal to the optimal values specified in table 1. The thermal conductivities specified above, i.e., 2.82 and 0.73 W/m·K, instead, stand for the target values of the present PEP, based on short-time TRT data.

It is well known [14] that a successful parameter estimation process requires that the matrix \([J]^T[J]\) is non-singular, i.e. its determinant differs from zero. This condition is verified if the parameter sensitivity vectors are linearly independent and if they have large and comparable magnitudes. A sensitivity analysis aimed at verifying the fulfillment of these conditions may be based on the comparison between the scaled or relative sensitivity vectors, which are defined as follows [14]:

\[
J_j^T = J_jP_j
\]
Because of the multiplication by the unknown parameter $P_j$, the scaled sensitivity coefficients assume the units of temperature. As a consequence, they can be compared as having the magnitude of the measured temperature as a basis.

For the considered PEP, the scaled sensitivities of the unknown thermal conductivities on the outlet fluid temperature distribution are shown in figure 3.

![Figure 3. Scaled parameter sensitivity versus time.](image)

In the considered 12 hours time interval the scaled sensitivities look linearly independent and their magnitudes are comparable. This pattern constitutes a precondition for the restoration of a reasonably approximate value of the unknown parameters.

The thermal conductivity values restored by means of the short-time TRT are reported in table 2. They agree with the target values within 1.4%, for both the soil and the grout. Furthermore, by processing the computer simulation output through equation (6), the borehole thermal resistance converged to the value 0.192 mK/W.

| Table 2. Thermal conductivity estimated by the short-time TRT. |
|---------------------------------------------------------------|
| Thermal conductivity (W/m·K)       | Soil  | Grout |
|-----------------------------------|-------|-------|
| 2.86                              |       | 0.74  |

Calculations by Kavanaugh [16] indicate a 10% error in soil thermal conductivity results in a 4.5% to 5.8% error in the design of borehole length and a 1% change in cooling capacity of a geothermal heat pump system. Thus, the 1.4% approximation in the estimated soil thermal conductivity is acceptable from the engineering point of view.

The residual distribution calculated at the end of the PEP is reported in figure 4. The model fits the experimental data within a maximum approximation of about 0.2 K. Moreover, if the first 40 minutes are omitted, corresponding to the heating system warming up, this approximation drops to less than 0.1 K. These data confirm that the minimisation algorithm works properly since the model’s prediction fluctuates randomly from the raw data around a nearly zero mean value, with the exclusion of the warming up period and of some time intervals, for instance around t=7 h, where the time averaged residual departs from zero, may be due to an accidental thermal transient in the test operation.

However, the adoption of a different value for the volumetric heat capacity, $C_s$ or $C_g$, for soil and grout, respectively, might significantly affect both the restored soil thermal conductivity and the
borehole thermal resistance. Figure 5 shows the variation of the estimated parameters due to a model soil or grout heat capacity change within ±20% from the previously assumed values (table 1).

The soil heat capacity value has a quite limited influence on the unknown parameters restoration. Instead, grout heat capacity influences less than 10% the restored value of the grout thermal conductivity and up to about 25% that of soil. On the other hand, this effect can be neglected because, in geothermal applications, the grout heat capacity is generally known with relatively great confidence.

![Figure 4. Residuals plot.](image)

![Figure 5. Restored thermal conductivity variation due to a model soil or grout volumetric heat capacity change within ±20% from their optimal values.](image)

6. Conclusions
The here presented parameter estimation procedure is based on a short-time thermal response test (12 hours instead of 48 hours analyzed in [11]) has showed to be effective when some assumptions on borehole and ground are acceptable, i.e., homogeneous ground, known geometry, known heat capacities. Indeed, it has to be stressed that a short-time TRT has a small radius of influence [17] which means that the subsurface thermal conductivity is evaluated for a distance that is shorter than the radius of influence of an actual borehole heat exchanger coupled with a heat pump system. As a
consequence, only when the ground around the pipes can be considered homogeneous, adopting estimation techniques based on short-time TRT data should be suggested. Regarding to the effect of volumetric heat capacity on the restored thermal conductivity values, the presented results have pointed out that a soil heat capacity variation around its optimal value has a quite limited effect. A possible uncertainty on the grout heat capacity value, instead, might considerably affect the soil thermal conductivity. However, in geothermal applications the grout heat capacity is generally known with relatively great confidence.

Acknowledgements
Doctor John A. Shonder, Professor Jeffrey D. Spitler and the Oak Ridge National Laboratory Research Group (USA), who kindly provided the experimental data, are gratefully acknowledged.

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