REFINEMENT AND VALIDATION OF IN SITU PARAMETER ESTIMATION MODELS.

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KEY WORDS

geothermal energy, ground coupled, heat pump, heat exchanger, in situ testing, simulation, thermal response, thermal storage, thermal conductivity.

PROJECT BACKGROUND AND STATUS

Determination of the thermal conductivity of the ground formation is a significant challenge facing designers of Ground Source Heat Pump (GSHP) systems, particularly those used in commercial or institutional buildings. The number of boreholes and the depth and cost of each borehole are highly dependent on the ground formation thermal properties. Hence, depending on the geographic location and the local drilling costs, the formation thermal properties strongly influence the initial cost to install a GSHP system.

The initial work to develop suitable methods to predict ground formation thermal conductivity was funded by the National Rural Electric Cooperative Association. This project involves additional research to validate and improve the procedure.

PROJECT OBJECTIVES

The project objectives are to provide an experimental validation for the in situ methodology and to reduce the time required to 1) perform a test on-site and 2) analyze the results.

Technical Objectives

- Validate the parameter estimation procedure, using several experimental comparisons.
- Shorten the required length of in situ tests.
- Shorten the analysis time required for the parameter estimation algorithm.
- Perform a joint validation of the in situ methodology and current design methodology.

Expected Outcomes

- Increased confidence in in situ test results, resulting in wider usage of the procedure.
- Quantify the uncertainty of in situ test estimates of ground thermal conductivity so that designers know what safety factor might be needed.

- Decrease in the in situ testing duration. If test duration can be significantly shortened, the procedure will be used more widely.
- Decrease the computational time required for analysis.
- Increased confidence in design methods.

APPROACH

The ground formation thermal conductivity can not be directly measured – its value must either be estimated based on physical analysis of core samples or inferred from temperature and heat flux measurements. The parameter estimation technique used to predict formation thermal conductivity implements the Nelder and Mead (1965) simplex algorithm based on a detailed transient, two-dimensional finite volume model of a ground loop heat exchanger (Yavuzturk et al. 1999). The finite volume model provides a detailed representation of the borehole geometry and thermal properties of the fluid, pipe, grout, and ground.

The method relies on an experimental measurement of the ground thermal response to a heat flux imposed on a test borehole. Mogensen (1983) described the concept of using such a measurement to estimate the ground thermal conductivity. Subsequently, development of an experimental apparatus began in 1995 at Oklahoma State University and was described by Austin (1998).

An information flow diagram of the parameter estimation model using the numerical objective function evaluation approach is shown in Figure 1. Austin et al. (1999) gives a detailed procedure validation and a sensitivity analysis on the predicted parameters.

RESEARCH RESULTS

- Some validation of the in situ methodology via comparison to cored samples has been performed for borehole #6 on Site A at the Oklahoma State University. The thermal conductivity of the ground formation for this borehole was established independently using the guarded hot plate method (ASTM 1963) and a physical analysis of the formation core sample (EPRI 1989). A 260-hour long in situ test was conducted with the in situ test apparatus.

  The thermal conductivities of the ground and grout were estimated simultaneously data lengths in 20-hour increments. The results are provided in Figure 2 below. The independently established effective thermal conductivity for the ground formation at borehole Site A#6 is reported by Smith (1998) to fluctuate in a range from 0.9 Btu/hr-ft-F (1.6 W/m-K) to about 1.9 Btu/hr-ft-F (3.3 W/m-K). A weighted average based on the types of soils identified in the core sample suggest a value of about 1.35 Btu/hr-ft-F (2.33 W/m-K). In this test the ‘converged’ value of the effective thermal conductivity only deviates by about 6% from the independently established best estimate value.

- A medium-scale laboratory test (sandbox test) where a homogeneous soil (dry or saturated sand) surrounds a simulated borehole (Smith 1998) was conducted to provide validation for the parameter estimation procedure. The thermal conductivity of the dry and wet sand was independently determined. With 46-50 hours of measured data, the in situ analysis predicted the conductivities for both cases within 2% of the independently determined values. Austin et al. (2000) provides details on the model validation and sensitivity analyses of the predicted parameters as well as details of the configuration of the test apparatus.

- Additional in situ tests were performed at two of the Lincoln, Nebraska school district facilities. The length of these tests varied between 50 to 60 hours. These in situ test results will be used for joint validation of the parameter estimation method and the design and modeling software.

- A refinement of the numerical model and the parameter estimation techniques was achieved via the implementation of a 'hybrid' numerical model and an exploratory initial search algorithm.

  To reduce the computational effort, the extent of the numerical domain in the radial direction is made smaller (1/4th of its initial size) and a time-dependent boundary condition (based on the line source) is enforced at the outer domain boundary. The error introduced by using the line source model to determine the outer domain boundary condition is negligible (less than $\pm 1\%$), since the radial is computed at some distance from the source. This refinement reduced the analysis time by approximately 50%.

  The final predictions of the parameter estimation algorithm are dependent on the initial guesses for the estimated parameters. Starting with a 'lucky' initial guess the Nelder-Mead simplex routine can reach the minimum in significantly less time than if the initial guess was made farther away from the minimum. For this purpose the line source model is implemented to 'feed' initial guesses to the Nelder-Mead simplex routine in order to make it start with an initial simplex that is closer to the global minimum. The results of the exploratory search algorithm decreased the total number of objective function evaluations on the average by about 10%.

- The comparison of both gradient based and non-gradient based parameter estimation techniques showed that O'Neill's (1971) implementation of the Nelder-Mead simplex method yields the minimum number of objective function evaluations. While some gradient-based techniques could not find the domain minimum at all, others such as genetic algorithms required a significantly larger computational time.

FUTURE PLANS

- Further improve the numerical model by using a boundary-fitted coordinates approach in representing the U-tube pipes of the ground loop heat exchanger. It is expected that boundary-fitted coordinates representation would provide even more accurate average borehole temperature predictions especially during early times of simulation. Combined with a revised test procedure, where the U-tube position in the borehole is controlled, this may allow significantly shorter test duration.

- Improve the exploratory search algorithm using other analytical (cylinder source model) or exploratory numerical models (exploratory models with coarser grid and larger time steps). This may allow us to further reduce the analysis time, which is typically on the order of 3-4 hours.

- Develop an on-line parameter estimation procedure. This procedure may allow the data analysis to be done during the test, and therefore tell the operator when the test is done, rather than waiting until after the test is over and hoping that enough data have been collected.

- Continue validation of the in situ methodology. Additional test data collected by Dr. Smith will be used for validation of the procedure. Also, in situ test data collected at schools in Lincoln, Nebraska will be used in combination with monitored data to jointly validate the in situ methodology, design procedures, and short time step simulation models.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	***Type and Extent of Interest***
Ewbanks and Associates	In situ validation and shorter test duration.
Geothermal Design and Engineering	In situ validation and shorter test duration.
Middleton Corporation	In situ validation and shorter test duration.

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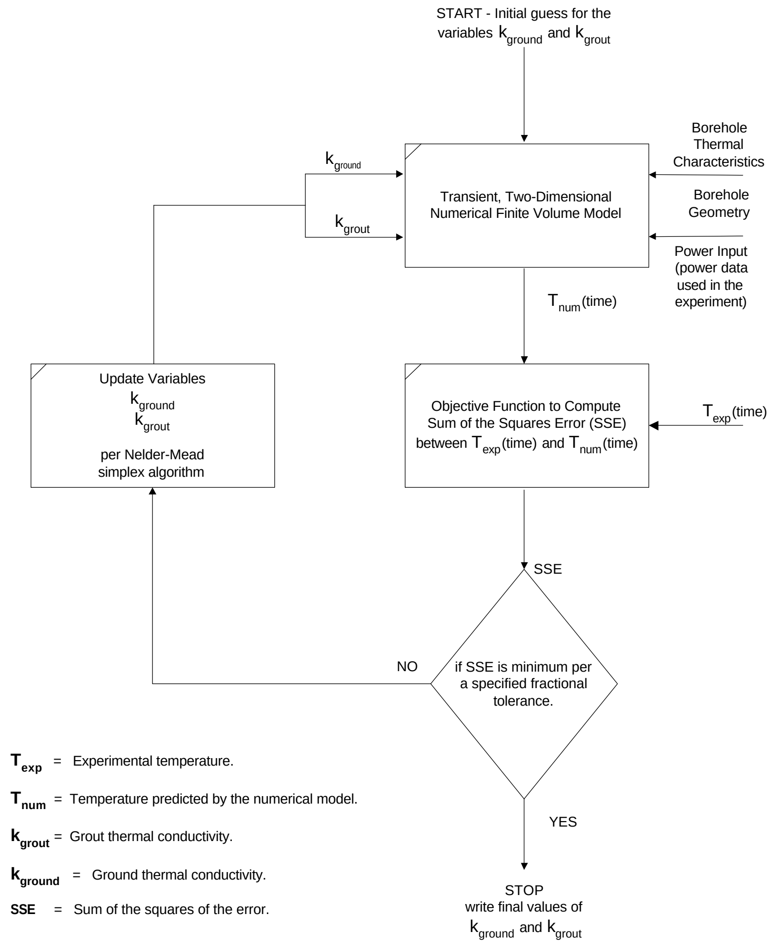

Figure 1 *Information flow diagram for the parameter estimation algorithm.*

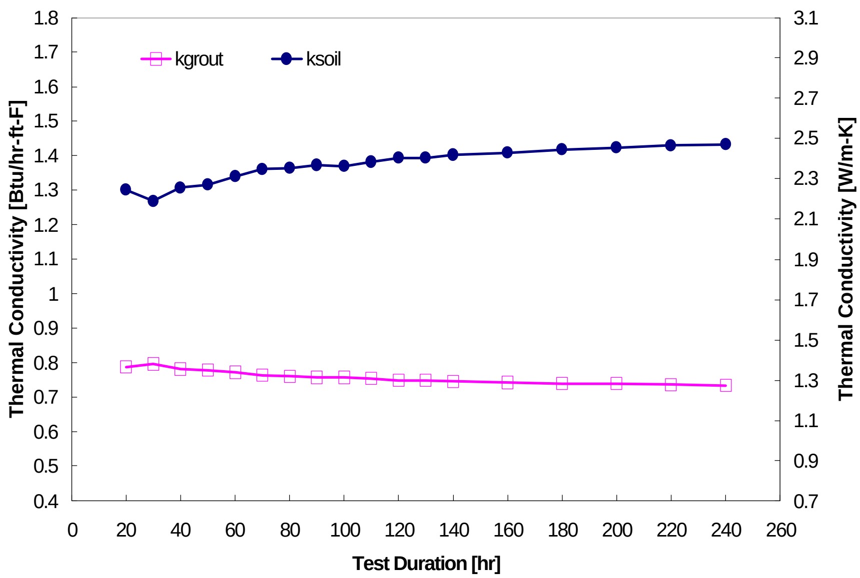

Figure 2. Parameter estimation results via long-term in situ. Site A#6 Oklahoma State University.