In Situ Measurement of Ground Thermal Conductivity: The Dutch Perspective

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Determination of the ground's thermal conductivity is a significant challenge facing designers of Ground Source Heat Pump (GSHP) systems applied in commercial buildings. The ground heat exchanger size and cost are highly dependent on the ground thermal properties. In order to be able to predict ground thermal properties, an experimental apparatus has been built capable of imposing a heat injection or heat extraction pulse on a test borehole, and measuring its temperature response. Analysis of a detailed in situ test using a line source approach and bootstrap uncertainty analysis is presented. Results are compared with a "traditional estimate" based on a detailed geological description and with results of laboratory measurements. These results are also compared to those determined using parameter estimation in conjunction with a two-dimensional finite volume model.

KEYWORDS: conduction, geothermal energy, ground coupled, heat pump, heat exchanger, simulation, thermal response, thermal storage.

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Abstract

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Introduction

This paper describes an *in situ* test facility to measure ground thermal properties. In contrast to previously described facilities, this one allows both heat injection as well as heat extraction using realistic temperature ranges. The test rig has been used to determine the thermal characteristics of several sites, using both energy injection and extraction, leading to improved and more confident designs. In practice, the test rig provides a reliable and robust method of estimating ground thermal properties. The test apparatus, built into a shipping container, is sufficiently mobile and can be operated without supervision. The power needed to run the test facility can either be obtained from the power grid or from a (low noise emission) generator. To allow remote monitoring, a telemetry system has been developed.

We will discuss results of an extensive test, including a high-resolution time series of experimental data, detailed geological descriptions and cone penetration tests, additional temperature measurements made in observation wells and independent measurements of thermal conductivity. Several caveats of the method, as well as possible solutions, will be presented.

The ground thermal properties are among the most critical parameters in ground heat exchanger design, and among the most difficult to quantify with sufficient accuracy or confidence. Methods for estimating the thermal properties of the ground include using values from literature, conducting laboratory experiments on soil/rock samples and performing *in situ* tests.

Using literature values requires the least effort, but the range of thermal conductivity values reported in literature is often quite large, due to the fact that local circumstances have a big influence. Moreover, these general values for specific types of soil/rock need to be translated to a value representative of the whole soil profile. A prudent design will use the lower values to ensure proper thermal operation of the system, but resulting in a (possibly not competitive) costly design.

An alternative to the use of literature values is determining, in the laboratory, the thermal characteristics of samples obtained from the profile. The drawback of this method is that only individual samples are analysed, which still need to be translated to a representative value for the entire profile. Moreover, only relatively small volumes are tested and inhomogeneities occurring at larger spatial scales are not incorporated. Also any disturbance of the sample during sampling or storage will affect the results. Finally, both methods do not provide any direct information on the influence of groundwater flow on the thermal properties of subsurface on the site.

In situ tests for estimating the thermal characteristics of a ground loop – borehole system have been developed by others and ourselves (Austin, 1998; Austin et al. 2000; Gehlin, 1998; van Gelder et al, 1999; Witte et al 2000). Using an *in situ* test is attractive as it provides information on the thermal conductivity and volumetric heat capacity of a considerable volume of the specific soil profile, under realistic conditions and taking into account the actual borehole – ground loop configuration. Apart from information on the ground-thermal properties, the testing provides crucial information regarding the actual drilling conditions on the site and, moreover, makes it possible to accurately predict project feasibility (both from an energy and economic point of view). Of course, the *in situ* test presents a number of specific problems as well. These mainly have to do with the influence of outside perturbations, the length of testing required (very long when compared to laboratory experiments) and the limitation of current analysis methodology.

In this paper, a comparison of different analysis methods will be presented. Moreover, we will discuss some aspects of the analysis procedure of the *in situ* test data, using additional information on temperature development in and near the borehole.

Background and analysis methods

The thermal conductivity of a material has to be inferred from the relation between energy flux and temperature. The *In situ* tests for estimating ground thermal conductivity impose a pulse of known and fixed energy flux on the borehole, and measure the resulting temperature response. The response test described here operates by heating or cooling the circulation medium (using a reversible heat pump). During the experiment, the volume flow as well as the temperature difference between inlet and outlet are held constant, allowing energy fluxes (heat extraction or heat injection) of between 50 and 2000 watts (170-6800 Btu/hr). Flow, temperature and several other test parameters are logged during the experiment at specific time intervals.

Several models for inferring the thermal properties from such a dataset are available. These models, all based on Fourier's law of heat conduction, include the analytical line source model (Kelvin 1882, Ingersoll et al. 1954) and the cylindrical source model (Carslaw and Jaeger 1946), and several numerical models (e.g. Eskilson 1987; Hellstrom 1989, 1991; Muraya 1995; Shonder and Beck, 1999;Yavuzturk, et al.

1999). In this paper, we will mainly focus on the line source model, which is the most widely used method at this time.

The data analysis is based on the theory describing the response of an infinite line source model (Ingersoll and Plass, 1948; Mogeson, 1983). Although this model is a simplification of the actual experiment, it can successfully be used to derive the geothermal properties (e.g. Kavanaugh, 1984; Austin, 1998; Gehlin, 1998).

The model approximates the transient process of heat injection or extraction by:

$$T_f = \frac{-\left(\dot{m}c_p\left(T_{out} - T_{in}\right)\right)}{4\pi kH}\left[\ln\left[\frac{4\alpha t}{r_0^2}\right] - \gamma\right] + \frac{\dot{m}c_p\left(T_{out} - T_{in}\right)R_b}{H} + T_{sur} \qquad 1.$$

where:

$\dot{m}$	:	mass flow rate	kg/s or lbm/hr
c_p	:	specific heat	J/kgK or Btu/lbm-R
$V\rho c(T_{out}-T_{in})$	:	energy injected / extracted	W or Btu/hr
T_f	:	average temperature of circulation medium	°C or °F
T_{sur}	:	far field temperature	°C or °F
k	:	ground thermal conductivity	W/mK or Btu/hr ft
H	:	borehole length	m or ft
R_b	:	borehole resistance	K/(W/m) or R/(Btu/hr/ft)
γ	:	Eulers constant	-
t	:	time	s or hr
r_0	:	borehole radius	m or ft
α	:	thermal diffusivity ($\kappa/\rho c_p$, where ρ is the density)	m^2/s or ft^2/hr

This formula can be used as an approximation of the transient process under the condition that:

$$t \geq \frac{5r_0^2}{\alpha} \qquad 2.$$

The thermal conductivity can be estimated from the data by:

$$k = \frac{-\left(\dot{m}c_p\left(T_{out} - T_{in}\right)\right)}{4\pi Hs} \qquad 3.$$

Where the parameter [s] equals the slope of a linear regression of temperature with logarithmic time. When k has been estimated, the borehole resistance R_b can be calculated using (1).

When applying this model several questions arise. The first question, how much of the beginning of the data series to ignore, deals with the fact that the first part of the data series only represents the response of the borehole itself. Secondly, we ask how long the experiment needs to be run, and at what time interval the data needs to be collected. In principle the amount of time needs to be larger than the condition imposed by eq. (2), but this value can only be calculated with an initial guess of the thermal diffusivity, and can be evaluated afterwards using the results from the experiment. Long series with a high time resolution may lead to cumbersome data processing, while too short series or series with a low time resolution may result in biased estimates or estimates with higher standard deviations. The third question is related to the fact that outside perturbations, as imposed by the diurnal temperature cycle, have a large influence on the result of the estimate of thermal conductivity (see e.g. Austin, 1998). Not only do these perturbations influence the resulting estimate due to the exact data period that has been selected for analysis, but they may also introduce a bias when the total flux is not balanced, a situation that may arise during a heat extraction experiment in summer when the temperature difference between atmosphere and circulation medium is small at night but large during the day. In winter the reverse situation may occur. This influence can be minimised by selecting appropriate experiment parameters (mainly keeping the medium temperature as close as possible to the outside temperature and imposing a relatively large energy flux), and proper insulation of the apparatus and connecting pipe work, but nevertheless is a point worth considering.

Austin (1998) addressed the first two questions by calculating the conductivity using different starting points and then including more data in a stepwise fashion. The resulting thermal conductivity estimates can be plotted with time to observe the convergence speed and value. We have noted in several experiments that this method is quite sensitive to the starting point and window size (the amount of data that is included at each step). The third problem, of cyclicity in the temperature response, is harder to address. The effect can be visualised by calculating the λ for a certain time-window that is shifted along the series. Again the results are very sensitive to the starting point and time window selected, in practice any value of k can be obtained. Moreover, it should be noted that the linear regression method makes certain assumptions about the distribution of the data and errors. One of the assumptions is that the errors (the residuals) are uncorrelated, while the residuals of typical *In situ* response series have very high autocorrelations. As a result, the regression coefficients obtained cannot be considered stable. Instead a weighted regression can be used, but it is quite difficult to obtain a vector of appropriate weights.

We have applied a bootstrap method to the data (Effron and Tibshirani, 1993), using Monte Carlo simulation. This procedure draws observation points from the complete set of observations in a random fashion, after which the regression coefficients are calculated. Subsequently a new sample is drawn, and new regression coefficients are calculated. This procedure is repeated a number of times and the variation in the regression coefficients obtained from all these samples yields an estimate of the confidence interval of the regression coefficients and the influence of individual data points. Bootstrap regression coefficients were calculated using different parts of the data series and using different bootstrap sample sizes. The resulting regression coefficients can be statistically analysed to estimate the stability and standard deviation of the thermal conductivity values obtained.

During a typical experiment, only temperatures of the circulation medium are measured. At one location, we have conducted an experiment which includes temperatures measured in the borehole itself, and in an observation well located 0.75 meters (2.5 ft) from the borehole. Temperatures were regularly logged at a depth of 15 meters (49 ft), and each day a complete temperature profile was made. This data augments the data from the experiment, and may be used to evaluate the possible differences in fluxes over the soil profile. Also, the time at which the temperature front reaches the second observation well can be used to check the results of several models.

During installation of the observation well a detailed description of the profile was made. Samples from the profile were collected in sampling tubes, which were immediately capped to prevent changes in moisture content. The samples were sent to the laboratory for analysis of the thermal conductivity using a none-steady state probe method (van Haneghem 1981). Samples were also analysed on particle size and organic content. A cone penetration test on the entire soil column was also carried out.

Experimental Apparatus

The experimental apparatus is similar, in many respects, to those described by Austin (1998) and Gehlin (1998). The main difference between the systems is that the experimental apparatus described here does not use electrical power to directly heat the circulation fluid, but maintains a fixed temperature difference between the inlet and outlet. Due to this approach, the energy-rate is not influenced by variations in the power supply during the experiment. Also, whereas those systems could only inject heat into the ground, this system can either inject heat or extract heat. This is made possible with a reversible water-to-air heat pump that can either heat or cool the circulating fluid. Additional components of the system include a heat pump, a 0.5 m^3 (17.66 ft^3) buffer tank, two circulation pumps (one that circulates fluid between the heat pump and the buffer tank, and one that circulates fluid between the buffer tank and the ground loop), a three-way regulating valve, a flow sensor and several temperature sensors. Temperature is measured in the buffer tank, in the fluid entering the ground loop and in the fluid returning from the ground loop. The system is configured as shown in Figure 1.

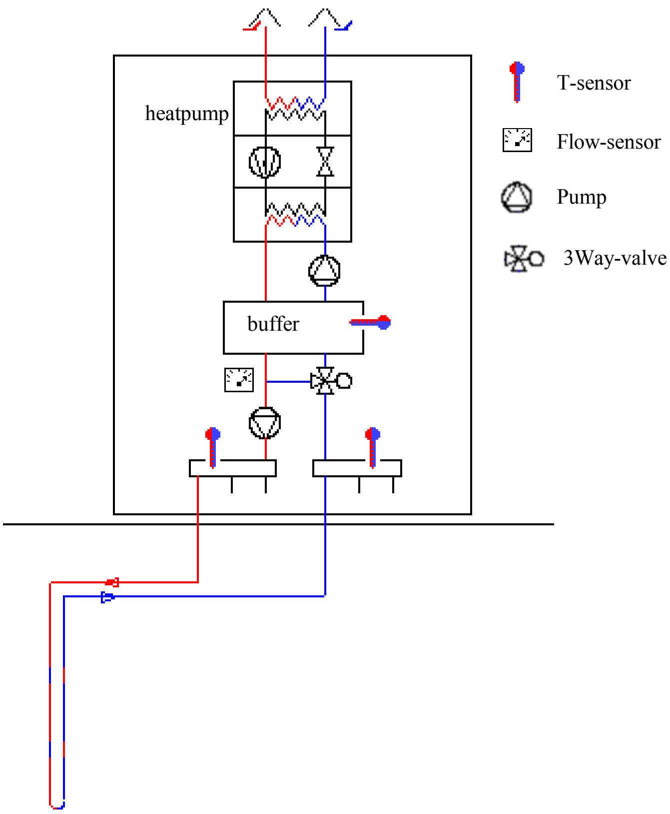

Figure 1 Experimental Apparatus

The heat pump generates a supply of warm or cold water. Using the temperature sensor in the buffer tank and the entering ground loop temperature, a specified difference is maintained. The buffer tank is therefore always between 4 - 6ºC (7-11ºF) warmer or colder than the entering ground loop temperature. Other temperature difference setpoints may be chosen.

This supply of water is used to achieve a certain temperature difference between the entering and return ground loop temperature, e.g. 2.5ºC (4.5ºF). This temperature difference is achieved by mixing in more or less water from the buffer vessel, by the regulating valve. The amount of energy injected or extracted from the ground is a function of the flow and temperature difference selected.

When the measured temperature difference (between entering and return sensor) is not equal to the selected temperature difference, this error is used to adjust the regulating valve. When, for instance, the set ΔT is 2.5 and the measured ΔT is 2.3 the regulating valve will be adjusted until the measured ΔT is again 2.5.

The accuracy of the experimental apparatus is related to two types of uncertainty: random measurement errors and systematic measurement errors. For this apparatus, the random measurement error is calculated for the experiment using the bootstrap method (Efron and Tibshirani 1993). Although it is calculated for each test, a typical value is ±1%.

The uncertainty due to possible systematic measurement errors may be estimated by considering the uncertainty in each of the measurements. The rated accuracy of the temperature sensors is ±0.1ºC (±0.2ºF) and, as two sensors are involved in the actual measurement, the two errors may be added in quadrature (Taylor 1997) to give an error of ±0.14ºC (±0.3ºF). However, the temperature sensors are calibrated, and measure equal temperatures when immersed in a constant temperature bath; therefore, the actual uncertainty is probably lower. (A reasonable estimate might be made by inferring from the calibration that the actual uncertainty in each sensor is ±0.05ºC (±0.1ºF), and adding the uncertainties in quadrature to give an uncertainty in the ΔT measurement of ±0.07ºC (±0.1ºF).)

The other sensor involved in establishing the energy rate is the flow sensor. This sensor has a rated accuracy of ±0.3 to ±0.9 % at flow rates below 1.5 m^3/hr (6.6 GPM) and of ±0.2% above.

Of course, the relative error depends on the ΔT and flow rate selected. Using small values (low power rates) will give a higher relative error. For the experiment described below, the average flow rate was 0.79 m^3/hr (3.5 gpm), with a random measurement error of ± 0.01 m^3/hr (0.04 gpm) or ±1.2%. The ΔT had an average value of 1.3 ºC (2.3ºF) with a random measurement error of ± 0.079 ºC (0.14ºF) or ±6%.

As discussed by Taylor (1997) there is no rigorously defensible procedure for combining the uncertainties due to systematic measurement error and random measurement error. A suggested method is to add the two in quadrature. For the ΔT measurement, adding the uncertainty inferred from the calibration and the uncertainty due to random measurement error gives a total estimated uncertainty of ±8%., Likewise, adding the flow measurement uncertainties (systematic: ±0.4 %; random: ±1.2%) in quadrature gives a total estimated uncertainty of 1.3%. Then, the uncertainty in the energy rate may be estimated by adding the uncertainty due to the flow measurement and the uncertainty due to the temperature difference in quadrature: ±8.1 %. Austin, et al. (2000) have shown that the uncertainty in the thermal conductivity estimate due to the uncertainty in the energy rate is the same. Therefore, the theoretical error in the conductivity estimate may be assumed to be approximately ±8.1 %. For a more detailed uncertainty analysis, see Austin, et al. (2000).

Results

A priori estimate of soil thermal conductivity

The traditional way of obtaining estimates of soil thermal conductivity is to ascertain the different types of soil or rock in the profile. In this study, a detailed soil profile description during the drilling was made. This profile was saturated from a depth of 1 m below surface level. This is shown in Table 1.

Table 1. Soil profile and traditional estimate of soil thermal characteristics (from 1 m below surface level the soilprofile was saturated).

Depth	Texture	Consolidation	Conductivity (k), W/m-K (Btu/hr-ft-F)			Volumetric heat capacity(ρc_p) MJ/m^3-K (Btu/ft^3-R)		
			min	max	avg	min	max	avg
0	Pavement		~	~	~	~	~	~
0 - 1	Sandy suppletion layer	Mixed, low	1.11 (0.64)	1.25 (0.72)	1.2 (0.69)	~	~	1.7 (25.32)
1 - 4	Fine grained sand, shells	Low	0.58 (0.34)	1.75 (1.01)	1 (0.58)	1.23 (18.32)	2.12 (31.57)	1.8 (26.81)
4 - 6	Peaty and clayey	Medium	0.9 (0.52)	1.32 (0.76)	0.8 (0.46)	1.1 (16.38)	3.6 (53.62)	1.9 (28.30)
6 - 13	Fine sand, silty clay with organic matter	Medium	~	~	1.3 (0.75)	~	~	2.3 (34.26)
13 - 16	Medium coarse sand with fine gravel	Medium	1.73 (1.00)	5.02 (2.90)	2.4 (1.39)	2.2 (32.77)	2.72 (40.51)	2.5 (37.24)
16 - 18	Medium coarse sand with fine gravel	Medium	1.73 (1.00)	5.02 (2.90)	2.4 (1.39)	2.2 (32.77)	2.72 (40.51)	2.5 (37.24)
18 - 27	Medium coarse sand with medium coarse gravel	Layered, High	1.73 (1.00)	5.02 (2.90)	2.4 (1.39)	2.2 (32.77)	2.72 (40.51)	2.5 (37.24)
27 - 29	Fine sand, clayey	Medium	1.34 (0.78)	4.8 (2.77)	1.8 (1.04)	1.9 (28.30)	2.6 (38.72)	2.3 (34.26)
29 - 30	Medium coarse sand with fine gravel	High	1.73 (1.00)	5.02 (2.90)	2.4 (1.39)	2.2 (32.77)	2.72 (40.51)	2.5 (37.24)
30 - 31	Fine sand with clay and silt lenses	Medium	1.34 (0.77)	4.8 (2.77)	1.8 (1.04)	1.9 (28.30)	2.6 (38.72)	2.3 (34.26)
31 - 35	Medium coarse sand	High	1.73 (1.00)	5.02 (2.90)	2.4 (1.39)	2.2 (32.77)	2.72 (40.51)	2.5 (37.24)
		Weighted average	1.19 (0.69)	3.40 (1.96)	1.88 (1.09)	1.53 (22.79)	2.09 (31.13)	2.33 (34.70)

To obtain more quantitative information on the different soil types a particle size analysis was carried out on several samples, and a cone penetration test (giving resistance and friction as a function of depth, indicating the state of compaction or density of the different soil strata) was performed. Based on this detailed geological information, "best values" were obtained from literature and a weighted average of soil conductivity was calculated.

Two limitations of this method are evident: First, it is quite difficult to obtain typical values for the different soil types at this level of detail. Especially when dealing with mixed soil types or inclusions, such as clay lenses or gravel, selecting or even finding appropriate values becomes quite problematic. The second problem is that the range of values is quite large, soil conductivity is estimated to vary between 1.19 W/mK and 3.40 W/mK (0.69-1.96 Btu/hr-ft-F). As a prudent design will use a value near the lower end of this range, the borehole length required will make the system very costly.

Estimates of soil conductivity using the “non-steady state probe” method

From the soil profile nine samples were taken and analysed by the Applied Physics group of the University of Wageningen. Depending on the structure of the sample, measurements were carried out two or three times. Overall inaccuracy was determined to be less than 5%. Results are presented in Table 2.

Table 2. Estimates of soil conductivity obtained with the non-steady state probe method.

Depth (meter) (ft)	Sample	Texture	Conductivity (k) W/m-K (Btu/hr-ft-F)			
			1	2	3	Average
0.8 (2.6)	1	Sandy suppletion layer	2.155 (1.24)	2.375 (1.37)		2.265 (1.31)
1.4 (4.6)	2	Fine grained sand, shells	2.486 (1.44)	2.583 (1.49)		2.535 (1.46)
4 (13.1)	4	Peaty and clayey	1.143 (0.66)	1.127 (0.65)	1.128 (0.65)	1.135 (0.66)
6 (19.7)	5	Fine sand, silty clay with organic matter	1.659 (0.96)			1.659 (0.96)
8 (26.2)	6	Fine sand, silty clay with organic matter	0.191 (0.11)			
10 (32.8)	7	Fine sand, silty clay with organic matter	1.165 (0.67)	1.016 (0.59)		1.091 (0.63)
14 (45.9)	9	Medium coarse sand with fine gravel	2.588 (1.50)	2.306 (1.33)	2.587 (1.49)	2.447 (1.41)
22 (72.2)	11	Medium coarse sand with medium coarse gravel	2.809 (1.62)	2.75 (1.59)		2.780 (1.61)
30 (98.4)	13	Fine sand with clay and silt lenses	2.801 (1.62)	2.934 (1.69)		2.868 (1.66)
					Average	**2.097 (1.21)**

One sample (6) yielded results an order of magnitude lower than the typical (and expected) results; consequently, we did not include this sample in our analysis. Obvious from the table are quite big differences in thermal conductivity between the different samples, conductivity values ranging between 1.09 W/mK and 2.868 W/mK. (0.63 Btu/hr-ft-F and 1.66 Btu/hr-ft-F).

In situ response test: line source model

In the 30-meter deep borehole a U-tube heat exchanger constructed of PN10 HDPE pipe, 25 mm (1 in.) diameter was installed. The two legs of the U-tube were held apart with 10 cm (4 in.) spacers. The borehole has a diameter of 0.25 m (0.82 ft), and was backfilled using the soil material itself. A heat extraction experiment was carried out with an energy flux of -1090 Watts (-3719 Btu/h) or -36.3 W/m(37.8 Btu/h-ft). Data was logged at 1-minute intervals and the experiment duration was 265 hours. Undisturbed ground temperature was 13.75 ºC (56.8ºF).

In addition to the data collected by the in situ apparatus, additional measurements were made using two observation wells. These two observation wells (figure 2) were installed to a depth of 30 meters, one in the borehole itself and another one at a distance 0f 0.75 m., and consist of a PVC-casing with a diameter of 40 mm. The observation well installed in the borehole is a screened well (filter length 2 meters, 28 - 30 meters depth), the observation well at 0.75 m consists of a closed standing column well. Temperature measurements were made at 10 minute intervals at a depth of 15 m (49.2 ft) below surface level, from an observation well in the heat exchanger borehole itself and in an observation well located at 0.75 meters (2.5 ft) from the heat exchanger. A complete temperature-depth profile was made daily.

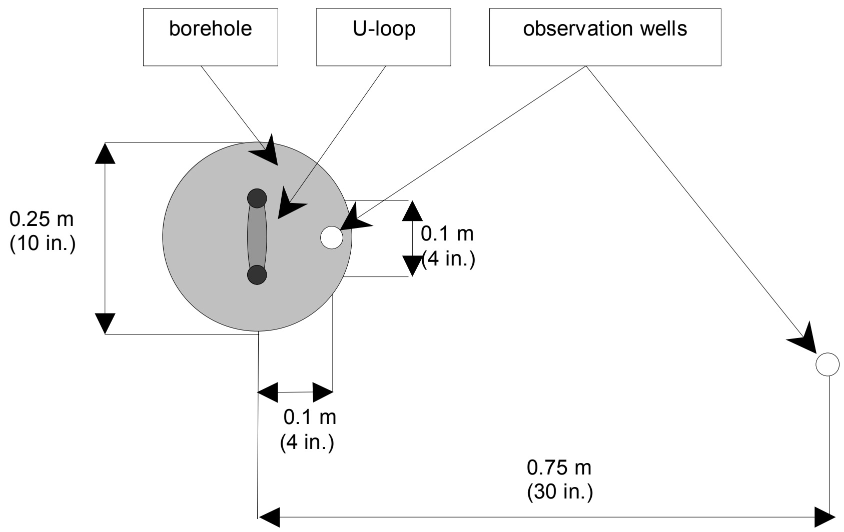

Figure 2. Borehole and loop configuration showing the two additional observation wells.

From the complete data series (figure 3) an average conductivity value of 2.1 ± 0.02 W/mK (1.2 ± 0.01 Btu/hr-ft-F) was calculated using the line source model. (Here, the uncertainty is that due to random measurement error, as estimated by the bootstrap method. Considering possible systematic measurement error, the estimate of thermal conductivity may be given more precisely as of 2.1 ± 0.2 W/mK (1.2 ± 0.1 Btu/hr-ft-F).) Calculating the conductivity during the first five hours (representing the borehole) and during the period 5 to 265 (representing the ground proper) hours gives estimates of thermal conductivity of 2.44 ± 0.03 W/mK (1.4 ± 0.02 Btu/hr-ft-F) and 2.13 ± 0.03 W/mK (1.2 ± 0.02 Btu/hr-ft-F).

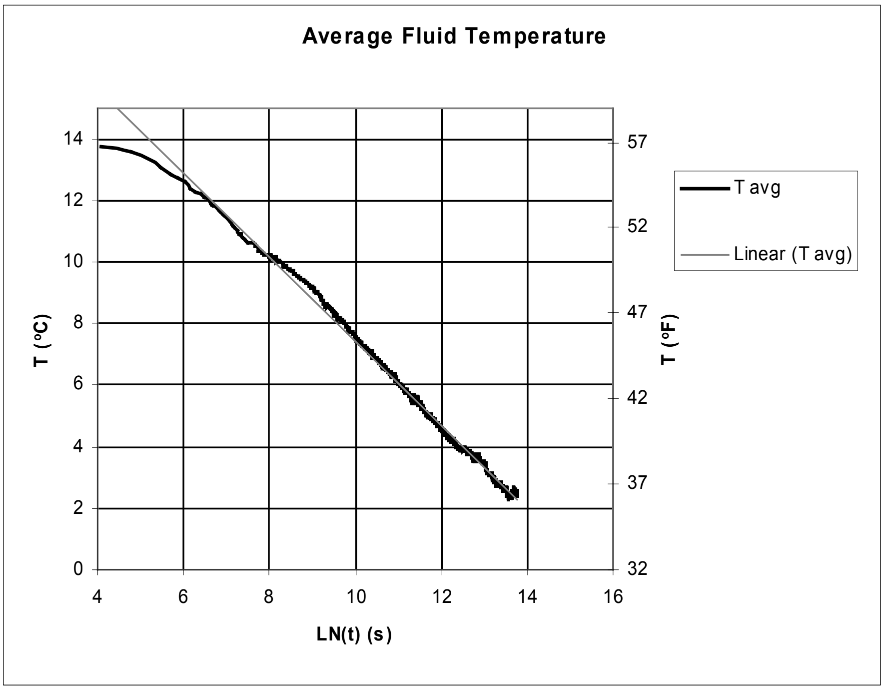

Figure 3. Results of heat extraction experiment, average fluid temperature with ln(time)
(30 meter U-loop, -36.3 W/m).

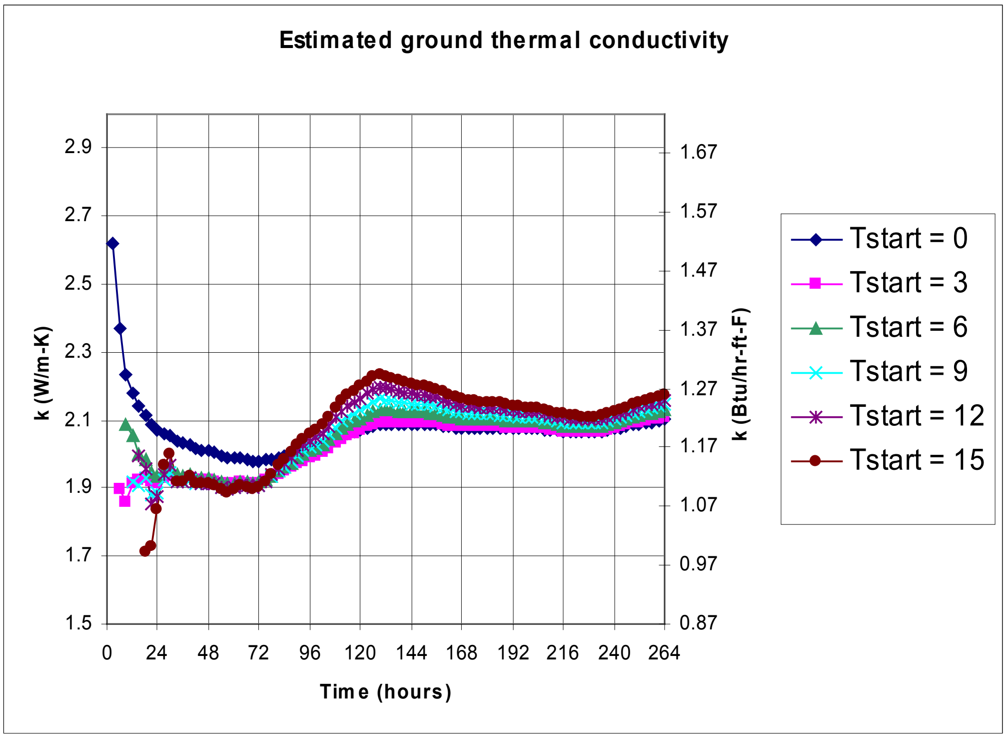

Figure 4. Soil conductivity values calculated using different starting points and extending the data series by adding data in a stepwise fashion in blocks of six hours.

Careful examination of the fluid temperature curve presented in figure 3 shows several small deviations from the ideal straight line, even when discounting the initial five hours of data. As there is some arbitrariness involved in exactly how much of the initial data to ignore, and even small perturbations may affect the estimates of thermal conductivity obtained (Austin, 1998) the thermal conductivity was calculated for several series with different starting points and adding data by blocks of six hours. When the resulting conductivity values are plotted as a function of data period (figure 4) these effects on the estimates can be evaluated (Austin, 1998).

Discarding at least the first three hours of data results in faster convergence of the estimated conductivity. Remarkable is that the conductivity values estimated using data up to 72 hours are about 1.95 W/mK (1.13 Btu/hr-ft-F), but that adding data after 72 hours shows increasing values for the estimates. The estimates stabilise again after 120 hours of data is added, at a value around 2.13 W/mK (1.23 Btu/hr-ft-F). Adding data after 230 hours again leads to increasing estimates for soil conductivity.

To investigate the underlying cause of these effects atmospheric temperature data from a nearby climate station were superimposed on the fluid medium temperatures (figure 5).

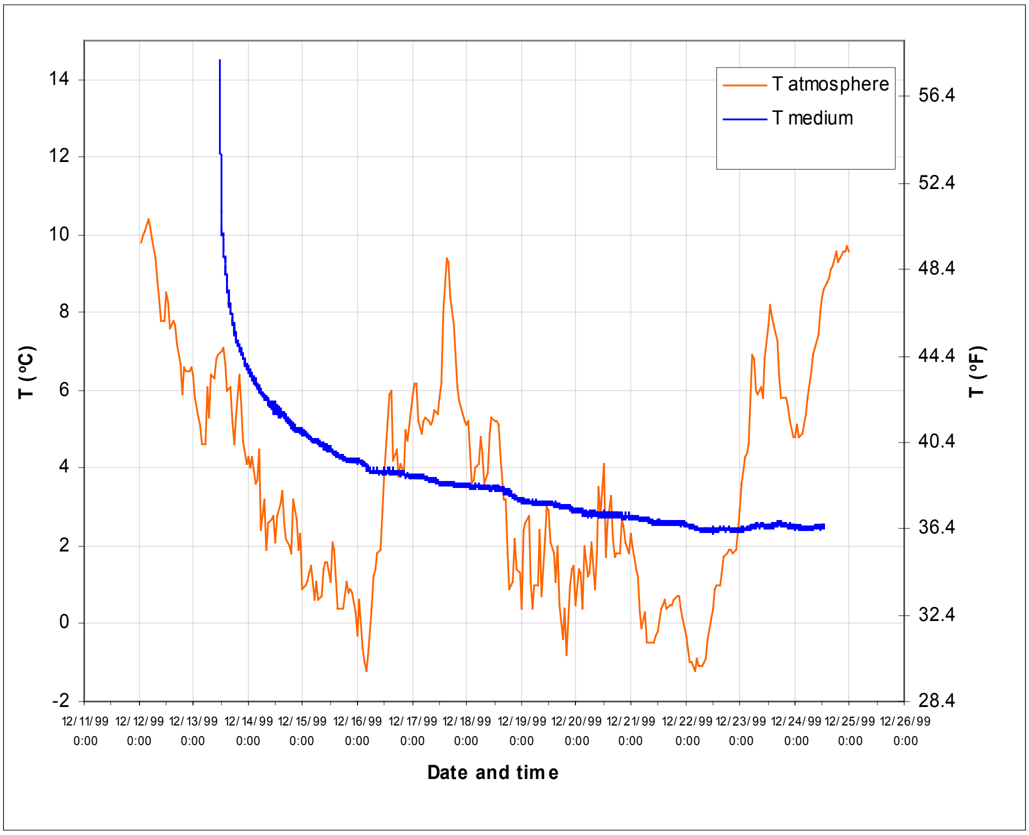

Figure 5. Atmospheric temperature data superimposed on the experimental average fluid temperatures.

The atmospheric temperatures measured during the experiment run show a clear correlation with the different data periods. During the first 72 hours the atmospheric temperatures show a decreasing trend. During the period 72 to 120 hours, temperatures are relatively high. Lower atmospheric temperatures are evident during the subsequent period up to 220 hours. Higher temperatures were recorded during the final stage of the experiment.

Although the effects of the atmospheric temperature on the average fluid temperature is very small (on the order of ± 0.15 ^{o}C or ±0.27ºF) it affects the estimate of thermal conductivity significantly.

The sensitivity of the estimates of thermal conductivity was further investigated by bootstrapped regressions, for each of the time-periods with a different response. Using the bootstrap regression coefficients, the sensitivity of the solution to individual data points is quantified. The results are summarised in table 3.

With the exception of the periods 0 – 265 hours and 5 – 265 hours none of the confidence regions overlap, indicating that each period yields significantly different estimates of soil conductivity. Estimated conductivity during the period 72 – 120 hours (high atmospheric temperature) is relatively high, while the period 120 – 220 hours shows relatively low values (low atmospheric temperature). A likely explanation for this is that with higher atmospheric temperatures, excess heat is added to the fluid outside of where the temperature measurements are made; this reduces the actual heat extraction rate from the ground, giving a lower rate of temperature decrease, and hence, a higher estimate of thermal conductivity.

Ultimately, the results should be compared to the non-steady state probe method, from which a "best estimate" of 2.1± 0.1 W/mK (1.2±0.1 Btu/hr-ft-F) was obtained. When the uncertainty of ± 8.1% is added to the line source predictions, the estimates for 0-72 hrs, 5-72 hrs, 0-265 hrs, and 5-265 hours are all within the estimated experimental uncertainty.

Table 3. Bootstrap thermal conductivity values for several time periods, 100 bootstrap replicate samples of 500 data points each were evaluated.

DATA RANGE (hour)	k Median	k 95% confidence interval	
		Low	high
0 - 5	2.43 (1.40)	2.39 (1.38)	2.49 (1.44)
0.1667 - 5	2.35 (1.36)	2.33 (1.35)	2.37 (1.37)
0 - 72	1.97 (1.14)	1.94 (1.12)	2.02 (1.17)
5 - 72	1.92 (1.11)	1.91 (1.10)	1.92 (1.11)
72 - 120	2.84 (1.64)	2.80 (1.62)	2.90 (1.68)
120 - 220	1.76 (1.02)	1.74 (1.01)	1.79 (1.03)
0 - 265	2.10 (1.21)	2.08 (1.20)	2.13 (1.23)
5 - 265	2.13 (1.23)	2.11 (1.22)	2.14 (1.24)

In situ response test: Two dimensional finite volume model

As an alternative to the line source analysis, a parameter estimation procedure coupled with a numerical model may be used to concurrently estimate soil and grout conductivity and heat capacity (Yavuzturk, et al. 1999; Austin et al., 2000; Spitler, et al. 2000). The advantage of using a numerical model over analytical models such as the line source model is that the loop and borehole configuration are explicitly modelled. Thereby it reduces uncertainties with respect to the simplifying assumptions used in an analytical model.

We used the model described by Spitler, et al. (2000) to calculate the conductivities for the same time periods of data as used in the bootstrap estimates. This model is similar to the one described by Austin, et al. (2000), but a boundary-fitted coordinate grid is used to model the borehole geometry. The results are summarized in table 4.

Table 4. Soil and grout conductivity and thermal capacity estimated using a 2D finite volume numerical model.

DATA RANGE (hour)	k **soil W/m, K (Btu/hr-ft-F)**	k **grout W/m, K (Btu/hr-ft-F)**
0 - 72	1.73 (1.00)	3.81 (2.20)
5 - 72	1.93 (1.11)	2.43 (1.41)
72 - 120	2.58 (1.49)	1.28 (0.74)
120 - 220	2.39 (1.38)	1.37 (0.79)
0 - 265	2.02 (1.17)	2.26 (1.31)
5 - 265	2.08 (1.20)	2.11 (1.22)

In comparing the results of the finite volume method to the line source analysis method, it might first be noted that the conductivities predicted using the complete data set or the complete data set, except for the first five hours, are very close (within 4%) of each other. Likewise, the results for the first 72 hours are almost identical when the first five hours are ignored. For other data ranges, the results are more disparate, although the finite volume method results are not expected to be meaningful for cases where large numbers of hours are ignored, as in the 72-120 or 120-220 cases. (The line source method estimates the ground conductivity from the slope, and can then estimate the grout conductivity sequentially. The finite volume, parameter-estimation-based method estimates both conductivities simultaneously. Presumably, ignoring significant numbers of hours reduces the likelihood that the two different conductivities will be resolved correctly).

Likewise, comparing the results to the non-steady state probe method, the estimates for 5-72 hrs, 0-265 hrs, and 5-265 hours are all within the estimated experimental uncertainty. The results for 0-72 hours fall slightly below what could be explained with the experimental uncertainty analysis. As described by Austin, et al. (2000) there are other sources of uncertainty, such as uncertainty in the undisturbed ground temperature and the numerical model that may account for this difference.

Figure 6 shows the temperatures predicted by the finite volume method, using the thermal conductivities determined using the entire data set. The results match closely, but it is noted that the finite volume method results vary at a relatively high frequency compared to the experimental results. This is caused by the fact that the fluid temperature measurements were recorded with one significant digit to the right of the decimal place, and the heat transfer rate, being determined by the ΔT, fluctuates from measurement to measurement. In this particular experiment, the ΔT was set to be 1.3ºC (2.3ºF), but it varied from 1.2ºC (2.2ºF) to 1.4ºC (2.5ºF). This variation in ΔT results in a ±7.7% variation in heat transfer rate, which in turn causes the temperatures predicted by the finite volume method to fluctuate as shown in Figure 5. This has little or no impact on the predicted conductivities, as the parameter estimation methodology minimizes the sum of the least squares, causing the predicted temperatures to match the actual temperatures as closely as possible. Still, using a higher ΔT would result in less oscillation.

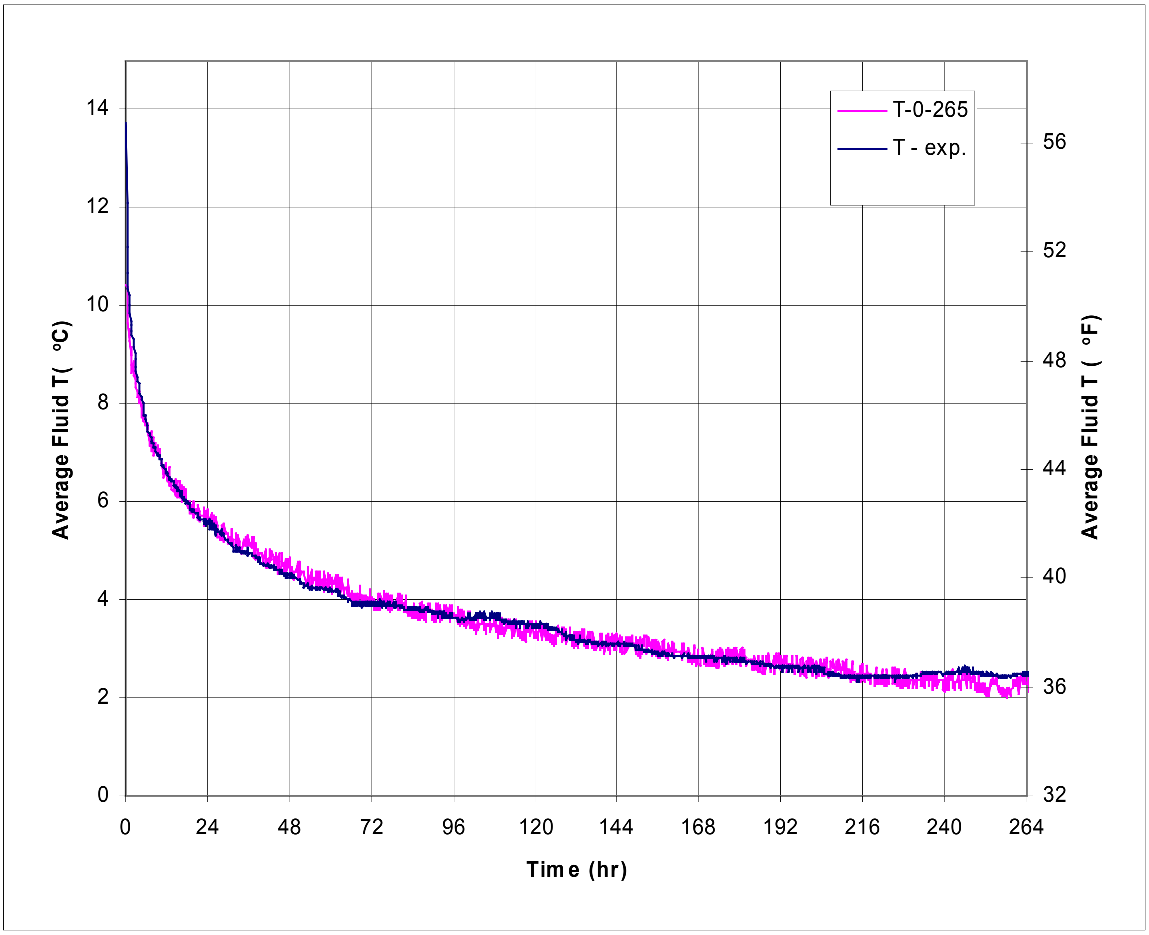

Figure 6. Temperatures predicted by the 2D finite volume model and observed temperatures.

Temperature measurements

As discussed above, temperatures were also measured in an observation well inside the borehole and in an observation well 0.75 m (2.46 ft) from the borehole. The temperature difference between the fluid and the borehole observation well decreases during the first 28 hours. Afterwards the temperature difference remains stable at 4°C (7.2ºF). After 49 hours of operation, the first temperature decline is measured at 0.75 metres (2.46 ft).

The daily temperature profiles in the borehole observation well (figure 7) show a different response at different depths. The depths up to 10 metres (33 ft) are relatively colder than the depths between 15 (49 ft) and 25 metres (82 ft). This corresponds well with the conductivity values measured in the laboratory, where higher conductivity values were measured for thee depths between 15 (49 ft) and 25 metres (82 ft). The higher conductivity results in higher energy fluxes, and therefore higher temperatures and higher temperature differences between the measured borehole observation well temperature and the fluid temperature.

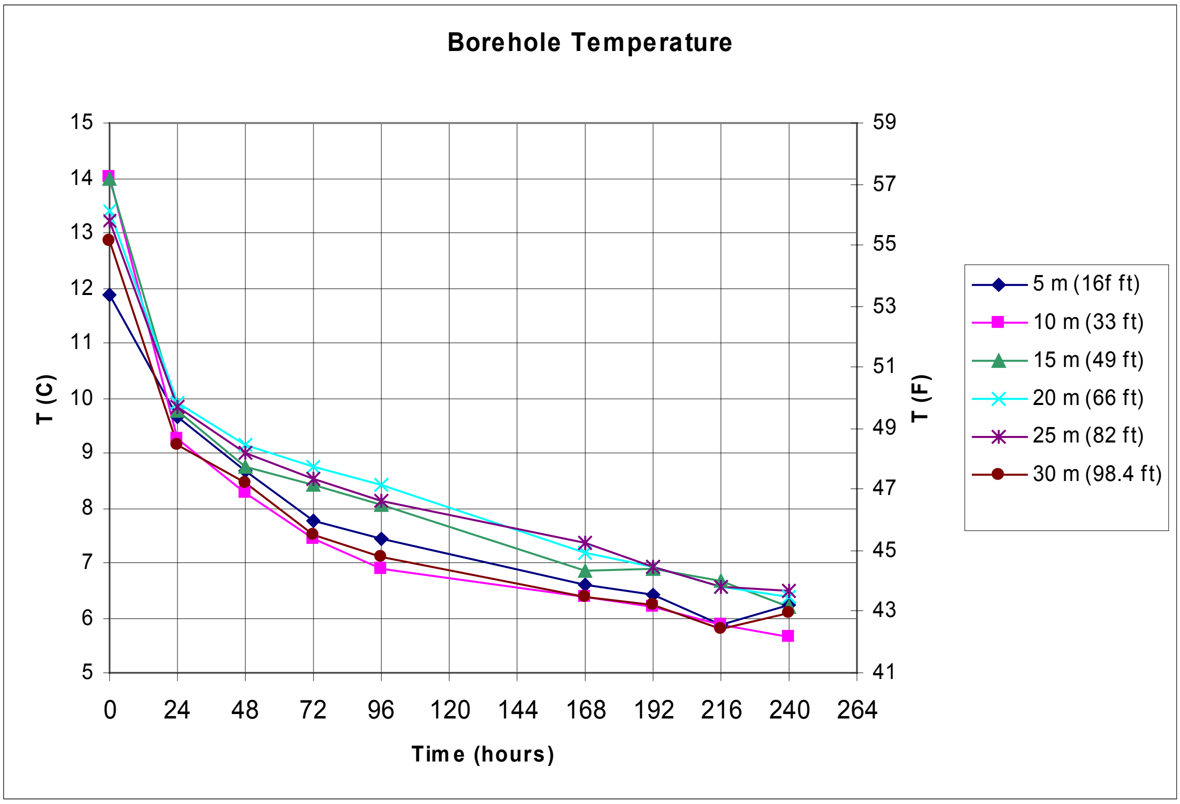

Figure 7. Temperatures profiles in the borehole observation well.

Conclusions and Recommendations

In this paper, we have presented several methods for obtaining estimates of soil thermal parameters. Clearly, the traditional method can only be used under circumstances where reliable, formation-specific, literature values are available, and the location has a relatively homogenous (and well known) geology with little or no groundwater flow. Even then, the effect of borehole and loop configuration cannot be accounted for.

Using a non-steady state probe method on samples obtained by coring gives highly accurate estimates of soil conductivity and soil heat capacity of individual samples. The drawback of this procedure is that relatively small samples are analysed and that again the hydrology, borehole and loop configuration are not accounted for. Moreover, as the results on the individual samples have to be aggregated into an overall average value for the borehole profile, the samples have to be highly representative with regard to the different geological strata present. Therefore, this method will only yield an acceptable estimate of ground thermal characteristics when a sufficient number of undisturbed samples of good quality can be obtained through coring, which will not always be possible in practice.

By applying the *in situ* response test, system and site specific values for soil thermal parameters can be obtained. These include the geology, hydrology, borehole and backfilling quality as well as loop configuration and positioning. In this paper, we have presented a relatively detailed analysis of such a data set. Although some care needs to be taken in selecting the appropriate experimental parameters and data period for analysis, quite accurate (only slightly lower accuracy than the laboratory method) and reproducible estimates can be obtained.

The *in situ* response test can be used specifically to estimate appropriate values for soil thermal characteristics. These measurements increase confidence in geothermal modelling results and improve overall design quality. In practice, this could also result in significant financial savings, as loop length may be reduced without affecting the thermal design limits of the ground loop heat exchanger.

As shown in this study, the results of an *in situ* test can be adversely influenced by the atmospheric conditions. This adverse influence can be mitigated by increased insulation of the above-ground piping and by installing additional temperature sensors in the borehole itself. As these sensors can be used to control the temperature difference, the experiment should be much less influenced by outside conditions. Accuracy of the measurements can further be increased by using a higher temperature difference, as the relative error of the temperature sensors is the largest factor influencing the error of the result. Finally, changes in viscosity of the circulation medium with temperature may lead to a change in flow rate over the duration of an experiment. To adjust for these changes in flow rate that could introduce a bias in the results, the control system can be adapted so that not the temperature difference itself, but a function of temperature difference and measured flow rate, i.e. the actual energy flux, is kept constant. These improvements have now been incorporated into the *in situ* response test apparatus described here, and are presently being evaluated.

The *in situ* response test has been used mainly to obtain accurate estimates of the thermal characteristics of the ground. However, there are a number of other important applications of such a test facility. In the design of a ground loop heat exchanger, many decisions have to be made beforehand: drilling method and depth, type of loop (concentric or U-loop), type of backfilling to use, etc. Many of these questions have both a cost aspect and a thermal efficiency aspect. With a test facility, it becomes possible to establish optimum drilling depth, for instance by creating a temperature-depth profile indicating the relative contribution of the different soil-strata. The performance of different loop-types and backfilling material, under specified circumstances, can be evaluated and the possible influence of groundwater flow directly ascertained. In this way, the total system design can be optimised both from the point of view of thermal performance as well as from a cost perspective. Finally, when building loads and duration of peak-load cycles are known, these can be simulated on the ground-loop heat exchanger allowing some verification of the design and anticipated thermal behaviour.

Other applications can be found in *a posteriori* evaluating an installed heat exchanger. In one such case, where due to technical difficulties the heat exchanger was significantly smaller than the original design prescribed, we simulated several peak loads to establish the heat extraction that could be sustained during a specified period.

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