In-Situ Thermal Conductivity Testing: The Dutch Perspective (and an English Case Study).

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Several recent articles in *The Source* have discussed the need for accurate soil conductivity data in order to improve heat exchanger design (e.g. Skouby 1998). Unlike other parameters influencing the design of the heat exchanger (such as the length and diameter of the groundloop), soil conductivity is not usually known with a degree of accuracy which allows for optimal design. Better estimates of soil conductivity lead to improved groundloop heat exchanger design, and hence, the economic viability of GSHP systems. The role that in-situ thermal conductivity testing can play in obtaining this information has also been discussed, along with some of the issues related to the accuracy, sensitivity, and precision of these tests such as data analysis methodology and required test duration (e.g. Smith 1999, Spitler et al 1999). These articles have focussed on work that is being carried out in the United States. In this article we describe some of the in-situ thermal conductivity measurement work that is being carried out on the other side of the Atlantic, including the test equipment being utilized, some test results, and the method of calculating conductivity values from these results.

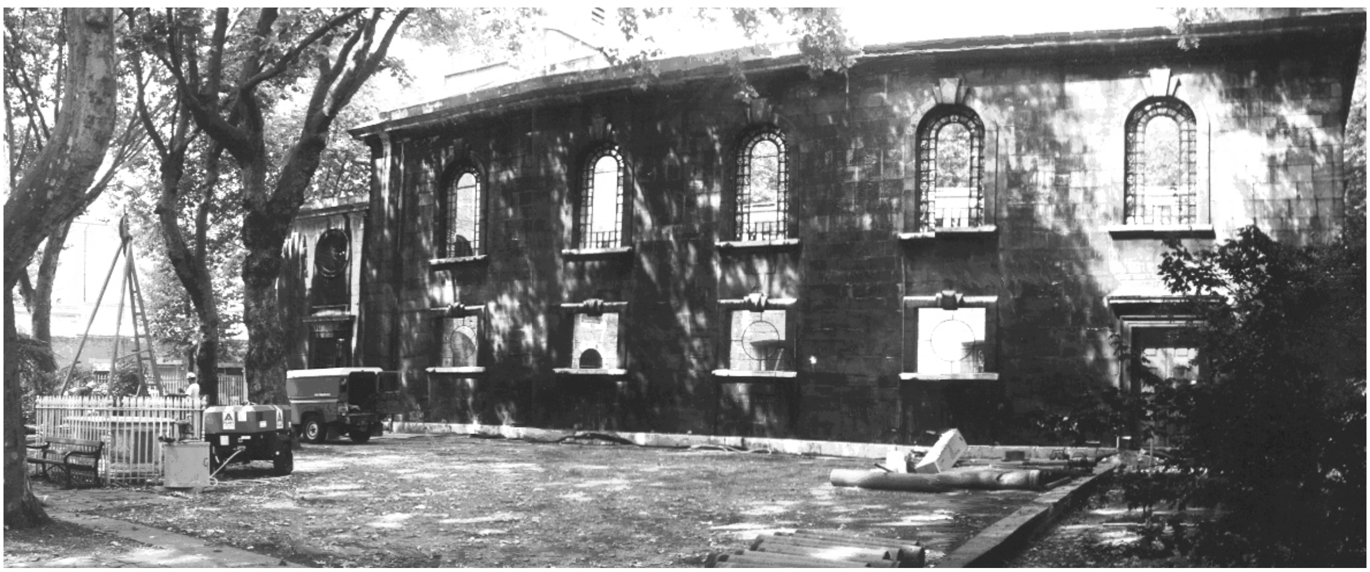
Thermal response tests, based on measuring the temperature response to heat injection in a borehole, have been developed at several places, including the United States (Austin 1998) and Sweden (Gehlin 1998). The systems used in these tests have been shown to accurately estimate the specific thermal capacity of the ground (Smith 1999). They are less suited for actual design verification of heating/cooling applications however, as they operate solely on the basis of injecting energy into the ground. For example, when the GSHP system is used for heating during winter, design temperatures of the circulating medium will be between –5 and 5 ^{o}C (25 - 40 ^{o}F). No measurement of thermal response at these temperatures (where phase changes in both the circulating medium and the soil may take place) can be performed with these test set-ups. Furthermore, when the GSHP system is utilized for heating an anti-freeze mixture is normally used; the thermal properties of which are also temperature dependent. Another issue which has been noted with respect to thermal response tests based on heat injection is that concerned with heat convection within the borehole, particularly when there is groundwater in the borehole (Eskilson 1987).

In an effort to address these issues the Dutch companies Groenholland B.V. and IF Technology B.V. have developed a thermal response test rig which can operate in both heating (energy extraction) and cooling (energy injection) modes. The rig operates by generating, using a reversible heatpump, a supply of relatively (with respect to the ground temperature) cold or warm fluid. This supply is used to maintain a certain difference between the fluid temperature entering and returning from the ground (ΔT). By selecting an appropriate ΔT and flow rate (between 0.5 and 3.0 m^{3}hour^{-1}), any energy load between 50 and 2000 Watts can be applied. Experiments using realistic energy profiles and fluid properties are therefore possible.

Figure 1. Thermal response test rig developed by Groenholland B.V. and IF Technology B.V.

After a period of initial testing and calibration of the equipment, Groenholland has now carried out a number of "real life" experiments with the test rig. The latest of these was a thermal response test (utilizing both energy extraction and injection modes) completed for the St. Lukes Church site in central London (Figure 2). The site is presently being redeveloped as an education and performance venue for the London Symphony Orchestra, and the intention is to make use of a GSHP system in various sections of the new building for both heating and cooling requirements. The consulting engineers on the project are Max Fordham & Partners, London.

Figure 2. St. Lukes Church grounds, London. The borehole for the heat injection experiment is being drilled in the left-hand foreground.



Two 0.25 m diameter boreholes, located approximately 20 m apart, were drilled at the site to a depth of 50 m. A "shell and auger" technique with continuous sampling was used, providing detailed geological information (drilling by Soil Mechanics Ltd., London). The local geology consists of mainly dry sand and clay beds overlying a chalk layer. Based on this information estimates of soil conductivity (using literature values) would be in the range 0.53 to 1.08 W/m, K (see Table 1).

Table 1. Soil thermal conductivity (λ) for St. Lukes Church site based on geological information and literature values. Values are weighted by the thickness of the layer.

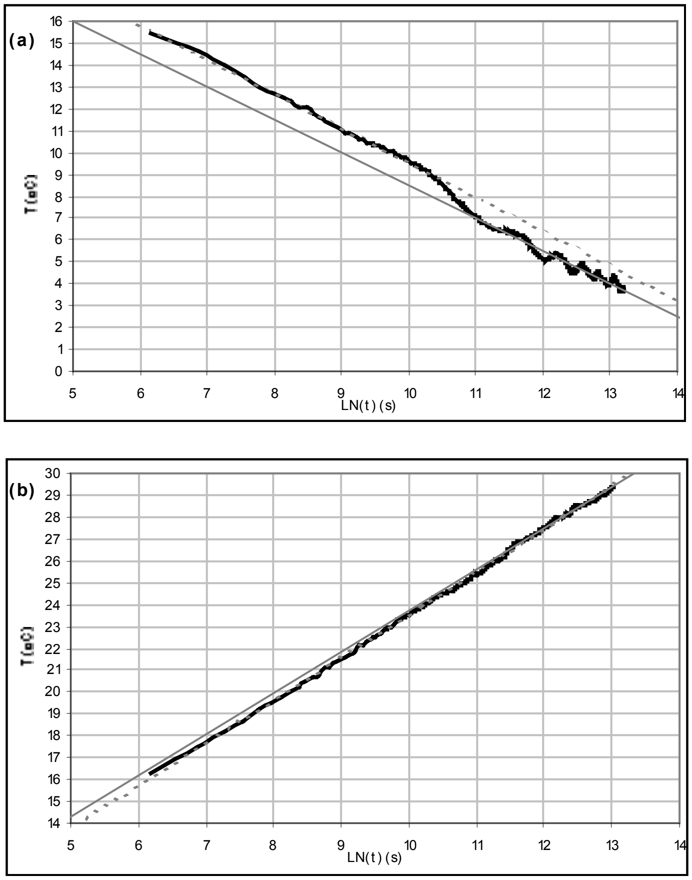
Depth (m)	Texture	Moisture	Conductivity (λ), W/m, K		
			Min.	Max.	Ave.
0 - 0.3	Paving/earthy fill	dry	~	~	~

0.3 - 8.3	Sand and gravel	dry/moist	0.83	1.04	0.93
8.3 - 27.9	Stiff clay	dry/moist	0.44	0.92	0.68
27.9 - 29.7	Dense silty clay	dry	0.75	1.07	0.91
29.7 - 34	Sandy clay/pebbles	dry/moist	0.48	0.85	0.67
34 - 46.7	Dense sand	dry/moist	0.58	1.75	1.17
46.7 - 50.4	Chalk and flints	dry/moist	~	~	~
Weighted average			**0.53**	**1.08**	**0.81**

Groundloops were installed in these boreholes consisting of HDPE PN10 (21 mm internal diameter, 25 mm external diameter) laid out in a U-loop construction using 0.1 m spacers. The holes were backfilled with a conventional grout (1:1 Portland cement/bentonite). The circulation medium used in the loops was an ethyleenglycol anti-freeze solution. An energy extraction experiment was run using the first borehole (27.1 Wm^{-1}), and an energy injection experiment was run using the second borehole (33.2 Wm^{-1}). Power was supplied to the test rig from a 35 kVA diesel generator, eliminating any problems with power surges/fluctuations from a mains source. Experimental data was collected for 148 hours and 128 hours for the energy extraction and injection experiments respectively.

Analysis of the experimental data was based on a line source model, whereby the slope of the line resulting from a plot of average fluid temperature against the natural log of time is used to obtain estimates of thermal conductivity (see Austin 1998, Gehlin 1998 for details on methodology). The length of the tests carried out at the St. Lukes site were such that they would comfortably meet the minimum time condition which is associated with use of the line source model. The results of the two experiments are presented in Figure 3.

Figure 3. Results from (a) the energy extraction experiment and (b) the energy injection experiment at St. Lukes Church Site showing average fluid temperature against ln(time). Graphs show T fluid (▬), and linear regressions of T fluid for t < 10 hours (- - -), and t > 10 hours (——).



Several observations can be made about the graphs presented in Figure 3; firstly, in both datasets there is a distinguishable change in slope after approximately 10 hours (ln(t) = 10). This corresponds well with the calculated time at which the temperature front is expected to reach the borehole wall (9.9 hours) (calculations based on line source model). The second observation is the oscillations, which are evident in the second part of the datasets, caused by changes in outside temperature during the day - night cycle. Oscillations of this nature have been noted before, and also reported in other studies (Austin 1998, Gehlin 1998).

Oscillations in the data presented here are a maximum of 0.2 ^{o}C (0.3 ^{o}F) (energy extraction experiment). This is small compared to the temperature change in the circulation medium (10 ^{o}C, 50 ^{o}F), and the changes in outside temperature (approx. 20 ^{o}C, 70 ^{o}F) during the experiment, and only slightly greater than the accuracy of the temperature sensors (0.1 ^{o}C, 0.2 ^{o}F). The oscillations in the energy injection experiment are even less pronounced, due largely to the fact that the average temperature of the circulation medium in this experiment was closer to the outside temperature.

There has been quite a deal of discussion within the GSHP community regarding the method of obtaining conductivity values from experimental test data. One criticism leveled at the use of the line source model is that it is sensitive to perturbations caused by outside influences (such as diurnal temperature cycles) with individual data points having a disproportionate affect on the regression result (e.g. Spitler et al 1999). It has been shown however, that if care is taken in the data interpretation stage, accurate estimates of thermal conductivity are obtainable (Smith 1999). One of the methods Groenholland uses to investigate the sensitivity of the regression results to the individual data points is the bootstrap method (Effron and Tibshirani 1993). This procedure provides an estimate of the confidence interval of the regression coefficients, and the influence of individual datapoints in thermal conductivity estimates.

In determining estimates of thermal conductivity for the St. Lukes site, the regression equations were solved for the complete data sets, for the first 10 hours (representing the borehole conductivity), and for the data range excluding the first 10 hours of data. Conductivity results are shown in Table 2 along with bootstrap confidence estimates.

Experiment	Data range (hours)	λ (W/m, K)	95% confidence interval	
			Lower	Upper
Energy extraction	10 - 148	1.43	1.40	1.47
Energy injection	10 - 128	1.38	1.37	1.39

Table 2. Thermal conductivity (λ) values calculated for St. Lukes Church site, London, and estimates of confidence intervals (calculated from 500 bootstrap replicate samples) associated with conductivity values.

Based on the detailed drillers logs for each borehole, the estimated thermal conductivity of the site was in the range 0.53 to 1.08 W/m, K. However, when the in-situ test was carried out, the thermal conductivity value for the site was found to be in the range 1.38 to 1.43 W/m, K. Of course, it is useful to have an idea of how these different values would affect the actual design of the GSHP system. For the St. Lukes project no design framework (building load, hydraulic design etc.) is available yet. However, in order to give an impression of the affect the different conductivity values would have on system design, the lengths of ground loop heat exchanger required to cope with a peak load of 2.7 kW (for a 48 hour period) have been calculated (Table 3) using the EED software package (Eskilson et al 1999).

Source of λ value	λ (W/m, K)	Loop length required (m), $T \geq 0^oC$
Literature min.	0.53	111.5
Literature ave.	0.81	99.8
Literature max.	1.08	93
Measured min.	1.37	87.4
Measured ave.	1.40	86.9
Measured max.	1.47	85.9

Table 3. Required heat exchanger loop lengths (to cope with a peak heating load of 2.7 kW for a 48 hour period, while maintaining circulation fluid temperature $\geq 0^oC$) at the St. Lukes Church site, London, for different soil conductivity (λ) values.

The difference in loop length between that calculated using the measured average λ value and values from literature is up to 25%. Of course, a conservative design based on λ values from literature alone would use a value of λ somewhere between the lower and average value, as risks of freezing or over-heating need to be minimized. It would seem realistic therefore, that the design of a groundloop heat exchanger for the St. Lukes site based on values of λ obtained from literature would result in an over design of approximately 15 %. This clearly illustrates the value of conducting an in-situ thermal conductivity test in the design/feasibility stage of a project.

It should be noted that the accuracy of in-situ ground thermal conductivity estimates increase with the length of the test (e.g. Austin et al 2000, Smith 1999). However, the nature of most in-situ test apparatus is such that they must be "baby sat" through the duration of the test experiment to ensure that the equipment is not interfered with and is running correctly, and that data quality is maintained. As a result there is typically a trade off between the cost of carrying out the experiment and the accuracy of the conductivity estimates. The test rig operated by Groenholland is housed in a shipping container which can be placed directly over a borehole, minimizing the chance of interference with the experimental setup, and allowing the test to be set up then left to run unattended.

Work is currently underway to incorporate telemetry in the test rig setup so that experiments can also be remotely monitored via a mobile phone and modem. Other work being carried out includes developing a methodology to measure the relative contribution of different soil layers in the profile, making concurrent estimates of soil thermal capacity, and the development of a more robust analysis method (based on a numerical model approach). There is also ongoing work developing protocols for design verification.

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