Measuring soil thermal properties for use in energy foundation design

La mesure des caractéristiques thermiques du sol pour la conception des fondations énergie

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ABSTRACT: Energy foundations incorporated into ground source heat pump systems provide a viable alternative to conventional building temperature regulation systems in the move towards sustainable building solutions. To design such a system, it is important to accurately model the heat transfer process between the foundations and the soil, which is largely governed by the soil thermal conductivity. This paper compares two laboratory test methods for determining soil thermal conductivity: the thermal cell which is a steady state method, and the needle probe which is a transient method.

RÉSUMÉ : Pour l'orientation vers des immeubles durables, les fondations énergie incorporées dans des systèmes de pompe à chaleur géothermique fournissent une alternative viable aux systèmes conventionnels de régulation de température des immeubles. La conception d'un tel système implique le modelage précis du processus, qui est en grande partie déterminé par la conductivité thermique du sol, de transfert thermique entre les fondations et le sol. Dans le texte qui suit l'on compare deux méthodes d'essai de laboratoire pour la détermination de la conductivité thermique du sol : la cellule thermique, méthode de régime établi, et sonde à aiguille, méthode de régime transitoire.

KEYWORDS: soil thermal conductivity, thermal cell, needle probe

1 INTRODUCTION

Ground source heat pump systems provide a viable alternative to conventional heating and cooling systems in the move towards sustainable building solutions (Banks, 2008). Heat is transferred between the ground and the building by means of a refrigerant which is pumped through a series of pipes buried in the ground. To minimize initial construction costs, the pipes can be cast into the foundations, eliminating the need to make further excavations. These systems are known as energy foundations. To design such a system, it is important to accurately model the heat transfer process between the foundations and the soil. This is largely governed by the soil thermal conductivity.

There are several different methods of measuring soil thermal conductivity (Mitchell and Kao, 1978). They fall into one of two categories: steady state or transient methods. At the laboratory scale, steady state methods involve applying one-directional heat flow to a specimen and measuring the power input and temperature difference across it when a steady state is reached. The thermal conductivity is then calculated directly using Fourier's Law of heat conduction. Transient methods involve applying heat to the specimen and monitoring temperature changes over time, and using the transient data to determine the thermal conductivity. This paper compares the two approaches using a thermal cell (steady state) and a needle probe (transient) apparatus. The tests were carried out on U100 samples of London Clay upon which a full soil classification was afterwards conducted.

2 BACKGROUND

There are several methods of measuring thermal conductivity which are considered as suitable for use with soils. For this study, the needle probe and thermal cell methods were chosen due to the simplicity of the apparatus.

2.1 *Needle probe*

The measurement of thermal conductivity using the needle probe method is based on the theory for an infinitely long, infinitely thin line heat source (Carslaw and Jaeger, 1959). If a constant power is applied to the heat source, the temperature rise ΔT at time t after the start of heating, at a radial distance r from the heat source, is:

$$\Delta T = -\frac{q}{4\pi\lambda} Ei\left(-\frac{r^2}{4\alpha t}\right) \qquad (1)$$

where q is the power per unit length of heater, λ is the thermal conductivity, α is the thermal diffusivity and Ei is the exponential integral. After the power is switched off, the temperature difference is given by:

$$\Delta T = -\frac{q}{4\pi\lambda}\left[-Ei\left(-\frac{r^2}{4\alpha t}\right) + Ei\left(-\frac{r^2}{4\alpha\left(t - t_{heat}\right)}\right)\right] \qquad (2)$$

where t_{heat} is the time at which the power is switched off. Equations (1) and (2) cannot be solved for λ and α explicitly, so a simplified analysis approximating the exponential integral is used which leads to (ASTM International, 2008):

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln(t) \qquad 0 < t < t_{heat} \qquad (3)$$

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln\left(\frac{t}{t - t_{heat}}\right) \qquad t > t_{heat} \qquad (4)$$

The needle probe used is the TP02 probe produced by Hukseflux Thermal Sensors (2003). It is 150mm long with a diameter of 1.5mm, and encloses a 100mm long heating wire with a thermocouple located midway along this heater measuring the temperature (see Figure 1).

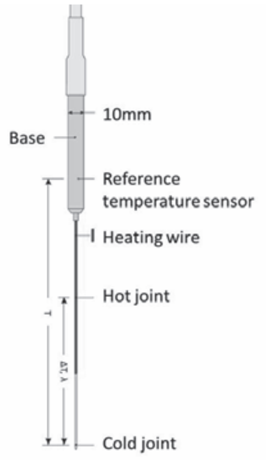

Figure 1. TP02 probe (Hukseflux, 2003).

2.2 *Thermal cell*

The thermal cell design was loosely based on Clarke et al. (2008). A diagram of the apparatus is shown in Figure 2. The thermal conductivity of a cylinder of soil is measured by generating one-directional heat flow along the axis of the specimen. The heat is generated by a cartridge heater embedded in the aluminium platen. Provided the specimen is well insulated so that radial heat losses can be neglected, the heat flow through the specimen during steady state is governed by Fourier's Law of heat conduction:

$$Q = -\lambda A \frac{\Delta T}{L} \tag{5}$$

where Q is the power input, A is the cross-sectional area, ΔT is the temperature difference across the length of the specimen, and L is the length of the specimen. If Q cannot be accurately determined, measurement of the temperatures in the specimen as it cools after the power is switched off (the recovery phase) can be used to determine the heat transfer coefficient between the top of the soil and the air and hence the power. This uses the lumped capacitance method, which is valid when the temperature difference across the soil is small compared with the temperature difference between the soil surface and the ambient temperature (Incropera et al., 2007):

$$\frac{T_{base} - T_{top}}{T_{top} - T_{amb}} < 0.1 \tag{6}$$

where subscripts *base*, *top* and *amb* refer to temperature at the base of the soil, top of the soil, and of the ambient air respectively. Where this is satisfied, the temperature of the soil at time t is (Clarke et al., 2008):

$$T = T_{amb} + \left(T_0 - T_{amb}\right)\exp\left(-\frac{hA}{mc_p}t\right) \tag{7}$$

where T_0 is the temperature of the soil at time $t = 0$ (when Equation (6) starts to apply), h is the convection heat transfer coefficient, m is the total mass of the soil, and c_p is the soil specific heat capacity. This is estimated from the properties of the soil constituents:

$$mc_p = \left(mc_p\right)_{soil} + \left(mc_p\right)_{water} \tag{8}$$

Equation (7) gives a theoretical decay curve which can be fitted to the experimental data by changing h until the two curves match. During steady state, conservation of energy dictates that the heat flow rate across the soil is equal to the heat flow rate at the top of the specimen from the soil to the air.

$$Q = \lambda A \frac{\left(T_{base} - T_{top}\right)}{L} = hA\left(T_{top} - T_{amb}\right) \tag{9}$$

This is used to calculate the thermal conductivity. It is worth noting that this method introduces an error associated with the estimation of the specific heat capacity from constituents whose properties may not be accurately known.

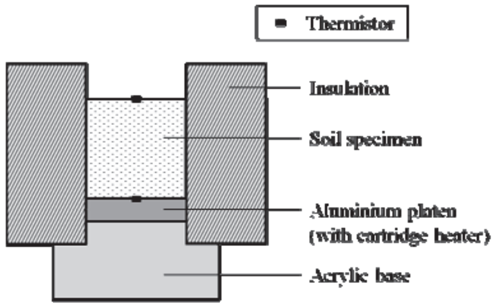

Figure 2. Thermal cell.

3 METHODOLOGY

3.1 *Measurement procedure*

The thermal conductivity of U100 samples of London Clay taken from a thermal response test borehole were tested using both techniques described in Section 2. Before any measurements were taken, the sealed samples were left in a temperature controlled room overnight to equilibrate. Each sample was treated as follows.

To accommodate the needle probe, a 200mm length specimen was prepared and secured in a rubber membrane. Shavings taken from the top of the sample were used to determine the initial moisture content at the top. The soil was found to be too hard to directly insert the probe. Therefore, a 5mm diameter hole had to be predrilled, and the hole filled with a high thermal conductivity contact fluid (in this case toothpaste was used) to reduce the contact resistance between the probe and the soil (Hukseflux, 2003). The probe was inserted into the hole, and secured with a clamp stand. It was then left for 20min to equilibrate with the soil. A constant power was then supplied to the needle probe heater for 300s, and then turned off. The temperatures during the heating and recovery periods were recorded. Using this procedure, five measurements were taken over the cross-sectional area of the specimen. One measurement was taken at the centre of the cross-section, the other four were equally spaced at a radial distance of 25mm from the centre.

To reduce the time it takes to reach steady state, the specimen was then cut in half and the top 100mm weighed and secured to the platen of the thermal cell (see Figure 2), and sealed at the top using aluminium foil to prevent moisture from leaving the top of the sample. Shavings taken from the bottom of the top half were used to determine the initial moisture content at the bottom. Insulation was then wrapped around the specimen. The temperature difference across the specimen is measured by two thermistors, one secured to the top of the platen, the other embedded at the top of the soil. The cartridge heater was then turned on, and the power controlled so that the platen remains at a constant temperature of 40°C. The power was measured using a MuRata ACM20-5-AC1-R-C wattmeter. Temperatures were monitored until steady state was reached and then maintained for at least 2hours. The power to the cartridge heater was then switched off, and the recovery period monitored. At the end of the test, shavings were taken from the top, middle and bottom of the specimen to determine the final moisture contents.

The holes drilled into the specimen and the contact fluid could potentially affect the thermal conductivity measurement using the thermal cell. To verify the result, the bottom half of the sample was also tested in the thermal cell, where these effects would be less significant.

A full soil classification was then conducted based on the British Standard 1377 (British Standards Institution, 1990), to determine the soil density, moisture content, liquid limit, plastic limit, particle density, and particle size distribution.

3.2 *Data analysis*

For the needle probe, using Equations (3) and (4) for heating and recovery respectively, graphs were plotted of temperature against the natural logarithm of time, and the gradient of the straight line section used to determine the thermal conductivity. A typical result is shown in Figure 3.

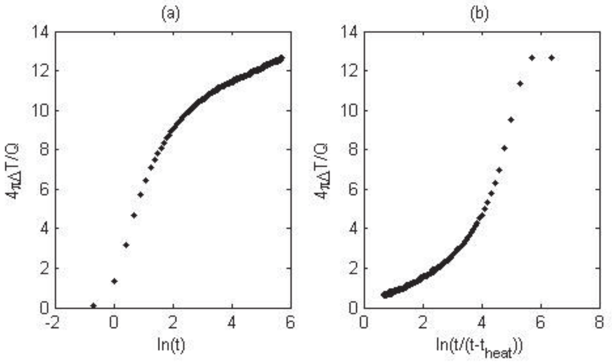

Figure 3. Graph of needle probe data for (a) heating and (b) recovery.

For the thermal cell, average temperatures during the steady state period were calculated for each thermistor. The average power supplied to the cartridge heater was also calculated. Equation (5) was then used to determine the thermal conductivity.

4 RESULTS AND DISCUSSION

The results of the tests are shown in Table 1, with the average value of the five needle probe readings given. The needle probe consistently gave lower values of thermal conductivity than the thermal cell. The sample properties are given in Table 2, where the moisture content given is the average of the values before and after testing. There is a decrease in thermal conductivity with depth. This may be due to a decrease in density, and also change in mineralogy. The top two samples were of firm slightly sandy clay. The bottom sample had a significant number of fissures, and a slightly greater sand content.

Table 1. Thermal conductivity measured using the needle probe for heating and recovery, and using the thermal cell.

Sample depth (m)	Thermal conductivity (Wm^{-1}K^{-1})		
	Needle probe in heating	Needle probe in recovery	Thermal cell
8.00-8.45	1.47	1.30	2.01 (t)* 1.88 (b)
10.00-10.45	1.24	1.36	1.85 (t) 1.91 (b)
19.00-19.45	1.06	0.93	1.65 (t) 1.75 (b)

*t – top half; b – bottom half.

4.1 *Needle probe*

The variation in the five needle probe readings within the same sample was about ±10% for heating and ±15% for recovery. The sample at depth 19.00-19.45m had less variation. When the needle probe was previously tested using five identical agar gel samples, it gave a repeatability of ±2% for both heating and recovery, so most of the variation in results would seem to be due to natural variation in thermal conductivity of the soil.

The greatest disadvantage with the needle probe is in the interpretation of results relying on human judgement. The calculated thermal conductivity is highly sensitive to the selection of the part of the graph deemed to be a straight line. Another factor which may affect the results is the use of contact fluid. In theory, the contact fluid should only decrease the time it takes to reach the straight line section of the graph, i.e. it should have no effect on the calculated thermal conductivity. However, the fluid could potentially seep into cracks in the soil, and in doing so alter the thermal conductivity. After testing, the specimens were cut up to see if this was the case. The soil at depths of 8.00-8.45m and 10.00-10.45m did not contain many fissures, and the contact fluid seemed to have stayed within the drilled holes. It can therefore be assumed that the contact fluid had little effect on the needle probe results. However, for the sample at depth 19.00-19.45m there were a significant number of fissures, which contact fluid had seeped into. This could affect both needle probe and thermal cell measurements, giving higher thermal conductivity results than otherwise.

4.2 *Thermal cell*

In Section 2.2, two methods for calculating the thermal conductivity using the thermal cell were outlined. One involves measuring the power directly, the other uses the lumped capacitance method to calculate the power. Only the first method was deemed suitable for this study, as the temperature difference across the soil after the power is switched off was too great for lumped capacitance to apply i.e. Equation (6) was not satisfied.

The difference in thermal conductivity values between the top and bottom sections was about 0.1Wm^{-1}K^{-1}. If the holes for the needle probe were to have a significant effect on the thermal conductivity values, the measurement for the top section would be expected to always be higher than for the bottom section, or vice versa. This is not the case, and as the area of the holes is only 1.25% of the total cross-sectional area, it can be assumed that the differences between the top and bottom sections are mainly due to the soil's natural variability.

The moisture content at the top of the specimens were measured before and after the thermal cell tests. The values after the test were consistently higher than those before the test. The greatest increase in moisture content was 5.2%. This shows that over the long heating period, moisture migration occurs in the direction of heat flow. This is where a temperature gradient causes the water to transfer latent heat through the pores as described by the liquid-island theory (Philip and de Vries, 1957). This theory suggests that in fairly dry media, the water is deposited in isolated pockets or 'islands', either filling small pores or attaching themselves between soil grains. When a temperature gradient is applied, there is a vapour flux in the direction of heat flow. Water evaporates from one island, and condenses at the boundary of the next island, thereby transferring heat from one island to the next.

4.3 *Comparing test methods*

The measured thermal conductivity for the thermal cell is higher than that of the needle probe by 40%, 45%, and 71% for a depth of 8.00-8.45m, 10.00-10.45m, and 19.00-19.45m respectively. This could be explained by a number of factors. The needle probe and thermal cell measure the thermal conductivity in the radial and axial directions respectively. It could be that the soil is anisotropic, and naturally has a higher thermal conductivity in the axial direction. However, the layers in the soil sample tended to be in the horizontal direction i.e. perpendicular to the cylinder axis. The thermal conductivity measured parallel to the layering should in general be higher than that measured perpendicular to the layering (Midttømme and Roaldset, 1998). If anisotropy was the reason behind the difference between needle probe and thermal cell values, then the needle probe would be expected to give higher values of thermal conductivity than the thermal cell. Therefore, it is unlikely that anisotropy is the reason behind these differences.

In the thermal cell calculations, the total power is used and any losses neglected. A simple finite element analysis was conducted, and indicated only minor losses. However, if losses are in fact significant, then the calculated thermal conductivities would be overestimates. A more thorough analysis would be necessary to determine whether this is the case.

The presence of contact fluid in the thermal cell test could potentially be aiding heat transfer. If the thermal conductivity of the contact fluid is determined, this would give a better indication as to what effect it could have. This should not be the main reason for higher thermal conductivity values, as the volume of contact fluid is comparatively small.

As previously mentioned, significant moisture migration occurs due to the large temperature gradient applied. As an additional mechanism for heat transfer, this may lead to higher measured values of thermal conductivity.

Table 2. Soil properties.

Sample depth (m)		Density (kgm^{-3})	Average moisture content (%)
8.00-8.45	Top Bottom	2092 2142	23.4 23.3
10.00-10.45	Top Bottom	2053 1951	26.9 27.1
19.00-19.45	Top Bottom	1783 1787	26.3 26.4

5 FURTHER RESEARCH

This study highlights the need for further investigation into the needle probe and thermal cell methods of thermal conductivity measurement for soils. With the needle probe, it is still unclear as to why heating and recovery gave different results for the thermal conductivity. As mentioned previously, the needle probe relies on human judgement in the interpretation of the results. Further research will be carried out to find a method which eliminates this source of error.

Some possible sources of error in the thermal cell method require investigation. A more detailed finite element analysis could be used to determine what power losses might be expected, so that this could be factored into the thermal conductivity calculation. The specimens were prepared by hand, so that the surface in contact with the platen may not be entirely flat. Tests on standard materials with and without a contact fluid between the platen and the soil could determine how significant the effects of this may be on the heat transfer. From the recovery data, there was a considerable temperature difference between the top and bottom of the soil for a long time after the power had been switched off. Clarke et al. (2008) was able to use the recovery curve to determine the power input, as the temperature difference was small. The reasons behind this discrepancy are unclear, so further tests using the thermal cell on different types of soil with a range of thermal conductivities will be beneficial.

The soil samples were taken from a borehole where a thermal response test was later conducted. Other samples were also taken to another laboratory to test for thermal conductivity using the thermal cell method. Once the results from these tests are known, a comparison will be made to the results gathered from this study.

6 CONCLUSION

Two test methods for thermal conductivity, the needle probe and thermal cell, have been compared. The needle probe takes less time to conduct, and the soil is only heated slightly and for a short period which means moisture migration is not expected to affect the results. However, hard soil samples may require predrilling, and the use of contact fluid which can seep into any existing fissures thereby potentially affecting the thermal conductivity measurements.

The thermal cell requires very little alterations to the soil sample, but raises some issues to do with power losses. The long heating time also means that moisture migrates towards the top of the specimen. Within the context of energy foundations, the thermal cell may prove more suitable for measuring the thermal conductivity of other relevant materials such as grout and concrete.

7 ACKNOWLEDGEMENTS

The authors would like to thank Harvey Skinner for his help in the design, build, and instrumentation of the apparatus. The soil samples were provided by Concept Engineering Consultants Ltd. The site work has been carried out by Arup, Canary Wharf Contractors Ltd, and Concept. This work forms part of a larger project funded by EPSRC (ref EP/H0490101/1) and supported by Mott MacDonald Group Ltd, Cementation Skanska Ltd, WJ Groundwater Ltd, and Golder Associates.

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