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A comparison of laboratory and in situ methods to determine soil thermal conductivity for energy foundations and other ground heat exchanger applications

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Abstract Soil thermal conductivity is an important factor in the design of energy foundations and other ground heat exchanger systems. It can be determined by a field thermal response test, which is both costly and time consuming, but tests a large volume of soil. Alternatively, cheaper and quicker laboratory test methods may be applied to smaller soil samples. This paper investigates two different laboratory methods: the steady state thermal cell and the transient needle probe. U100 soil samples were taken during the site investigation for a small diameter test pile, for which a thermal response test was later conducted. The thermal conductivities of the samples were measured using the two laboratory methods. The results from the thermal cell and needle probe were significantly different, with the thermal cell consistently giving higher values for thermal conductivity. The main difficulty with the thermal cell was determining the rate of heat flow, as the apparatus experiences significant heat losses. The needle probe was found to have fewer significant sources of error, but tests a smaller soil sample than the thermal cell. However, both laboratory methods gave much lower values of thermal conductivity compared to the in situ thermal response test. Possible reasons for these discrepancies are discussed, including sample size, orientation and disturbance.

Keywords thermal conductivity · thermal cell · needle probe · ground source heat pumps · energy foundations

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1 Introduction

Ground source heat pump (GSHP) systems provide a viable alternative to conventional heating and cooling systems in the move towards sustainable building solutions [6]. 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 minimise initial construction costs, the pipes can be cast into the foundations, eliminating the need to make further excavations. These systems are known as energy or thermal foundations. To design such a system, it is important to model accurately the heat transfer process between the foundations and the soil. One important input parameter for such analysis is the soil thermal conductivity.

There are several different laboratory methods for measuring soil thermal conductivity [26, 14]. 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. Transient methods involve applying heat to the specimen and monitoring temperature changes over time. The transient data is used to determine the thermal conductivity, usually by application of an analytical solution to the heat diffusion equation. Some transient methods can also be used to assess other thermal properties such as thermal diffusivity [8]. This paper compares the two approaches using a thermal cell (steady state) and a needle probe (transient) apparatus. Both the thermal cell and needle probe are currently industry recommended laboratory methods [4, 22, 18].

The thermal response test (TRT) [13] is currently the most widely used method for the determination of the in situ thermal conductivity for a GSHP system. It is a large-scale transient field test and involves construction of a ground heat exchanger. The test is analogous to the needle probe method, but at a much larger scale. In theory, the value of thermal conductivity obtained using this method would most closely relate to the heat transfer performance of a GSHP system, as it tests the largest volume of soil and also takes into account other ground characteristics such as groundwater flow and large scale soil layering. However, there can be other sources of error to the method. For example, a significant source of error could be the method by which the TRT data is analysed [28]. The laboratory methods will be compared to the results from a TRT.

2 Background

There are several laboratory 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. These were then compared to a field TRT.

2.1 Needle probe

The needle probe used is the TP02 probe produced by Hukseflux [20]. It is 150 mm long with a diameter of 1.5 mm, and encloses a 100 mm long heating wire with a thermocouple located midway along this heater measuring the temperature (see Figure 1).

The measurement of thermal conductivity using the needle probe method is based on the theory for an infinitely long, infinitely thin line heat source [10]. 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:

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

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 [1]:

$$\mathrm{Ei}(x) = -\int_{-x}^{\infty}\frac{e^{-u}}{u}\mathrm{d}u \quad (2)$$

After the power is switched off (start to the recovery phase), the temperature difference is given by:

$$\Delta T = -\frac{q}{4\pi\lambda}\left[-\mathrm{Ei}\left(-\frac{r^2}{4\alpha t}\right)+\mathrm{Ei}\left(-\frac{r^2}{4\alpha(t-t_{\mathrm{heat}})}\right)\right] \quad (3)$$

where t_{heat} is the time at which the power is switched off. Equations 1 and 3 cannot be solved for λ and α explicitly. The exponential integral (Equation 2) can be represented as a series expansion, and approximated using the first two terms in the expansion [1]:

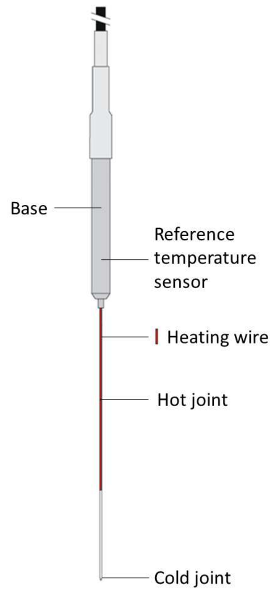

Fig. 1 Diagram of a needle probe (taken from Hukseflux [20])

$$\mathrm{Ei}(x) = \gamma + \ln|x| + \sum_{n=1}^{\infty}\frac{x^n}{nn!} \quad (4)$$

$$\mathrm{Ei}(x) \approx \gamma + \ln|x| \quad (5)$$

This approximation is valid for small values of x, which is the case when t is large. γ is Euler's constant. Substituting Equation 5 into Equations 1 and 3 gives [4]:

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln(t) - \frac{q}{4\pi\lambda}\left(\gamma + \ln\left(\frac{r^2}{4\alpha}\right)\right) \quad (6)$$

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln(t) + B \qquad 0 < t \leq t_{\mathrm{heat}} \quad (7)$$

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln\left(\frac{t}{t-t_{\mathrm{heat}}}\right) \qquad t > t_{\mathrm{heat}} \quad (8)$$

where B is a constant grouping together the end terms of Equation 6.

Graphs are plotted of change in temperature against $\ln(t)$ and $\ln(t/(t-t_{\mathrm{heat}}))$, for the heating and recovery phases respectively. During an initial phase, the contact resistance and thermal capacity of the probe are overcome. After this, the graphs become linear and the gradient can be used to calculate the thermal conductivity. The time it takes for linearity to occur depends on the contact between the probe and the soil, with a good contact giving a shorter initial phase.

2.2 Thermal cell

The thermal cell is based on a design by Clarke et al. [11], the recommended method for laboratory soil thermal conductivity testing according to the Ground Source Heat Pump

Association (GSHPA) [18]. A diagram of the apparatus is shown in Figure 2. The thermal conductivity of a U100 (undisturbed, 100 mm diameter) sample 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:

$$Q = -\lambda A \frac{\Delta T}{L} \tag{9}$$

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. To use Equation 9, the power input Q must be known. If Q cannot be measured directly, 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 approach, proposed by Clarke et al. [11], uses the lumped capacitance method, which is only valid when the temperature difference across the soil is small compared with the temperature difference between the soil surface and the ambient temperature [21]:

$$\frac{T_{\text{base}} - T_{\text{top}}}{T_{\text{top}} - T_{\text{amb}}} = Bi < 0.1 \tag{10}$$

where subscripts 'base', 'top' and 'amb' refer to the temperature at the base of the soil, top of the soil, and of the ambient air respectively. The ambient temperature is assumed to be constant. Bi is the Biot number, a dimensionless group which is the ratio of resistances to heat transfer by conduction and convection. Where this is satisfied, the temperature of the soil at time t is [11]:

$$T = T_{\text{amb}} + (T_0 - T_{\text{amb}}) \exp\left(-\frac{hA}{mc_p} t\right) \tag{11}$$

where T_0 is the temperature of the soil at time $t = 0$ (when Equation 10 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:

$$mc_p = (mc_p)_{\text{particles}} + (mc_p)_{\text{water}} \tag{12}$$

Equation 11 gives a theoretical decay curve which can be fitted to the experimental data by modifying 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:

$$Q = \lambda A \frac{T_{\text{base}} - T_{\text{top}}}{L} = hA\left(T_{\text{top}} - T_{\text{amb}}\right) \tag{13}$$

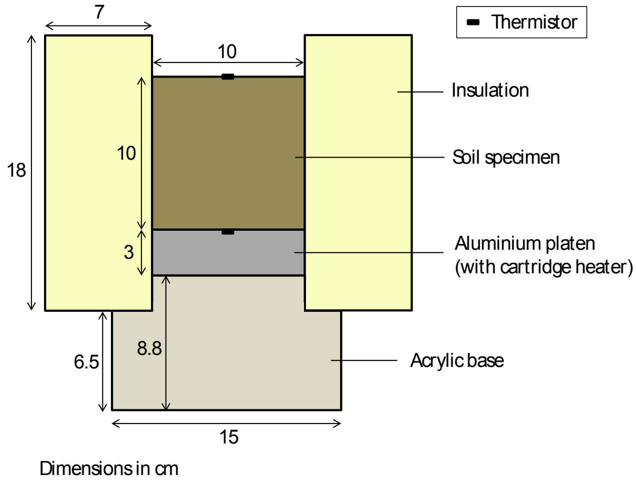

Fig. 2 Diagram of thermal cell cross-section.

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

2.3 Thermal response test

In a TRT, constant power is supplied to heat a fluid which is circulated through the pipes of a ground heat exchanger for a specified period. During the test, fluid temperatures at the inlet and outlet to the ground heat exchanger are recorded. As with the needle probe, the TRT data is interpreted by assuming the ground heat exchanger behaves as an infinite line heat source. From Equations 1 and 5 the change in ground temperature can be expressed by [10]:

$$\Delta T_g \cong \frac{q}{4\pi\lambda}\left(\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right) \tag{14}$$

where ΔT_g is the change in ground temperature. The fluid temperature is not the same as the ground temperature, as there is heat transfer between the fluid and the grout before the heat in the grout is then transferred to the ground. To account for this, a constant thermal resistance R_b is assumed for the borehole, with radius r_b. The temperature change in the fluid is given by:

$$\Delta T_f = qR_b + \Delta T_g = qR_b + \frac{q}{4\pi\lambda}\left(\ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right) \tag{15}$$

where ΔT_f is the change in fluid temperature. As there is a difference between the inlet and outlet fluid temperatures, the average of these is used in the calculation. In the same way as with the needle probe, the thermal conductivity can be found from the gradient of the straight line portion of a graph of ΔT_f against $\ln(t)$. The initial part of the graph should be ignored as it is influenced by the heat capacity of the ground heat exchanger. As a general rule, the time which should be used in calculations is [17]:

$$t > 5r_b^2/\alpha \tag{16}$$

where r_b is the borehole radius and α is the thermal diffusivity, calculated by estimating the thermal conductivity from the gradient of the graph.

3 Site

An opportunity to compare the laboratory tests to a field TRT presented itself at a Central London development site. The TRT was done on a test pile constructed by Concept Consultants Limited, as part of a site investigation to determine the geotechnical and thermal properties of the ground, and hence evaluate the ground source energy potential of the site using energy foundations. The pile was 0.3 m in diameter and 26 m deep. It was constructed by reaming out the site investigation borehole to a diameter of 0.3 m. The soil description is very stiff fissured dark brown CLAY (London Clay).

4 Method

Six U100 samples were taken from the pile bore during the site investigation. These were tested several months later, using the needle probe and thermal cell methods. Before any measurements were taken, the sealed samples were left in a temperature controlled room overnight to equilibrate. The samples were then extruded from the tubes before testing. Each sample was treated as follows.

4.1 Needle probe

To accommodate the needle probe, a 100 mm diameter, 200 mm length specimen was prepared and secured in a rubber membrane. The specimen was taken from the middle of the U100 sample as the ends may have experienced drying. Shavings taken from the top of the specimen were used to determine the initial moisture content at the top. The soil was too hard to directly insert the probe. Therefore, a 5 mm diameter hole had to be pre-drilled, and the hole filled with a high thermal conductivity contact fluid (toothpaste as suggested by the manufacturer) to reduce the contact resistance between the probe and the soil [19]. The probe was inserted into the hole, and secured with a clamp stand. It was left for 20 minutes to equilibrate with the soil. A constant power was supplied to the needle probe heater for 300-600 s, and then switched off. The heating time had to be increased from 300 s if the results showed a long initial period and hence had yet to display a linear relationship. 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 25 mm from the centre.

4.2 Thermal cell

To reduce the time it takes for the thermal cell sample to reach steady state, the needle probe specimen was cut in half and the top 100 mm weighed and secured to the platen of the thermal cell (see Figure 2). The specimen was 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 wrapped around the specimen. The temperature difference across the specimen was 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 turned on, and the power controlled so that the platen remained 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 2 hours. The power to the cartridge heater was 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. This is because the hole was 150 mm deep, which would go through the length of the top 100 mm specimen, but only through 50 mm of the bottom 100 mm specimen. Following testing, the specimens were cut up to confirm that the contact fluid had remained inside the drilled holes and did not seep into the surrounding soil.

A full soil classification was then conducted based on the British Standard 1377 [9], to determine the soil density, moisture content, liquid limit, plastic limit, particle density, and particle size distribution.

4.3 Laboratory data analysis

For the needle probe, graphs were plotted of temperature against the natural logarithm of time. The gradient of the straight line section was used to determine the thermal conductivity using Equations 7 and 8 for heating and recovery respectively. A typical result is shown in Figure 3.

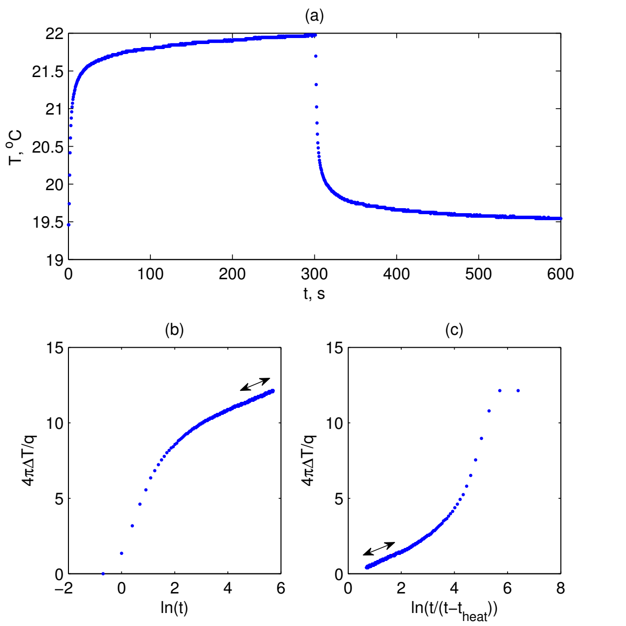

Fig. 3 Graph of needle probe data at a depth of 8.00–8.45 m, showing (a) temperature against time (measured at the mid point of the heating wire), and temperature against logarithmic time to calculate the thermal conductivity for (b) heating and (c) recovery. The straight line sections of the graph used in the calculations is shown by the arrows.

For the thermal cell, average temperatures during the steady state period were calculated for each thermistor. For the example thermal cell result in Figure 4, the steady state period was from 12 to 15.5 hours into the test. The average power supplied to the cartridge heater was also calculated. Equation 9 was used to determine the thermal conductivity. The recovery curve was also analysed using the method described in Section 2.2. However, the criterion in Equation 10 was never satisfied, reflecting the temperature difference across the sample. Figure 5 shows the Biot number during the thermal cell test recovery curve, confirming that it never fell below approximately 0.2. As the power was measured directly, the recovery curve method was not used. It is unclear as to why the tests performed by Clarke et al. [11] were able to satisfy the criterion in Equation 10, while the tests in this study never did.

4.4 Thermal response test

The TRT was conducted ten days after grouting the pile. The test was carried out by GECCO2 Ltd using their test rig. Water was used as the circulating fluid. The fluid flow rate and temperature were recorded at 5 minute intervals, using an electromagnetic flow meter and Iron-Constantan (J type) thermocouples respectively. After an initial circulation phase lasting 4.5 days, a 3 day heat injection test was performed, followed by a 3 day recovery period. The next

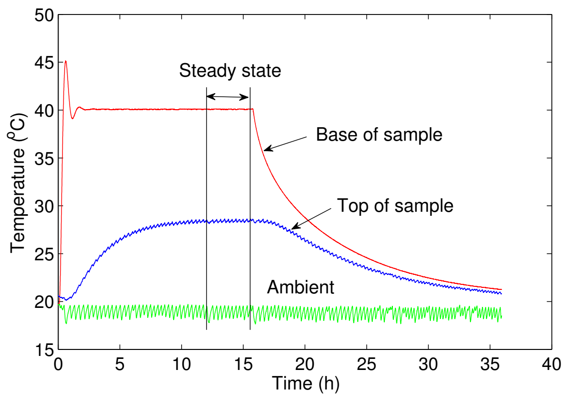

Fig. 4 Thermal cell result for the top half of the 8.00–8.45 m depth sample.

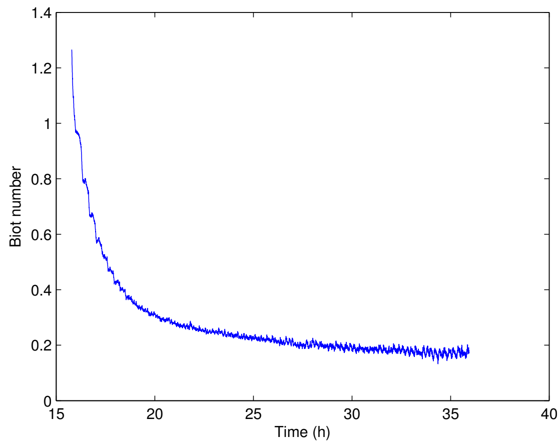

Fig. 5 Biot number over recovery period for thermal cell test (Figure 4).

stage was a 3 day heat extraction test, followed by a 4 day recovery period. The average power supplied to the heat exchanger was 2.2 kW and -2.1 kW during the heat injection and heat extraction phases respectively. Cyclic testing was then commenced comprising two heat injection phases separated by heat extraction phases. Here, only the results from the first heat injection and heat extraction phases are compared to the laboratory tests, as these are considered to be the most reliable. The thermal conductivity was calculated using the procedure described in Section 2.3 above, assuming $\alpha = 1.16 \times 10^{-6} \mathrm{m^2 s^{-1}}$. Details of the TRT analysis are given in Loveridge et al. [24].

5 Results and Discussion

The results are summarised in Table 1. The needle probe results are an average of the five measurements for each sample. The full range of results is represented in Figure 6. Fig-

Table 1 Summary of laboratory test results.

Depth (m)	Thermal conductivity ($Wm^{-1}K^{-1}$)			
	Needle Probe		Thermal Cell	
	Heating	Recovery	Top	Bottom
2.00–2.45	1.34	1.32	1.86	1.72
8.00–8.45	1.45	1.29	2.01	1.88
10.00–10.45	1.23	1.37	1.85	1.91
17.00–17.45	1.34	1.30	1.92	1.88
19.00–19.45	1.05	0.92	1.65	1.75
21.50–21.95	1.49	1.34	2.19	1.84

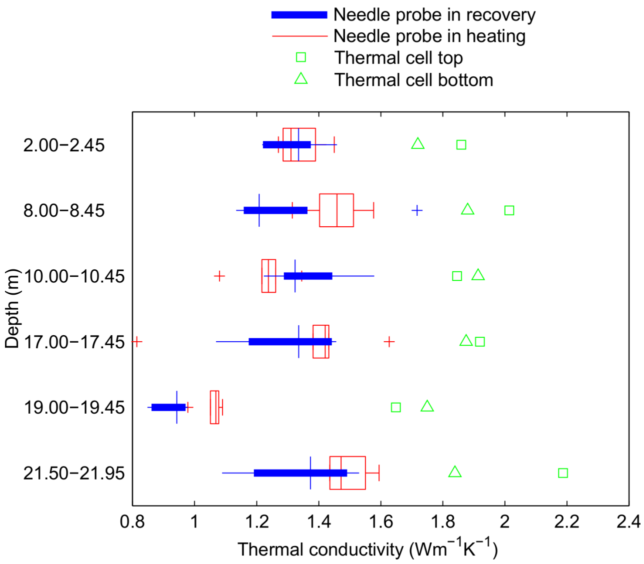

Fig. 6 Thermal conductivity with depth. For the needle probe results, on each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

ure 7 shows the variation in density and moisture content with depth.

5.1 Needle probe

The measured thermal conductivity ranges from 1.05 to 1.49 $Wm^{-1}K^{-1}$ for heating and 0.92 to 1.37 $Wm^{-1}K^{-1}$ for recovery. The variation in the five needle probe readings within the same sample was about $\pm 11\%$ for heating and $\pm 14\%$ for recovery. When the needle probe was previously tested using five identical agar gel samples, it gave a repeatability of $\pm 2\%$ for both heating and recovery, so most of the differences in results should be due to natural variability in thermal conductivity over the cross-section of the soil. London Clay can exhibit a variable coarse grain content, as well as moisture content and density [27]. In addition, moisture con-

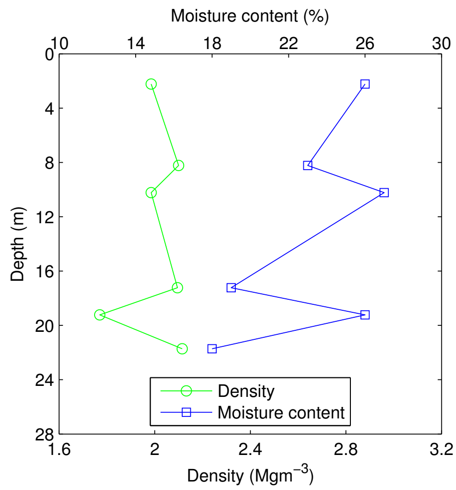

Fig. 7 Density and moisture content with depth.

tent variation can be introduced during the sampling process (see Section 5.4).

There is a general trend for a decrease in the moisture content of the samples with depth, which would be typical for London Clay. However, this is not reflected in the thermal conductivity values which show no significant variation with depth. The exception is the sample from 19.00–19.45 m depth which has a lower thermal conductivity despite having a high moisture content, perhaps reflecting the lower density of this sample. In general, the results show reasonable correlation between density and thermal conductivity, while variations in moisture content have less of an effect.

5.2 Thermal cell

A typical thermal cell result is shown in Figure 4. The measured thermal conductivity ranges from 1.65 to 2.19 $Wm^{-1}K^{-1}$ (Table 1).

The difference in thermal conductivity values between the top and bottom sections was between 2 and 17%. 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 was 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.

Moisture contents were taken before and after the thermal cell test, and a typical distribution through a specimen is shown in Figure 8. The moisture content at the top of the specimen after the test was consistently higher than before the test, as shown in Figure 9. The greatest increase in mois-

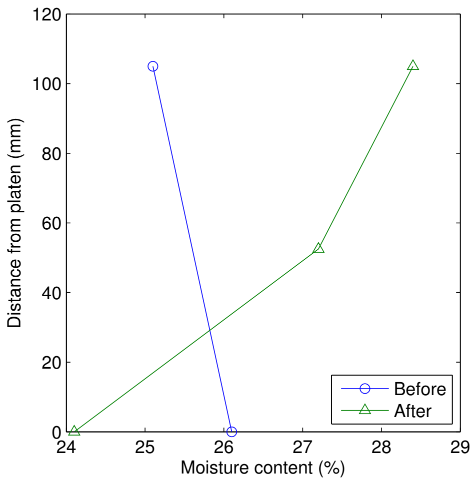

Fig. 8 Moisture content with depth before and after the thermal cell test. For depth 2.00–2.45 m, top half.

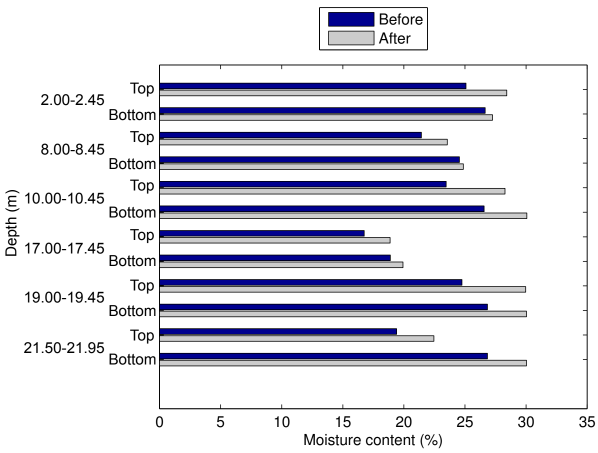

Fig. 9 Moisture content at the top of the soil specimen before and after each thermal response test. "Top" and "Bottom" refer to the top half and bottom half of the sample respectively, as the sample at each depth was cut in half for the thermal cell tests. Refer back to the methodology in Section 4.2.

ture content was 5.2%. This shows that over the long heating period, moisture migration occurs in the direction of heat flow.

5.3 Thermal response test

The TRT gave thermal conductivities of 2.5 and 2.7 $Wm^{-1}K^{-1}$ for heating and cooling phases respectively [24]. As these results are higher than the laboratory test results reported in Table 1, it is worth considering the accuracy of the in situ test. Various sources of uncertainty effect thermal response tests, those relevant for this test will include variability in the applied power, the larger diameter and relatively short length of the heat exchanger and any variability in the initial undisturbed temperature condition. Nevertheless, studies of errors in thermal response tests suggest that well conducted tests should be accurate to within 10% [28, 30, 23]. However, the error may be a little larger in this case as the pile is of greater diameter than usually recommended [5].

5.4 Comparison of methods

The measured thermal conductivity obtained using the thermal cell is consistently higher than that using the needle probe by around 40 to 50%. This could be explained by a number of factors. In the thermal cell calculations, the total power is used and any losses neglected. However, in reality some losses are likely to occur. Ideally these should be taken into account; this is difficult to do experimentally, although some attempts have been made [3]. There are suggestions that heat losses could be in excess of 20% (Hemmingway, P. 2013 pers. comm.), and if this were the case it could explain much of the variation between the thermal cell and the needle probe. Consequently, heat losses are most likely the greatest source of error in the thermal cell calculations.

Other factors could also be contributing to the difference in results. 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 were horizontal i.e. perpendicular to the cylinder axis. The thermal conductivity measured parallel to layering is in general found to be higher than that measured perpendicular to the layering [25]. 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. Anisotropy can be investigated by taking larger block samples and trimming specimens to the required sizes in both orientations. However, such large high quality samples were not available in this investigation. In any case, it is unlikely that anisotropy is the reason behind these differences.

The thermal cell test follows the needle probe tests, in which contact fluid was used to fill the holes. The contact fluid could have potentially been aiding heat transfer in the thermal cell test. However, this should not be the main reason for higher thermal conductivity values, as the volume of contact fluid is comparatively small (at most only 1.25% of the sample volume).

As previously mentioned, moisture migration occurs in the thermal cell owing to the large temperature gradient applied. As an additional mechanism for heat transfer, this may lead to higher measured values of thermal conductivity [14]. With the needle probe method, moisture migration should be insignificant as the power applied (and hence the temperature gradient) and the heating time are much smaller.

In summary, the main reasons why the measured thermal conductivity from the thermal cell is higher than that of the needle probe is that heat losses in the thermal cell have not been accounted for, and that there was moisture migration during the thermal cell test.

Both laboratory methods gave significantly lower values of thermal conductivity than the TRT. The TRT thermal conductivity value was about twice the needle probe value, and 40% higher than the thermal cell value. One possible reason is that after the soil samples are taken, the soil no longer experiences the same stresses as when it was in the ground; the laboratory tests were undertaken without any confining pressure. This could give a looser soil with diminished contact between particles [2]. Results from oedometer tests on London Clay from these depths have previously been documented, and show the relationship between void ratio and the natural logarithm of vertical effective stress, i.e. the slope of the one-dimensional compression line for unloading [15]. From this, we can infer that the change in void ratio for our samples was about 0.15. The effect this has on the thermal conductivity can be estimated from the De Vries equations for calculating the thermal conductivity of soils based on their constituents [14]. The thermal conductivities used for the clay minerals and water are 2 $Wm^{-1}K^{-1}$ [7] and 0.6 $Wm^{-1}K^{-1}$ [19] respectively. The value of thermal conductivity used for the air is 0.1 $Wm^{-1}K^{-1}$, which is an effective thermal conductivity taking into account a contribution from moisture migration at a temperature of 20 °C [12,14]. The sample water content is taken to be 0.2. It is assumed that the soil is saturated before the sampling process, after which the void ratio increases due to air being introduced. The calculated thermal conductivity was 1.36 and 1.20 $Wm^{-1}K^{-1}$ for the in situ and sample soil respectively, which is a 12% decrease. This cannot entirely explain the difference between TRT and laboratory results, but could be a contributing factor.

The process of taking samples also causes disturbance and it has been observed that U100 type samples in over consolidated clay will have a reduced moisture content in the middle of the sample compared with the circumference [16,29]. This could mean that the needle probe is testing drier soil (expected to have lower thermal conductivity on average) than the thermal cell. The samples were also tested some months after being taken from site, and despite being contained in a metal tube and sealed with wax on both ends, there could still have been some drying of the sample before testing, particularly as it was observed that the wax became brittle and pulled away from the tube edges over time.

Another issue is differences in scale. The laboratory tests are carried out on samples that are much smaller than the volume of soil tested in a TRT. This in itself would cause differences in results, as the TRT would take into account large scale soil layering. Properties such as moisture content and density vary with depth, so whereas a localised change in soil property at a depth at which a sample is taken would significantly effect the sample thermal conductivity, it would have a much smaller effect on the TRT which mirrors the averaged property over the length of the pile. There could also be localised laminations affecting the samples more than the TRT. The pile is located within the units near the base of the London Clay, which are known to exhibit greater grain size and mineralogical variations than other parts of the formation [27].

6 Conclusions

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 pre-drilling and back-filling with a contact fluid, which may increase the contact resistance. The thermal cell requires very little alteration to the soil sample, but raises some accuracy issues to do with power losses. The long heating time also means that moisture migrates towards the top of the specimen. The thermal cell gave higher thermal conductivity values than the needle probe, which is mainly due to the significant heat losses. As a consequence of these errors, the needle probe is the preferred laboratory method.

The laboratory test methods gave consistently lower values of thermal conductivity than the TRT. Possible reasons for this are the loss in confining pressure after the sample is taken, sample disturbance including drying during the sampling process, further drying of the sample after extraction, and the difference in the volume of soil tested. Some of these effects could be eliminated by only using high quality truly undisturbed samples for laboratory testing, and this is recommended wherever possible. While overall the thermal response test appears to give a better measurement of the in situ thermal conductivity, it is a more expensive and time consuming approach and does include other sources of error which need to be understood.

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References

1. Abramowitz, M., Stegun, I.A.: Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables. U.S. Government Printing Office (1972)
2. Abu-Hamdeh, N.H., Reeder, R.C.: Soil thermal conductivity: effects of density, moisture, salt concentration, and organic matter. Soil Science Society of America Journal **64**, 1285–1290 (2000)
3. Alrtimi, A.A., Rouainia, M., Manning, D.A.C.: Thermal enhancement of pfa–based grout for geothermal heat exchangers. Applied Thermal Engineering **54**, 559–564 (2013)
4. ASTM International: D 5334–08 Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure. ASTM International, West Conshohocken, PA (2008)
5. Austin III, W.A.: Development of an in situ system for measuring ground thermal properties. Master's thesis, Oklahoma State University (1998)
6. Banks, D.: An introduction to thermogeology: ground source heating and cooling. Blackwell Publishing Ltd (2008)
7. Brigaud, F., Vasseur, G.: Mineralogy, porosity and fluid control on thermal conductivity of sedimentary rocks. Geophysical Journal **98**, 525–542 (1989)
8. Bristow, K.L., Kluitenberg, G.J., Horton, R.: Measurement of soil thermal properties with a dual-probe heat-pulse technique. Soil Science Society of America Journal **58**, 1288–1294 (1994)
9. British Standards Institution: BS 1377:1990 Methods of test for soils for civil engineering purposes. BSI, London (1990)
10. Carslaw, H.S., Jaeger, J.C.: Conduction of heat in solids. Oxford University Press (1959)
11. Clarke, B.G., Agab, A., Nicholson, D.: Model specification to determine thermal conductivity of soils. Geotechnical Engineering **161**, 161–168 (2008)
12. De Vries, D.A.: Heat and Mass Transfer in the Biosphere: Transfer Processes in the Plant Environment. John Wiley & Sons Inc. (1974)
13. European Committee for Standardization: TC 341 WI 00341067.6 Geotechnical investigation and testing – Geothermal testing – Determination of thermal conductivity of soil and rock using a borehole heat exchanger (2011). Submitted to the CEN Enquiry.
14. Farouki, O.: Thermal properties of soils. Series on Rock and Soil Mechanics Series. Trans Tech Publications, Limited (1981)
15. Gasparre, A.: Advanced laboratory characterisation of London Clay. Ph.D. thesis, Imperial College London (2005)
16. Graham, J.: The 2003 R.M. Hardy Lecture: Soil parameters for numerical analysis in clay. Canadian Geotechnical Journal **43**, 187–209 (2006)
17. GSHPA: Closed-loop vertical borehole design, installation & materials standards (2011)
18. GSHPA: Thermal pile design, installation & materials standards (2012)
19. Hukseflux Thermal Sensors: TP02 Non-Steady-State Probe for Thermal Conductivity Measurement – manual v0908. Hukseflux Thermal Sensors, Delft (2003)
20. Hukseflux Thermal Sensors: TP02 Non-Steady-State Probe for Thermal Conductivity Measurement (2011). URL http://www.hukseflux.com/products/thermalConductivity/tp02.html
21. Incropera, F.P., DeWitt, D.P., Bergman, T.L., Lavine, A.S.: Fundamentals of Heat and Mass Transfer, 6 edn. John Wiley & Sons Inc. (2007)
22. Institute of Electrical and Electronics Engineers, Inc: IEEE Std 442–1981 Guide for Soil Thermal Resistivity Measurements. IEEE, New York (1996)
23. Javed, S., Fahlen, P.: Thermal response testing of a multiple borehole ground heat exchanger. International Journal of Low–Carbon Technologies **6**, 141–148 (2011)
24. Loveridge, F.A., Powrie, W., Nicholson, D.: Comparison of two different models for pile thermal response test interpretation. accepted by Acta Geotechnica (2014)
25. Midttømme, K., Roaldset, E.: The effect of grain size on thermal conductivity of quartz sands and silts. Petroleum Geoscience **4**, 165–172 (1998)
26. Mitchell, J.K., Kao, T.C.: Measurement of soil thermal resistivity. Journal of the Geotechnical Engineering Devision **104**, 1307–1320 (1978)
27. Pantelidou, H., Simpson, B.: Geotechnical variation of London Clay across central London. Géotechnique **57**, 101–112 (2007)
28. Signorelli, S., Bassetti, S., Pahud, D., Kohl, T.: Numerical evaluation of thermal response tests. Geothermics **36**, 141–166 (2007)
29. Vaughan, P.R., Chandler, R.J., Apted, J.P., Maguire, W.M., Sandroni, S.S.: Sampling disturbance – with particular reference to its effect on stiff clays. Predictive Soil Mechanics: Proceedings of the Wroth Memorial Symposium pp. 685–708 (1993)
30. Witte, H.J.L.: Error analysis of thermal response tests. Energy (2013). DOI 10.1016/j.apenergy.2012.11.060