Title: *Thermal conductivity of soils by the needle probe method, for energy foundation applications* for inclusion in the 32nd International Thermal Conductivity Conference and the 20th International Thermal Expansion Symposium

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ABSTRACT

Soil thermal conductivity is an important parameter in the design of ground source heat pump and energy foundation systems. One laboratory method for measuring the soil thermal conductivity is the needle probe method. Previously, analysis of the needle probe test data has been simplistic, relying heavily on human judgment and rules of thumb. This paper presents an alternative method of analyzing the needle probe data with the aid of a MATLAB program. Four agar-kaolin specimens of varying densities were prepared to resemble simple soils. These were tested using the needle probe for a range of heating times and heating powers, to see what effect these parameters would have on the results. The repeatability when keeping the heating time and heating power constant was within ±2%. When the heating time and heating power were varied, the variation in results from the average for a given specimen ranged from ±4% to +10%/-8%. This range is significantly higher than the repeatability. Possible reasons for this are discussed.

INTRODUCTION

Ground source heat pump (GSHP) systems provide a viable alternative to conventional heating and cooling systems in the development of sustainable building solutions [1]. Heat is transferred between the ground and the building by means of a refrigerant pumped through a series of pipes buried in the ground. To minimize initial construction costs, the pipes can be cast into the building foundations, eliminating the need for further excavations. These are known as energy foundations. To design such a system, it is important to model accurately the heat transfer process between the foundations and the soil. An important input parameter for such analysis is the soil thermal conductivity.

The thermal response test (TRT) is currently the most widely used method for the determination of the in situ soil thermal conductivity for a GSHP system [2]. It is a large-scale transient field test involving the construction of a ground heat exchanger. In theory, the value of thermal conductivity obtained using this method should relate directly to the heat transfer performance of a GSHP system. However, performing a TRT is both expensive and time consuming, so it may be preferable to measure the soil thermal conductivity using a laboratory method.

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Laboratory methods for measuring soil thermal conductivity fall into one of two categories: steady state or transient methods [3,4]. 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. However, steady state methods can be difficult to implement as heat losses must be minimized for the results to be reliable.

Transient methods involve applying heat to the specimen and monitoring temperature changes over time. The transient data are used to determine the thermal conductivity, usually by application of an analytical solution to the heat diffusion equation. One transient method is the needle probe method. It is analogous to the TRT, but at a much smaller scale.

The method by which data from a needle probe test is analyzed can significantly affect the thermal conductivity. There are several standards on the needle probe, but they do not elaborate on the data analysis, which relies mainly on a visual interpretation of the data. [5,6]. In this paper, a more rigorous method of analyzing the data is developed, which aims to minimize the human error associated with current methods.

THEORY

The calculation of thermal conductivity is based on the theory for an infinitely long, infinitely thin line heat source [7]. 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:

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

where q is the power per unit length of heater, λ is the thermal conductivity of the soil, α is the thermal diffusivity and Ei is the exponential integral [8]:

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

After the power has been switched off (i.e. the start of the recovery phase), the temperature difference is given by:

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

where t_{heat} is the time at which the power is switched off. Equations (1) and (3) cannot be solved explicitly for λ and α. The exponential integral can be represented as a series expansion, and approximated using the first two terms as [8]:

$$\mathrm{Ei}(x) = \gamma + \ln|x| \tag{4}$$

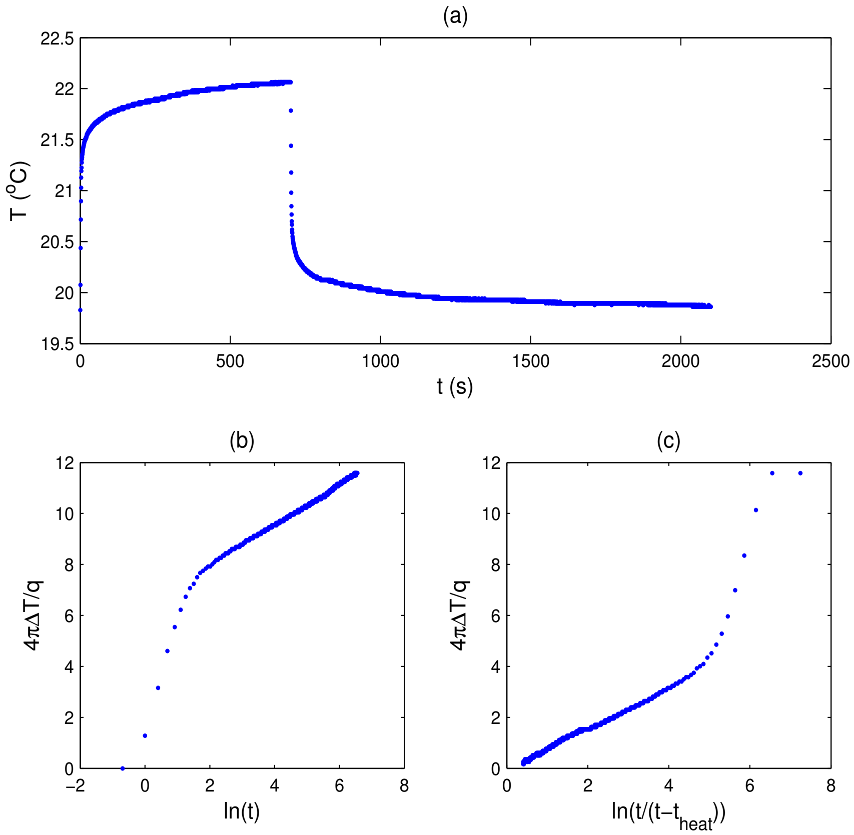

Figure 1. Typical needle probe results showing (a) temperature against time, and change in temperature against logarithmic time for (b) heating and (c) recovery.

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

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln(t) - \frac{q}{4\pi\lambda}\left(\gamma + \ln\left(\frac{r^2}{4\alpha}\right)\right) \tag{5}$$

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln(t) + B \qquad 0 < t \leq t_{\text{heat}} \tag{6}$$

$$\Delta T \cong \frac{q}{4\pi\lambda}\ln\left(\frac{t}{t - t_{\text{heat}}}\right) \qquad t > t_{\text{heat}} \tag{7}$$

where B is a constant, grouping together the end terms of Equation (5).

Graphs are plotted of change in temperature against $\ln(t)$ and $\ln(t/(t - t_{\text{heat}}))$, for the heating and recovery phases respectively (Figure 1). During the initial part of each phase, the contact resistance and thermal capacity of the probe are overcome. After this, the logarithmic 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 quality of the contact between the probe and the soil. The better the contact, the shorter the time taken to reach linearity. The last part of the graph for each phase can also become non-linear, as boundary conditions at the outer surfaces of the sample may start to have an effect.

Current standards suggest selecting the linear section of the graph by visual inspection [5,6], or excluding the first 10 to 30 seconds from the analysis for smaller diameter probes [5]. Both methods can be subjective and introduce significant errors. Commercial needle probes may have built in programs for calculating the thermal conductivity, e.g. the KD2 Pro Thermal Properties Analyzer by Decagon Devices [9]. They use a similar method to the standards and exclude the first third of data in their analysis. Subsequent research has been done by King et al. where the thermal conductivity is calculated for different intervals during the heating time to then find the average [10]. They suggest that a reliable value is obtained when the standard deviation is <0.1 $Wm^{-1}K^{-1}$ or <10%.

METHOD

The needle probe used was the TP02 probe produced by Hukseflux [11]. This 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 its length to measure the temperature (see Figure 2). The radius of the soil specimen should be at least 20 mm and encompass the length of the needle [11]. The range of thermal conductivities that can be measured by the probe is 0.1 to 6 $Wm^{-1}K^{-1}$ [11].

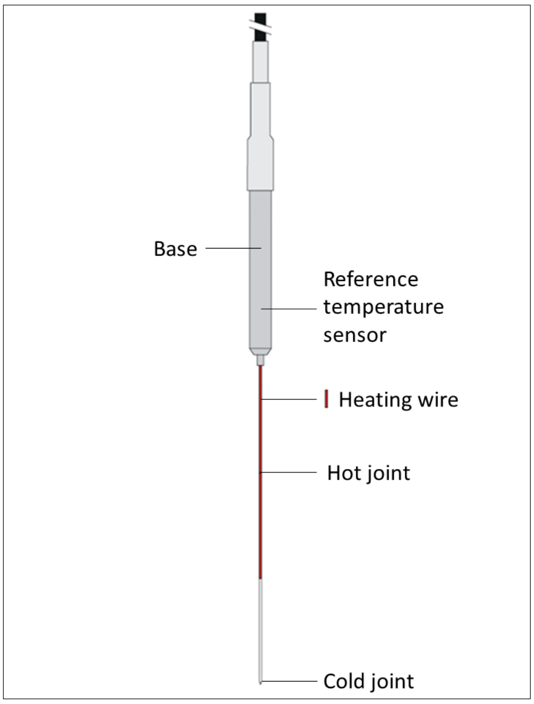

Figure 2. Diagram of needle probe (after Hukseflux [11]).

Preparation

Four agar-kaolin specimens resembling a simple two-phase soil were prepared as follows. (Agar is a gelling agent and is used to solidify the water, preventing moisture migration when the specimens are heated.) De-aired water was heated in a conical flask over a hot plate. The temperature of the hot plate was set at 370°C, and the water was gently stirred using a magnetic stirrer. A thermometer was used to measure the temperature of the water every few minutes. When the water reached 85°C (the melting temperature of agar) the hot plate temperature was reduced to 200°C, and the stirrer speed was increased slightly to prevent agar from sticking to the bottom of the flask. The agar was added to the water, with 4 grams of agar to every liter of water. When the agar had dissolved (which took approximately 20 minutes) the hot plate was switched off. The mixture was poured into a large tray, and the stir bar removed. Kaolin was gradually mixed in using palette knives. When a smooth consistency with minimal air bubbles had been reached, the mixture was poured into a 100 mm internal diameter cylinder, 220 mm long.

Different water to kaolin ratios were used for each specimen to achieve a range of thermal conductivities, as summarized in Table I. The specimens were left overnight in a 20 ℃ temperature controlled room to equilibrate. To ensure good contact between the probe and the specimen, the probe was inserted into the mixture while it was still liquid. The base of the probe was secured by clamping it so that the probe stood vertically through the center of the sample.

Measurement

To prevent the specimens from drying out, thermal conductivity measurements were taken the day after the specimen was made, when the specimens had cooled to form a jelly. Measurements were taken for heating times of 100, 300, 500, and 700 seconds, at low, medium, and high power (0.82, 2.43, and 4.13 Wm^{-1} respectively). Each measurement had three phases, and lasted four times the heating time. In the first phase (the same length as the heating time) the power was off, and the thermocouple measured the initial temperature of the soil to ensure that the temperature was not drifting. The second phase was the heating phase. The final phase was recovery, which was twice as long as the heating time. There were therefore a total of twelve measurements (4 heating times × 3 heating powers) per specimen.

The repeatability of the needle probe was also determined, by taking eight needle probe readings in the agar jelly (with no added kaolin) for 300 seconds of heating at medium power.

Analysis

The thermal conductivity was calculated from the graphs of change in temperature against $\ln(t)$ and $\ln(t/(t - t_{\text{heat}}))$, for the heating and recovery phases respectively. The thermal conductivity is inversely proportional to the gradient of the straight line section (Equations (6)

TABLE I. SPECIMEN DENSITIES

Specimen No.	Density (kgm^{-3})
1	1000
2	1181
3	1275
4	1444

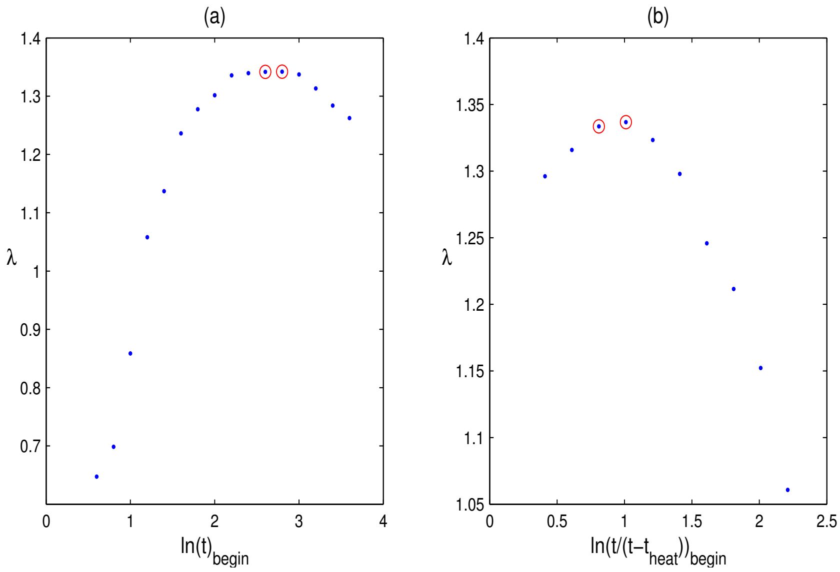

Figure 1. Thermal conductivity during (a) heating and (b) recovery, for different starting times. For this example, the heating time is 700 seconds and the section length is fixed at 2.8. The consecutive points circled have the closest values and are therefore used to calculate the thermal conductivity.

and (7)). To determine the linear section of the graph more systematically, a MATLAB code was produced. Linear regression was used to determine the gradient, but as time is plotted on a logarithmic scale, if all data points were taken into account the best-fit line would have a bias towards the end of the line where the points are closer together. Therefore, points evenly spaced in logarithmic time were used for the linear regression.

There are two aspects in the positioning of the straight line section: the starting time ($\ln(t)_{\text{begin}}$ and $\ln(t/(t-t_{\text{heat}}))_{\text{begin}}$ for the heating and recovery phases respectively) and the length of the section. To begin with, the section length was fixed. For different starting times, the thermal conductivity was calculated based on the gradient of that section of the graph. The two consecutive sections with the most similar gradients were identified, and the average gradient of those sections used to calculate the thermal conductivity. An example of this is shown in Figure 3. The graphs show an increase in calculated thermal conductivity with starting time before reaching a plateau and decreasing again. The plateaus in Figure 3 help identify the linear sections of Figure 1 (b) and (c).

This whole process was repeated for different section lengths for both heating and recovery phases. When the calculated thermal conductivities were plotted against the length of section, it was found that after an initial phase with significant scatter, the thermal conductivities for heating and recovery converged and then diverged again slightly. An example of this is shown in Figure 2. For small section lengths, the calculated thermal conductivity can be influenced by small fluctuations in the data, causing scatter. As the section length increases, these fluctuations have less of an effect as more data are taken into consideration. The point of convergence is where the section length reaches the length of the straight line section of the graph. After this point, increasing the section length starts to include data that should be excluded due to contact resistance or boundary influences. Inspection of Figure 1 graphs (b) and (c) show that including these extra data in the linear regression would cause the gradient to increase for both heating and recovery, and the calculated thermal conductivity to decrease. This is the case in Figure 4 after the point of convergence.

The point of convergence is found in the MATLAB program by determining the difference between the calculated thermal conductivities for heating and recovery. The two consecutive section lengths with the smallest combined difference were then used to calculate the final thermal conductivity, which is the average of the four points (circled in Figure 4).

RESULTS AND DISCUSSION

The repeatability in the agar jelly for the same heating time and heating power was found to be within ±2%, which is slightly worse than the repeatability stated by the manufacturer of ±1% [11]. The results from the four samples with varying heating time and heating power are plotted in Figure 5. The deviation in results from the average of the 12 measurements ranged from ±4% for Sample 2, to +10% to -8% for Sample 1, which is within the limits set by King et al. discussed previously [10]. This is significantly higher than when the heating time and heating power were kept constant, and shows that the needle probe method is not as repeatable as it may initially seem. The variation is slightly greater for the low power measurements. This may be because low power gives smaller temperature differences and the limitations in sensitivity of the needle probe thermocouple cause the temperature data to rise in steps, making it more difficult to determine the gradient accurately.

There are several possible reasons for the greater range of results when heating time and heating power are varied. It may reasonably be assumed that moisture migration is not a heat transfer mechanism as the water is solidified into jelly using the agar. The thermal conductivity of soils can increase with temperature but this is largely attributed to latent heat transfer by

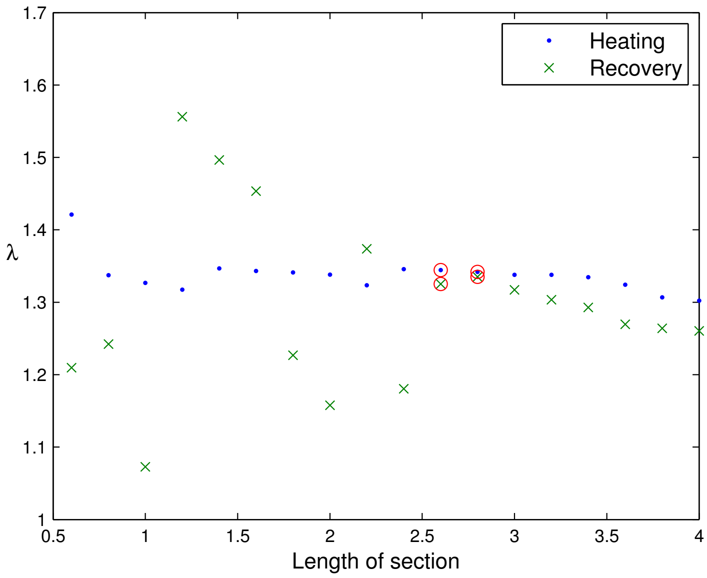

Figure 2. Thermal conductivity for heating and recovery against length of section used in the calculation. The data points used in the final thermal conductivity calculation are circled.

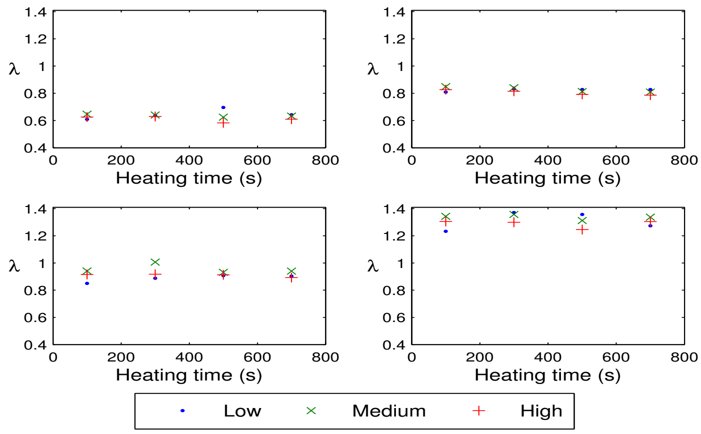

Figure 5. Thermal conductivities for a range of heating times and heating powers, for (a) Specimen 1, (b) Specimen 2, (c) Specimen 3, and (d) Specimen 4 (in order of increasing density).

moisture migration [12]. It is possible that the agar does not eliminate moisture migration entirely, which could be a contributing factor at high power and longer heating times. The total temperature change during heating varies between 0.6 °C and 5 °C. However, if moisture migration were a factor then a trend of measured thermal conductivity increasing with heating power and heating time would be expected; this is not the case.

Although moisture migration is not expected to be a significant factor, evidence of water evaporation at the top of the sample was seen; the specimen was weighed after preparation and after testing. After leaving a specimen in the temperature controlled room overnight, small cracks at the surface around the circumference were already observed. The total testing time for one sample was six hours, so some evaporation may have occurred during that time. This could alter the thermal conductivity close to the surface of the sample.

A further possible factor is that, at the shorter heating times, the contact resistance affects the results, or that the straight line section is too short to give an accurate gradient. It can be seen in Figure 5 that the calculated thermal conductivities at a heating time of 100 seconds deviate more from the mean value than for longer heating times. At longer heating times, boundary effects could also be influencing the results.

Figure 6 shows the variation of the average thermal conductivity of the twelve measurements with density. The thermal conductivity increases almost linearly with density, in agreement with previous research [3].

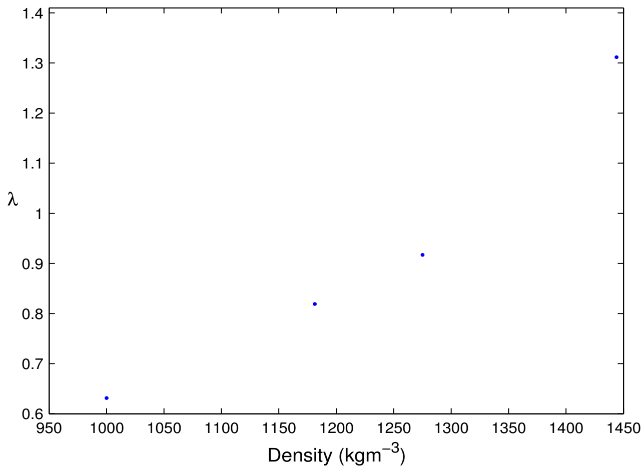

Figure 6. Average thermal conductivity against density.

CONCLUSIONS

A detailed method for calculating the thermal conductivity using the needle probe has been proposed. In contrast to previous methods which rely heavily on human judgment, this method has been fully programmed, to reduce the potential for user error. A visual inspection of the data should always still be carried out to check that a sensible result is obtained. This method was used in subsequent tests on agar-kaolin samples.

The repeatability of the needle probe method was found to be within ±2% for tests using the same heating power and heating time. When the heating power and heating time were varied, the range in results was significantly greater. Surface water evaporation may be a contributing factor. Contact resistance could affect tests with shorter heating times, and boundary conditions could affect tests with longer heating times. Even in a well-controlled environment these test variables have a significant impact on the results, so it is worth choosing the heating time and heating power carefully on the basis of the properties of the soil.

When using the needle probe method, it is advisable to use a program that excludes the data affected by contact resistance or boundary conditions, while using as much of the relevant data as possible to ensure an accurate calculation of the thermal conductivity.

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