A Dual-Probe Heat Pulse Approach using Heated Fiber-Optic Temperature Sensing

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Abstract. The distributed actively heated fiber-optic method is widely used to measure soil thermal conductivity and water content. However, the significant limitations of this technique are that prior soil specific calibration is required, and the measurement of soil volumetric heat capacity, a critical soil thermal parameter, is restricted. This study investigates a novel fiber-optic dual-probe heat pulse method, which utilizes fiber-optics to monitor the temperature response at a certain distance from the heat source to obtain the thermal conductivity and the volumetric heat capacity. Subsequently, the water content can be estimated from its linear relationship with soil volumetric heat capacity. The fiber-optic dual-probe heat pulse method is aimed to overcome the spatial-scale measurement limitations considering the distributed sensing capability of fiber-optic. This requires the sensor to be more robust than the traditional dual-probe method, hence a completely different ratio of the probe diameter to the distance between adjacent cables. Therefore, the applicability of the existing theory needs further verification, and the heating strategies need careful consideration. This study uses a 6 mm diameter fiber Bragg grating (FBG) sensor encapsulated by the alundum tube to conduct laboratory feasibility tests. Two adjacent sensors are fixed in the soil at a distance of 14.60 mm. Different heating powers (30 W/m, 40 W/m, and 50 W/m) and heating durations (10 s, 30 s, 50 s, and 120 s) are implemented. The results showed that the novel approach allows accurate soil volumetric heat capacity and water content estimation with appropriate heating strategies and data interpretation methods. The heating duration below 30 s is a poor fit because of the low-temperature rise, requiring a longer heating duration. For the 120 s heating duration, the measurement error in soil volumetric capacity is less than 2%. On the other hand, the instantaneous line heat source theory overestimates the soil volumetric heat capacity by 5%, while the short-duration line heat source theory performs well in the method.

1 Introduction

Soil thermal properties are used in geotechnical and geo-environmental applications: geothermal energy resources, radioactive waste disposal, and geological CO₂ sequestration. In cold regions, thermal properties are essential for understanding the engineering properties of frozen grounds. In addition, they are necessary for the estimation and simulation of the surface energy balance. These applications require measurements of thermal properties. Moreover, they can be used for indirect measurements of water content, dry density, soil evaporation, and water seepage [1].

There are three interrelated thermal properties: thermal conductivity, volumetric heat capacity, and thermal diffusivity. The heat pulse method is widely used in measuring these soil thermal properties because of its advantages in terms of measurement time and portability for laboratory and field
applications. This method has two categories: (1) the single probe heat pulse method, where the heater and temperature sensor are mounted in a stainless steel tube; (2) the dual-probe heat pulse (DPHP) method, with the heater and temperature sensors in separated needles. The single probe method has high accuracy in determining thermal conductivity, but the accuracy in determining the soil volumetric heat capacity is low [2]. The dual-probe method measures the temperature change at a certain distance from the heater, improving the precision of soil volumetric heat capacity measurement. It is also a possible way to estimate soil water content [3].

The heat pulse method is limited by the discrete measuring points and is only suitable for shallow soil layers. However, thermal properties and the depth in layer sediments are required in many geotechnical applications. Fiber-optic sensing offers an efficient solution to this problem because this technology allows distributed measurement along a fiber to obtain a continuous profile. In addition, it provides anti-electromagnetic interference and good corrosion resistance. Therefore, the actively heated fiber-optic (AHFO) method, with an aggregated heater and temperature sensing fiber in one cable, has been proposed to provide thermal conductivity and water content distribution on a large scale [4–6]. However, the AHFO method can only estimate the soil thermal conductivity without computing the soil volumetric heat capacity, which is used to directly calculate the soil water content. Hence, many calibration tests need to be conducted to establish the relationship between soil thermal conductivity and temperature characteristic value to evaluate the soil water content. Sayde et al. (2014) proposed a novel fiber-optic dual-probe heat pulse method (FO-DPHP) [7,8], which used fiber-optic to record the temperature response at a certain distance from the heat source to obtain thermal conductivity and soil volumetric heat capacity. This method takes advantage of the distributed sensing capability of fiber-optics to achieve in situ spatial-scale measurements. Hence, robust sensors and a larger probe spacing are required than those used in the traditional dual-probe method. In addition, the heating methods and their theoretical applicability for the FO-DPHP methods need further research.

In this study, laboratory tests were conducted to investigate the feasibility of the FO-DPHP method. Furthermore, the effect of heating strategies was studied to guide future applications in this field. In addition, the applicability of the different analytical theories in the FO-DPHP method was discussed.

2 Theory
The DPHP method monitors the temperature change at a distance away from the heater. G.S Campbell (1991) [3] developed the DPHP sensor and used a new data interpretation method based on the instantaneous line heat source (ILHS) theory:

$$T(r,t) = \frac{Q}{4\pi kC_v}\exp(-\frac{r^2}{4kt})$$ (1)

where $T$ is temperature rise (K), $r$ is the radial distance from the line heat source (m), $t$ is time (s), $Q$ is the heating power per unit length (W/m), $k$ is the thermal diffusivity of the medium surrounding the heater (m$^2$/s), and $C_v$ is the soil volumetric heat capacity (J/(m$^3$·K)).

By taking the derivative of equation (1) with respect to time, $k$ and $C_v$ can be determined by:

$$C_v = \frac{Q}{enr^2\Delta T_m}$$ (2)

$$k = \frac{r^2}{4t_m}$$ (3)

where $\Delta T_m$ is the maximum temperature change at a distance $r$ from the line heat source, $t_m$ is the time corresponding to the $\Delta T_m$, $\lambda$ is the soil thermal conductivity (W/(m·K)).

This ILHS solution-based method assumes instantaneous release of heat to an infinite porous medium. However, it is not possible to heat the line source instantaneously, so the short-duration line heat source (SLHS) theory was applied [9]:

$$f(t) = \frac{Q}{\sqrt{(\pi kHz)^2}}\exp\left(-\frac{(r-x)^2}{(kHz)^2}\right)$$
\[ T(r,t) = \begin{cases} \frac{Q}{4\pi kC_v} E_i\left(\frac{r^2}{4kt}\right) \\ \frac{Q}{4\pi kC_v} \left[\left(E_i\left(\frac{r^2}{4kt}\right) - E_i\left(\frac{r^2}{4k(t-t_0)}\right)\right)\right] \end{cases} \]

where \( t_0 \) is the heating duration (s), \( E_i(x)=\int_x^\infty \frac{\exp(-n)}{n} dn \), and \( n \) is a variable of integration.

The formula derived are:

\[ k = \frac{r^2}{4} \left\{ \frac{1}{(t_m-t_0)} - \frac{1}{t_m} \right\} \ln\left[\frac{t_m}{(t_m-t_0)}\right] \]

\[ C_v = \frac{Q}{\varepsilon \pi r^2 \Delta T_m \left[1 - \varepsilon + \left(\varepsilon^2 / 48\right)\right]} \]

\[ \varepsilon = \frac{t_0}{t_m} \]

Therefore, the thermal conductivity (\( \lambda \)) can be estimated from:

\[ \lambda = C_v \cdot k \]

### 3 Materials and methods

The fiber-optic dual-probe consists of two fibers Bragg grating (FBG) encapsulated in the alundum tubes with a diameter of 6 mm and a length of 120 mm to form two FBG sensors. The distance between the two FBG sensors is 14.6 mm. The test configuration is shown in figure 1(a). The test apparatus comprises five components: a soil box, two FBG sensors, a heating module, an FBG interrogator, and a computer for data collection.

Silty soil with certain water content was prepared previously and then stood for 24 hours to ensure uniform water distribution. The final water content was obtained by the oven-dry method. Then, the soil was filled into a 200 mm × 150 mm × 200 mm acrylic box layer-wise. The dry bulk density was carefully controlled to 1.4 Mg/m³. The thermal properties were determined using the steady-state plate method and the differential thermal analysis. The basic properties of the soil are shown in table 1.

When half of the box was filled, the sensors were inserted into the box. The heating sensor was placed in the middle of the box, and the temperature sensor at 14.6 mm away from the heating sensor in parallel. The probe spacing is shown in figure 1(b), with a pen cap used as a reference.

A heating module was connected to the heater to provide a stable current. The FBG interrogator (model NZS-FBG-A01, Nanzee Sensing, Suzhou, China) has a temperature accuracy of 0.1 °C and a sampling interval of 1 s. Both the heater and the temperature sensor were connected to the interrogator to record temperature change.

In the test, heating with different powers (30 W/m, 40 W/m, and 50 W/m) and times (10 s, 30 s, 50 s, and 120 s) are performed, totaling 12 heating tests. Each heating is followed by four hours of cooling.

| Soil type | Water content (%) | Dry density (Mg/m³) | \( C_v \) (MJ/(m³·K)) | \( \lambda \) (W/(m·K)) |
|-----------|------------------|---------------------|------------------------|------------------------|
| Silty     | 7.6              | 1.4                 | 1.79                   | 0.942                  |
4 Results and discussion

The temperature rise in the two sensors at 40 W/m and 120 s is presented in figure 2. The temperature of the heating sensor increased sharply, but the sensor away from the heater lagged in recording the temperature change. Thus, defining the maximum temperature value while extracting the peak value of time poses challenges. Similar results were reported by Bristow et al. (1994), who investigated the effect of the probe spacing in the traditional DPHP method. They found it challenging to ascertain the peak value at the larger spacing by simply inspecting the raw data. Therefore, lows smoothing was applied in this study to reduce the data noise.

Figure 1. Test device: (a) photograph of the laboratory tests; (b) photograph of the probe spacing.

Figure 2. The measured temperature rise of the dual fiber-optic probe in 40 W–120 s.
Table 2 The peak value of the temperature sensor using different heating methods.

| t (s) | 30 W/m | 40 W/m | 50 W/m |
|-------|--------|--------|--------|
|       | $\Delta T_m$ (°C) | $t_m$ (s) | $\Delta T_m$ (°C) | $t_m$ (s) | $\Delta T_m$ (°C) | $t_m$ (s) |
| 10    | 0.19   | 159    | 0.09   | 40     | 0.19   | 157    |
| 30    | 0.28   | 150    | 0.48   | 157    | 0.57   | 160    |
| 50    | 0.48   | 173    | 0.68   | 171    | 0.76   | 175    |
| 120   | 1.06   | 220    | 1.43   | 232    | 1.27   | 211    |

The peak values ($\Delta T_m, t_m$) obtained using different heating strategies are shown in table 2. The $C_v$ is calculated based on equation (6). As shown in figure 3, heating power and time have significant effects on the measurement results. Errors were observed in 10 s and 30 s heating durations. The main reason is that the temperature rise under 0.5 °C is not exactly reliable, limited by the temperature measurement accuracy of the interrogator. For the 50 s heating duration, the accuracy increases with the heating power. Therefore, 50 W/m–50 s heating method has a good performance, but 30 W/m–50 s and 40 W/m–50 s heating methods led to a 10% and 4% underestimation of the soil volumetric heat capacity, respectively. For all the heating powers, when heating duration is 120 s, the results obtained agree well with the value obtained by the differential scanning calorimetry. The measurement error is less than 2%, corresponding to the 1% volumetric water content accuracy. This indicates that the precision in the determination of $C_v$ depends on the temperature increment value. Therefore, the heating power and time should be matched to attain a relatively high-temperature rise to reduce the noise induced by temperature measurement. Compared with the traditional DPHP method, higher heating time, and power are required because of the large probe diameter and probe space. Given that the distributed measurement limits the amount of power supplied, a long heating time must be employed. Therefore, the 30 W/m–120 s heating method is recommended in this study. It is noteworthy that a long duration of heating possibly would cause water migration in soil samples with high water content.

The thermal conductivity was calculated by equations (5)–(8). Figure 4 shows that only 50 W/m and 120 s heating gave accurate $\lambda$ values, while other heating methods severely underestimated it except for 40 W/m–10 s that gave abnormal data. Besides the reason related to temperature measurement accuracy mentioned above, the main reason for this phenomenon is that the thermal conductivity is more sensitive to the $t_m$, such that a small deviation in $t_m$ causes a rather significant error. In addition, the large probe diameter causes a delay in temperature response, which increases the $t_m$. Hence, the method for defining the $t_m$ should be improved using the nonlinear model. Furthermore,
the model accounting for probe radius and heat capacity can be employed to enhance the precision in determining thermal conductivity.

The \( C_v \) values calculated based on the ILHS and SLHS theory are compared in figure 5. In the traditional dual-probe method, Kluitenberg et al. (1993) [10] concluded that the heat capacities calculated by equation (2) are slightly higher but within 1% of those calculated by equation (6) based on the SLHS method. However, in the FO-DPHP method, the ILHS theory overestimated the \( C_v \) by 5% for the 120 s heating duration. This is because the heating time used in this method is so long that the assumption of an instantaneous heat release is invalid. Therefore, it can be concluded that the SLHS theory performs better in the FO-DPHP method than the ILHS theory.

5 Summary

Laboratory tests with different heating strategies were conducted to investigate the feasibility of the novel FO-DPHP method. The measurement accuracy of the soil volumetric heat capacity was studied to find the optimum heating strategy. In addition, the applicability of the ILHS and SLHS theory in the FO-DPHP method was compared. The following conclusions are drawn:

1. The FO-DPHP method can measure the soil volumetric capacity accurately with a suitable heating power and duration.
(2) A longer heating duration in the FO-DPHP method is required than the traditional methods because of the large probe space. When the heating lasts for 120 s, the error in the determination of $C_v$ is less than 2% for all heating powers used. In addition, the 30 W/m$^{-1}$–120 s is recommended as the optimum heating strategy.

(3) The volumetric heat capacity calculated based on SLHS theory has higher accuracy than that of the ILHS theory.

(4) The measurement accuracy of the thermal conductivity should be improved using better methods to precisely record the $t_m$.

In conclusion, the FO-DPHP has a huge potential for distributed measurement of thermal properties and water content in geotechnical applications. However, the field application of this method needs further study to verify the heating strategy proposed in this study. In addition, maintaining the accurate distance between the two sensors in field distributed measurement is a possible direction for future studies.

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