Experimental Study of the Thermal Conductivity of Sand Soils of Different Dry Densities and Water Contents with the Needle Probe Method

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Keywords: Soil Thermal Conductivity, Needle Probe, Dry density, Water Content.

Abstract. In this study, the thermal conductivity of formulated sand specimens was tested in laboratory with the needle probe method. The measurements represented that the thermal conductivity of sand soil increases corresponding increase of the dry density and water content. Based on the experimental measurement, an empirical equation has been proposed to characterise the relationship between the thermal conductivity and the dry density and water content. It has shown a good performance.

Introduction

Owing to global warming and fossil-fuel depletion, ground thermal energy is increasingly used as a sustainable resource in recent decades. Ground Source Heat Pump (GSHP) systems, which fitted to ground thermal energy use, have raised increasing interest in the efforts for sustainable energy resources \cite{1, 3}. Thermal conductivity, which is important for many thermo-active underground engineering areas \cite{4, 5} such as underground building \cite{6}, pipeline \cite{7, 8}, cable \cite{9, 10}, and transportation projects \cite{11}, has become a key parameter for design and operation of the GSHP systems. The property of soil thermal conductivity is also essential in the numerical modelling and analysis of the coupled hydro-thermal subsurface processes \cite{12, 13}. Many factors influence the thermal conductivity of soils, such as the soil type, organic components, particle size distribution, density and compaction, moisture and water content, and the dynamic state of the pore moisture and pore water \cite{14, 17}. Tang et al. \cite{18} studied the thermal conductivity of compacted bentonite of varied dry density, water content and saturation. Abuel-Naga et al. \cite{19} showed that the thermal conductivity increases with soil density. O’Donnell et al. \cite{20} studied the relation between thermal conductivity and moisture of soil.

In practice, measuring the soil thermal conductivity of laboratory methods are classified into two approaches. There are steady state and transient method. The steady state method on a specimen is based on the Fourier’s Law by applying a one-directional heat flow. The transient method is based on the heat diffusion equation by applying a constant heat source to the specimen. There is a constant temperature gradient between the two surfaces of the specimen while a steady state is arrived in the testing of steady method, and a temperature change at a specific location over a period of testing time in the transient method. The main disadvantage of the steady state method is the potential heat loss of the experimental cell to the surrounding environment, which will affect the accuracy of the measurement \cite{21, 22}. So the needle probe method \cite{23}, a transient method, was chosen for experiment of formulated sand specimen.

In this paper, the effect of the dry density and water content on the thermal conductivity of a sandy soil was tested on the specimen of formulated sand. Furthermore, based on the experimental results, an empirical formula was presented.
Methodology

The needle probe method of measuring thermal conductivity has three assumptions, i.e.:

1. The needle probe is sufficiently long to simulate a 1D heat transfer, its length to diameter ratio (l/d) is normally greater than 50;
2. Supplied with a constant power, the probe acts as a stable heat source;
3. The thermal resistance at the interface between the soil specimen and the probe is neglected.

Based on three assumptions, the thermal conductivity can be calculated in accordance to the temperature rise $\Delta T$ at time $t$ after the start of heating, at a radial distance $r$ from the heat source according to the following procedure [21, 23].

\[
\Delta T = \frac{q}{4\pi\lambda} E_i \left( \frac{r^2}{4a\tau} \right)
\]

(1)

Where, $\tau$ is the heating time (s), $q$ is the unit length heating power (W/m), $\lambda$ is the thermal conductivity (W/m·k), $a$ is the thermal diffusivity (m$^2$/s), $r$ is the distance to the probe heat source, $E_i$ is the exponential integral. Then the thermal conductivity can be simplified as following Eq. (2):

\[
\lambda = \frac{q d \ln \tau}{4\pi d T}
\]

(2)

Experiment

Setup

Figure 1 depicts the instrument of the needle probe used in this experimental study. The technical parameters of needle probe are listed below. The length (l) and diameter (d) are 167mm, 2mm separately, and l/d is 83.5 which is satisfied l/d should greater than 50. The electrical resistance of heating wire is 22.46 $\Omega$/m. The thermocouple is T-type and the accuracy is ±0.1℃. The temperatures are collected by UT325 that is no compensation at the cool end.

![Figure 1. The needle probe.](image)

Before the test, the needle probe was calibrated with Glycerol ($C_3H_8O_3$) of 99% purity [24].

Materials

The soil specimens were prepared using the sand from a construction site in the Taiyuan city, Shanxi province in China. Firstly, the sands were heated and sieved in laboratory. Then, the sand used for the test was made from different particular particle sizes following a reference (GB 50027-2001) [25].
The particle size distribution is showed in Fig. 2. Afterward, the dry sand was added with water to form four different water contents (5%, 10%, 15% and 20%) corresponding to the dry sand weight. The formulated sands then were put in airtight containers for 24 hours without any disturb to achieve a stable water distribution situation. After 24 hours, the sand of 20% water content on top surface was found to have a water film which suggested a sign of over saturated. So the sand of the 20% water content was discarded in consideration of the potential inaccuracy due to the over saturation. At last, the 5%, 10%, and 15% of water content sands were put into a stainless container of the size of 150×150×200 for width by depth by height and compacted to obtain different dry densities \( \rho_d \). Five measurements were taken for each specimen at five different locations. The final result took the average of the five measurements.

**Results and Discussion**

Figure 3 shows the measured thermal conductivity of different dry densities for the specimens of 0%, 5%, 10% and 15% water contents, respectively. The plot of the result presents at 0% water content that the dry density has a very small influence on the thermal conductivity. This implied that the air content in soils has no significant effect on the thermal conductivity. With the increase of the water content, the thermal conductivity increases. For the water content of 5% and 10%, with the increase of the dry density, the pore size will be decrease correspondingly. The capillary condensation effect will increase. The thermal conductivity has a relatively quick increase with the increase of the dry density. In the 15% water content, the thermal conductivity increase with the increase of dry density in an almost straight line which can be explained that there may not have the variation of the capillary condensed water, the decrease of the air content with the increase of the dry density is the key effect factor.

![Figure 2. The Particle Size Distribution of the Sand Used.](image)

![Figure 3. The Thermal Conductivity vs Dry Densities at Different Water Contents.](image)
Figure 4 shows the variation of the thermal conductivity against the water content at different dry density. The thermal conductivity increases in a linear trend with the water content increase from 0 to a specific content. After the specific point, the thermal conductivity has no significant change anymore. The initial linear increase of thermal conductivity with the water content increase from 0% can be explained that the initial water forms the water film coating on pore surface which has a constant surface area, and the water content increase corresponds to the water film thickness increase which presents a linear relationship with the thermal conductivity. When the water increases to certain content, more bulk of pore water occupies the pore volume space due to the capillary condensation. So the water volume to the pore surface area ratio decreases, and, as a result, the increase rate of the thermal conductivity decreases. Theoretically, the thermal conductivity reaches a constant when soil becomes fully saturated.

![Figure 4. The Thermal Conductivity vs Water Contents at Different Dry Densities.](image)

Figure 5 shows the thermal conductivity occurring with the pore water saturation at different dry densities. It indicates a similar trend as that of the Fig. 5. In Fig. 5 in the case of $\rho_d = 1.305\text{g/cm}^3$ and $\rho_d = 1.42\text{g/cm}^3$, the thermal conductivity can reach a maximum value in the range of $S = 25$–$40\%$, which demonstrates that there are dead locked pore spaces which are not accessible to the water.

![Figure 5. The Thermal Conductivity vs Water Saturation at Different Dry Densities.](image)

Figure 6 shows a 2D contour map of the measured thermal conductivity against to the dry density and water content. It shows that there is a low thermal conductivity at the parts of dry soil and a low dry density. With the increase of water content and dry density, the corresponding thermal conductivity
conductivity increases. For quantifying description relationship of thermal conductivity with water content and dry density, the Eq. 3 was presented in this paper.

\[ \lambda = a_1 \omega^{b_1} + a_2 \rho_d^{b_2} + a_3 \omega^{c_1} \rho_d^{c_3} \]  
(3)

Where, \( \omega \) is the water content and \( \rho_d \) is the dry density. Figure 8 shows the result using the Eq. (3) to fit the measured result in the space of \( \lambda - \omega - \rho_d \).

According to the experimental data, using MATLAB calculate the coefficients of Eq.3, hence the Eq.3 become:

\[ \lambda = 0.0039\omega^2 + 0.126\rho_d^2 + 0.088\omega \rho_d \]  
(4)

And the correlation coefficient is 0.99, which illustrates that the model fits the data very well.

Figure 6. The Influence of Dry Densities and Water Contents on the Thermal Conductivity.  
Figure 7. The Modelling Result using Eq. (4) to fit the Measurements.

Conclusions
In this study, the thermal conductivity with different water contents and dry densities was investigated. The following conclusions were drawn.

(1) At a certain water content, the thermal conductivity of sand soil increases with increase of the dry density; and at a certain dry density, the thermal conductivity of sand soil increases as well with the water content. That is due to the decrease of the air content.
(2) Capillary condensation has a significant influence on the thermal conductivity at the low water content and large dry density with small pore sizes, because the capillary condensation will affect the water volume to pore surface area ratio.

(3) An empirical equation has been presented to characterize the dependence of the thermal conductivity on the dry density and water content. It has shown a good performance.

Acknowledgement
This study was funded by the National Natural Science Foundation of China (No. 41372247) and Shanxi Scholarship Council of China (No. 2017-045).

References


