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Investigation on thermal characteristics and prediction models of soils

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ABSTRACT

This paper presents details of a study that deals with evaluation of thermal characteristics of soils across a range of soil types and saturation levels. Investigations were carried out with respect to the effect of moisture content, dry density, degree of saturation, particle size, and mineralogy composition on thermal resistivity of the soils. In addition, the prediction models developed by previous researchers for estimating the thermal conductivity of various soils at unfrozen state were reviewed and evaluated. The study reveals that the moisture content, dry density, and mineralogy composition have a considerable influence on the thermal resistivity of a soil. The critical moisture content is an important index to characterize the rates of change in thermal resistivity with increasing moisture content. An exponential decrease in thermal resistivity with degree of saturation is observed for fine-grained soils, whereas a linear correlation between thermal resistivity and dry density is shown for soils regardless of the moisture contents. The differences in thermal resistivity of samples with the same dry density are mainly attributed to variations of mineralogy composition. Based on the concept of normalized thermal conductivity, a simple step by step method to calculate the thermal conductivity is proposed and the empirical soil parameters for fine-grained soils in different areas are also presented. It has been demonstrated that the normalized thermal conductivity is able to correlate the actual thermal conductivity with thermophysical parameters of the soils (viz., moisture content, degree of saturation, porosity, and thermal conductivity of solid particles). The accuracy of the prediction method can be improved by employing the empirical parameters to fit the experimental data.

1. Introduction

Under the background of sustainable development, thermally active engineering projects, such as energy piles, geothermal energy foundations, and heat exchange systems are of great concern to Chinese professionals and planners due to the potential use as an aid in tackling energy shortage and greenhouse gas emissions [30,29,10,3,23,43]. The working performance of these projects is mostly dependent on the heat transfer behaviours of the soils and rocks where they are embedded in or built on. Consequently, the knowledge of thermal properties of various soils is required for engineering design. Thermal conductivity is one of the most important parameters in heat transfer analyses among the various thermal properties. It is well known that the thermal conductivity of a soil is strongly affected by its density, porosity, moisture content, degree of saturation, mineralogy composition, and temperature [28,11,2,24,39,25]. Therefore, it is difficult to evaluate the thermal characteristics of soils and to estimate the value of thermal conductivity or resistivity by indirect methods.

In the last number of decades, a considerable number of studies have been conducted to quantify the effects of these influencing factors on the thermal conductivity of the soils. The thermal characteristics of the soils in Nanjing (China) and Melbourne (Australia) have been investigated by Cai et al. [13] and Barry-Macaulay et al. [7], respectively. These studies indicate that the moisture content, dry density, and mineralogy composition have significant effects on the value of thermal resistivity or conductivity of soils. Moreover, the effects of ice, frozen and unfrozen state, and organic content have also been investigated by previous researchers [36,31,6,42]. The results demonstrate that the complex external environment and internal texture could result in a considerable change in thermal conductivity of a soil. As so many factors controlling the heat transfer in porous geomaterials, a lot of

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relationships have been developed to predict the thermal conductivity of soils [37,41,21,1,14,20,38]. As reported in the literature, these prediction models can be classified into two types: (1) empirical models, which are derived from experimental test data analysis and (2) theoretical models, which simplify the structure of soils to get a mathematical relationship. Empirical models were proposed to fit experimental data for moist soils [9,18,16]. Theoretical models were usually employed to calculate the thermal conductivity of solid particles and dry soils. It is a fact that for most natural deposit of fine-grained soils, the process of weathering, transport, and mixing during the soil formation will make the determination of thermal conductivity of soil particles difficult. Moreover, most theoretical models need to rely on the empirical parameters, which making them semi-empirical models. Therefore, one should consider using empirical models to estimate the thermal conductivity of soils, especially for fine-grained soils. These proposed models provide estimates of the thermal conductivity of soils by using basic engineering property indexes, which can be easily obtained, compared to the measurements of thermal conductivity. Johansen [21] firstly proposed the concept of normalized thermal conductivity and gave the best agreement with experimental data for sands and fine-grained soils available in the literature. However, Farouki [17] have evaluated some commonly used prediction models for thermal conductivity of soils. It is indicated that any of the evaluated models give the satisfactory results for fine-grained soils and coarse-grained sands across a range of dry densities and saturation levels. Johansen's model also failed to give the most accurate prediction results for coarse-grained sands with a lower saturation level. Besides, studies on the thermal characteristics of soils in various areas and the independent assessment of the prediction models have been noticed quite limited.

This paper presents details of investigation on thermal characteristics and prediction models of various soils. The experimental thermal resistivity data from more than 200 tests reported in the literature was systematically analyzed. The effects of moisture content, dry density, degree of saturation, particle size, and mineralogy on thermal resistivity were studied. In addition, the prediction models for estimating the thermal conductivity of dried, saturated, and unsaturated soils were summarized. The concept of normalized thermal conductivity proposed by Johansen [21] was also employed to estimate the thermal conductivity of soils across a range of soil types. Based on these results, an effort has been made to provide a new step by step method for predicting thermal conductivity of soils at unfrozen state. Hence, the influences relating to ice and organic matter have not been included in this paper. The modified empirical parameters for soils in different areas were proposed in this study to improve the accuracy of the prediction model. It is believed that such investigations would be quite useful to understand the heat transfer mechanism of soils and facilitate the engineers to obtain more accurate thermal design parameters.

2. Data base

Experimental thermal resistivity data from nearly 200 tests on dozens different soil types from studies undertaken by Kersten [22], Horai [19], Gangadhara Rao and Singh [18], Côté and Konrad [14,15], Barry-Macaulay et al. [7] and Cai et al. [13] were used to investigate the thermal conductivity characteristics and prediction models of the soils. The thermal resistivity r of these soils was all measured at room temperature (approximately 20 ± 3°) across a wide range of dry densities and moisture contents by resort to different testing techniques. Detailed information of the soil types and particle size distribution are summarized for most soils in Table 1.

There are many types of equipment employed to measure the thermal resistivity of geomaterials in the laboratory. However, these laboratory test equipments generally can be devided into two categories: thermal needle probe and divided hot plate apparatus, for soil samples and rock samples, respectively. The thermal resistivity tests of soils reported by Barry-Macaulay [7], Gangadhara Rao and Singh [18], and Cai et al. [13] were undertaken using a commercially available non-steady-state thermal needle probe. Fig. 1(a) shows schematic diagram of thermal needle probe employed to test the soil thermal resistivity. The technique of thermal needle probe is based on the principle of linear heat transfer. When the probe inserted into the soil sample, the heating wire installed on the probe represents a perfect line source and the temperature changes were monitored by the sensor. After the thermal equilibrium was reached, the thermal conductivity of soil sample was determined using the following equation:

$$k = \left(\frac{Q}{4\pi\Delta T}\right)\ln\left(\frac{t_2}{t_1}\right) \tag{1}$$

where k (W/mK) is the thermal conductivity of soil sample, which is the reciprocal of thermal resistivity r; Q (W/m^2) represents the heat flux; and ΔT (K) is the temperature gradient between the measurement at time t_1 and t_2. In previous studies, the time interval between the t_1 and t_2 is typically 150 s. The thermal needle probe needs to be calibrated prior to testing using glycerol supplied by manufacturer. The standard deviation of test results is less than 0.1, if the deviation is greater than the requirements, testing equipment shall be checked and measured again. Three measurements were generally performed for each identical sample, which took approximately 15 min apart. The temperature for each sample was recorded by heat sensor and its value ranged between 20° and 25°. For rock samples, it is impractical to insert a needle into them. Therefore, another thermal resistivity test technique needs to be developed. Fig. 1(b) represents schematic diagram of divided hot plate apparatus used to measure thermal resistivity of rock samples in previous studies. Two temperature controlled plates at the top and bottom of the cell are arranged on the sample. The bottom plate contains an electric heater which could generate a heat source of constant temperature. At the same time, cool water is circulated through the top plate from a temperature controlled water tank. Four heat flux sensors are positioned both top and bottom sides of the sample to monitor the heat flux flowing through the rock and calculate the temperature gradient across the sample during the test. When the rock sample reached the thermal equilibrium, the thermal conductivity can be calculated using Fourier's law of heat conduction as follows:

$$k = \frac{Q}{\Delta T/L} \tag{2}$$

where k (W/mK) is the thermal conductivity of rock sample; L is the height of sample; and Q, ΔT are the same with Eq. (1). The contact pressure (of approximately 2 kPa) was applied on the plate to ensure that good contact was obtained and minimise the contact resistance errors between sample and heat sensors. The polyethylene foam was installed around the rock sample to minimise any radial heat losses. Heat losses during test were monitored by taking heat flux measurements at both the top and bottom of the sample. The minimal heat loss occurring across the sample should be obtained according to the heat flux measurements.

3. Thermal characteristics of soils

The thermal resistivity of various types of soil was measured across a range of moisture contents and dry densities. Soil samples were prepared by static compaction for thermal resistivity testing.