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Variation of the thermal conductivity of a silty clay during a freezing-thawing process

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ABSTRACT

The thermal conductivity of soils is a key factor in calculating soil heat transfer and analyzing temperature fields of geotechnical engineering in cold regions. We measured the thermal conductivity of a silty clay by a QuickLine-30 Thermal Properties Analyzer during a freezing-thawing process, and analyzed the variation of the thermal conductivity. We then calculated the thermal conductivity under the same experimental conditions using the three general models, i.e. weighted arithmetic mean model, weighted harmonic mean model, and weighted geometric mean model. The results show that for the thawed or frozen soils with little variation of unfrozen water content, the thermal conductivity is slightly influenced by temperature; however, for the soils in the major phase transition zone, the variation of the thermal conductivity with temperature is significant. After a freezing-thawing process, the thermal conductivities of the soils with higher initial dry densities become smaller, while those with lower initial dry densities become larger. We also found that the variation of porosity and hysteresis effect of unfrozen water content cause the difference of the thermal conductivity of soils between freezing and thawing processes, however the variation of porosity acts as the primary role. Furthermore, the three general models can all be used to calculate the thermal conductivity of soils; however, the weighted geometric mean model agrees best with the experimental data.

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1. Introduction

Properties of soils, such as thermal conductivity, significantly influence the thermal regimes of geological formations and geotechnical constructions in cold regions [1]. The thermal conductivity of soils is a key factor in thermal analyses of civil engineering infrastructures [2]. Also, it helps to determine the heat transfer rate and the freezing-thawing depth in predicting the thermal stability of cold regions engineering [3]. At present, engineering constructions in cold regions have greatly increased, and those engineering activities strongly influence the heat transfer in soils, and eventually change the thermal balance and the temperature fields [4–6]. Therefore, it is very necessary to study the characteristics of the thermal conductivity of soils for the cold regions engineering.

Measurements and theoretical models of the thermal conductivity have been researched. Xu et al. [3] tested the thermal conductivity of soils in freezing and thawing states, and found the relationships between the thermal conductivity and various influence factors. Tao and Zhang [7] analyzed the thermal conductivity of thawed and frozen soils with high water contents for engineering application via the comparative method. Goodrich [8] measured the thermal conductivity of active layer soils using a transient probe method. Smits et al. [9] measured the thermal conductivity of sands under varying moisture and porosity in drainage-wetting cycles. Li and Liang [10] applied a single-sided transient plane source (TPS) technique to determine the thermal conductivity of hydrate-bearing sand. In addition, many thermal conductivity models were developed to evaluate the thermal conductivity of media. Cheng and Vachon [11] developed a theoretical technique to model the thermal conductivity of heterogeneous solid mixtures by introducing a function of the discontinuous phase volume fraction. Overduin et al. [12] presented an improved technique model for heat flow around a linear heat source, and demonstrated the use of this model in the laboratory and field measurements at temperatures close to phase change in freezing

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and thawing soils. Recently, Gangadhara Rao and Singh [13] established a new relationship to predict the thermal conductivity of soils, but the grain structure and mineral content were not taken into account. Côté and Konrad [14] developed a new thermal conductivity model to assess the effect of structure on the thermal conductivity of two-phase porous geomaterials. Liu et al. [15] established a simple model that allowed the estimation of the thermal conductivity of soils from the porosity and saturation degree. Latter, Braginsky et al. [16] developed a model which permitted regular power-series expansion of the thermal conductivity expression as a function of porosity, and the coefficient of the expression could be calculated from the microscopy image of the structure. Pei et al. [4] established a multiple linear regression model including parameters such as porosity, dry density, water content and saturation degree to evaluate the thermal conductivity of rock-soil media. Based on the random mixed media theory and on the steady heat conduction equation, Zhang et al. [17] and Tan et al. [18] developed the randomly mixed model (RMM) to calculate the thermal conductivity of the multi-phase geomaterials. Orakoglu et al. [19] applied a statistical-physical model, in which the thermal conductivity is a function of each solid component volume fraction, water content, freeze-thaw processes and temperature, to evaluate the thermal characteristics of the fiber-reinforced soil samples. Similarly, Usowicz et al. [20] developed a non-linear regression model based on a statistical-physical method using the parameters of water content, dry density, organic matter, and content of minerals. Besides, a generalized normalized thermal conductivity model [21,22] and BP neural network technique model [23] were used in evaluation of the thermal conductivity of soils.

Some research have shown that freezing-thawing processes could cause the variations of the structures and mechanical properties of soils, and then the densities of loose and dense soils were changed in opposite ways [24–26]. Therefore, in cold regions, as the seasons alternating, the freezing-thawing processes are bound to influence the thermal conductivity of soils. At the same time, the hysteresis effect of volumetric unfrozen water content between the freezing and thawing processes affects the thermal conductivity of soils. However, the thermal conductivity is a key parameter in determining the numerical results in the heat transfer simulation of soils. Therefore, to increase the accuracy of numerical simulation, we study the variation of the thermal conductivity of soils during a freezing-thawing process. By considering the effect of a freezing-thawing process, we evaluate the three general thermal conductivity models, i.e. weighted arithmetic mean model, weighted harmonic mean model, and weighted geometric mean model.

2. Experimental apparatus and method

2.1. Experimental apparatus

In this study, a QuickLine-30 Thermal Properties Analyzer (Fig. 1) was used to test the thermal conductivity of soils, and the experimental apparatus was based on the transient hot-wire method [27].

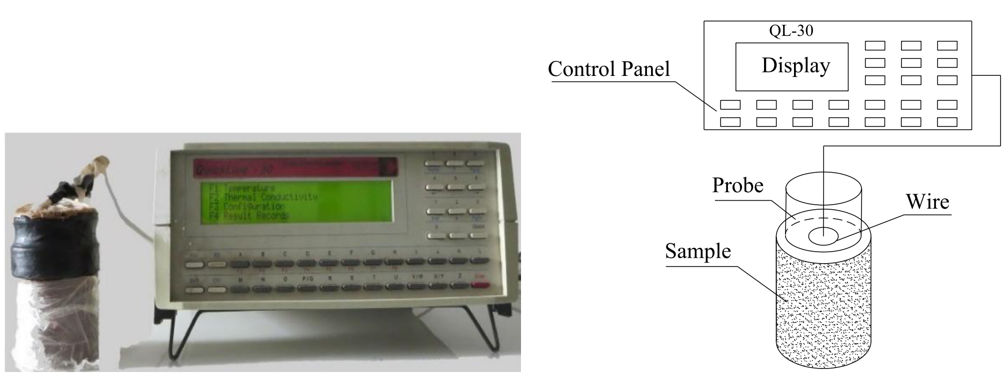
For a soil sample with a initial temperature (T_0), according to the thermal equilibrium equation, when heat flow starts at the top of the sample $y = 0$ and $t > 0$, the distribution of temperature within the soil sample will depend only on the heat transfer distance y and the time t. Thus, it can be considered as a 1-D problem [27], and its transient equation can be expressed as:

$$T(t) - T_0 = \frac{q}{4\pi\lambda}\ln\left(\frac{4K}{a^2c}t\right) \tag{1}$$

where $T(t)$ is the temperature of the wire at time t; T_0 is the initial temperature of the wire; $q = I^2R/A$, is the heat flux, where I is the heating current, R and A are the resistance and area of the plane heat source, respectively; λ is the thermal conductivity; K is the thermal diffusivity; a is the radius of wire; and $\ln c = v$, where v is Euler's constant.

2.2. Experimental method

The silty clay was obtained from the soil from the Qinghai-Tibet Plateau in the experiment, through series of disposition processes, i.e. washed with distilled deionized water, dried, crushed, and sieved over 2 mm in the laboratory. The grain-size distribution of the silty clay is shown in Fig. 2, and its liquid and plastic limits are 31.87% and 17.44%, respectively. Because the natural dry density of the soil from the Qinghai-Tibet Plateau is about 1.62×10^3 kg/m^3, two kinds of dry densities, i.e. 1.75×10^3 kg/m^3 (the maximum dry density) and 1.50×10^3 kg/m^3, were chosen to evaluate the effect of dry densities on the thermal conductivity of soils in this study. The initial water content is another important factor to determine the thermal conductivity of soils; therefore, the silty clay was mixed with the distilled deionized water to the desired water contents. Here, eight column soil samples with different initial dry densities and initial water contents (Table 1) were prepared with the diameter of 63 mm and the height of 72 mm. In order to research the effect of freezing and thawing processes on the thermal conductivity of soils, the experiments were divided into two processes, i.e. cooling process and warming process. The circumstance temperature was changed step by step during a



(a) Photo (b) Schematic diagram

Fig. 1. Experiment apparatus for thermal conductivity.

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