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Technical Note

Estimation methods for thermal conductivity of sandy soil with electrical characteristics

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Abstract

This study estimates the water dependence of the thermal conductivity of soils and proposes a new thermal conductivity model and empirical equation for soil. Thermal conductivity tests for three different soil types were conducted under different moisture contents using the thermal probe method. Electrical conductivity tests were also performed to obtain the electrical resistibilities of the soils, and the influence of the moisture content on thermal conductivity was examined using the electrical conductivity data. The results show that the water dependence of thermal conductivity strongly correlates to the electrical resistibility. The relationships between the moisture contents and the thermal conductivities of the three soil types are found to be nonlinear, with an inflection point in each relationship. The moisture contents corresponding to these inflection points approximately agree with each other. The provision of a current flow largely along the pore water indicates that the thermal conductivity of a soil depends on whether or not the pore water, which significantly contributes to heat conduction, is continuous. The presence of pore water in soils can explain the water dependence of thermal conductivity. This study further proposes a model to estimate the thermal conductivity of soil and an empirical equation based on electrical conductivity test results.

Keywords: Thermal conductivity; Thermal property; Thermal probe method; Electrical resistibility; Saturated-unsaturated soil (IGC: D08)

1. Introduction

The freeze–thaw action is the key triggering factor in many geotechnical disasters in cold regions during both winter and spring. Estimations of the temperature distribution underneath soil layers and the frost-penetration depth, in consideration of the thermal conductivities of soils, are critical for the prevention of such disasters. In the last few decades, a number of experimental and theoretical approaches have been proposed for the measurement of thermal conductivity. The thermal probe method was widely used in the 1950s (De Vries, 1952; Hopper and Chang, 1953) to measure the thermal conductivity of soils after its development in the 1940s (Kersten, 1952; De Vries and Peck, 1958). Kasubuchi (1977) subsequently developed a twin-thermal probe method as an improvement over the original method. Many empirical equations and theoretical models have also been proposed as alternatives to the experimental determination of thermal conductivity. Kersten (1949) proposed an empirical equation for determining the thermal conductivity of soils after analyzing the outcomes

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of thermal conductivity experiments on 19 different soil types. Johansen (1975) established an empirical equation that considered the quartz content, which typically leads to larger predicted thermal conductivities for soils.

Many of the theoretical models for estimating the thermal conductivities of soils apply the same analogy, i.e., electrical resistance in series, parallel, and series–parallel flow models (e.g., Woodside and Messmer, 1961; Kasubuchi, 1975). The thermal conductivity models proposed above and the empirical equations will be discussed in detail in the next chapter. These models and empirical equations, however, are unable to quantitatively explain the thermal conductivities of soils because the factors that influence thermal conductivity, such as dry density, moisture content, and soil mineral composition, are intertwined in a complex and causal correlation with thermal conductivity, and the factors have not been evaluated to a sufficient degree. Thus, it is necessary to reveal the mechanism of the thermal flow in soil in order to speculate on the thermal conductivity of soil.

The purpose of this study is to clarify the impact of the water content on the thermal conductivity of sandy soils. In this study, thermal conductivity tests were conducted on three different soil types using the thermal probe method. Electrical conductivity tests were also conducted to examine the water dependence on the thermal conductivity in detail. A new model and empirical equation are proposed after an analysis of the experimental results.

2. Review of thermal conductivity models and empirical Equations

Although a number of difficulties are encountered when estimating the thermal conductivity of sandy soils empirically, many theoretical thermal conductivity models have been proposed to estimate this property over the last few decades, and most of them are based on resistor equations. Woodside and Messmer (1961) used a series–parallel model, suggested by Wyllie and Southwick (1954), to determine the electrical conductivity of granular materials, similar to the thermal conductivity models for soils that have been fully saturated by water, oil, or gas. Fig. 1 shows the heat flow of Woodside's

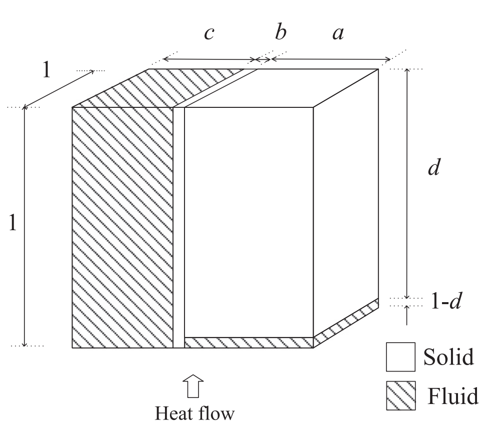

Fig. 1. Thermal conductivity model.

model, visualized as a unit cube of soil. The model has three paths of heat flow, as shown in Fig. 1. The values of a, b, and, c are the proportion of the heat flow through each cuboid to the total heat flow, and each cuboid has the following meaning:

(a) The cuboid with length a represents the heat flow through the fluid and solid in a series.
(b) The cuboid with length b represents the heat flow through a continuous solid.
(c) The cuboid with length c represents the heat flow through a continuous fluid.

Although it is difficult to determine the parameters, the thermal conductivity of fully saturated and dry soil can be expressed using Woodside's model. Subsequently, many researchers have extended Woodside's model to a three-phase model in order to estimate the thermal conductivities of saturated and unsaturated soils. Kasubuchi (1975) developed a qualitative model, in which thermal conduction takes place along soil particles and water. This model is not capable of explaining the non-linear relationship between thermal conductivity and moisture content. Matsumoto and Ohkubo (1977) modified Kasubuchi's model by addressing the non-linear thermal conductivity of soils. This model was not, however, quantitative, since the parameters were not linked with either thermal conductivity or physical properties. Mitsuno et al. (1983) developed a new model to account for the nonlinearity of the thermal conductivity of soil by separating the void into three parts to account for the pore-water contribution in the thermal conductivity calculation. For this model, it was necessary to set the sizes of the two voids. On the basis that suction values of 6 and 980 kPa were used as an indication of macropores and the beginning point of capillary condensation, respectively, the sizes of the voids were determined by the water volumes during outflow to these suction magnitudes using the drainage-path soil water-characteristic curve.

As the inflection points depend on the soil under consideration, these values could not be set as constant and there is no well-established theory to explain them. Tarnawski and Leong (2012) concluded that a series–parallel model-extension to three-phase porous media did not produce a satisfactory outcome. Kersten (1949) proposed empirical equations developed from thermal conductivity tests using 19 different soil types. The thermal conductivity, λ, for the unfrozen condition for silt and clay and for only sand is expressed in Eqs. (1) and (2), respectively:

$$\lambda = \left\{(0.9 \log w - 0.2) \times 10^{0.6242\rho_d - 3.4628}\right\} \times 418.6 (\text{for silt and clay}) \quad (1)$$

$$\lambda = \left\{(0.7 \log w + 0.4) \times 10^{0.6242\rho_d - 3.4628}\right\} \times 418.6 (\text{for sand}) \quad (2)$$

where λ is the thermal conductivity of the soil $\left(\text{Wm}^{-1}\,\text{K}^{-1}\right)$, w is the moisture content (%), and ρ_d is the dry density (g/cm^3).