Assessment of Calculation Methods for Thermal Conductivity of Saturated Kaolinite

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This paper presents the results of an experimental study carried out using modified consolidation tests with the needle probe method to measure thermal conductivity. Experimental results are used to assess theoretical and empirical models, which are categorized into four groups, to calculate the thermal conductivity of saturated kaolinite.

INTRODUCTION

Heat transfer in clayey soils is an important factor that must be considered in the design of engineering structures, such as clay barriers for nuclear waste repositories (Gera et al., 1996; Tien et al., 2004) and vertical drains in soft Bangkok clay (Abuel-Naga et al., 2008). Many researchers have discussed the factors affecting thermal conductivity in soils, and major factors have been established (Kersten, 1949; Mickley, 1951; Johansen, 1975). Thermal conductivity depends on dry density, water content, particle size, unfrozen and frozen condition, saturation degree and soil components.

However, there are few studies on the thermal conductivity of saturated clay because laboratory tests must be performed under conditions that minimize specimen disturbance while confirming saturation level and carefully control the heat boundary conditions of the apparatus (Abuel-Naga et al., 2008). Penner (1962) measured the thermal conductivity of remolded saturated Leda clay. The soil sample was cut and predrilled to place thermocouples within the sample, but it is possible that the tested specimens were disturbed during cutting and drilling. Abuel-Naga et al. (2008) performed consolidation tests to measure the thermal conductivity of Bangkok clay with an oedometer cell including the top and bottom heat sources. The measured thermal conductivity increases as the temperature gradient between the top and bottom boundaries increases.

Numerous theoretical and empirical approaches have been developed to estimate the thermal conductivity of soils. Previous research can be categorized into 4 main groups:

1. thermal conductivity as a function of dry density and water content (Kersten, 1949; Gangadhar Rao and Singh, 1999);
2. consideration of particle shape factors (Mickley, 1951; de Vries, 1952);
3. the use of semi-empirical equations that include a geometric mean method (Johansen, 1975; Cote and Konrad, 2005; Tarnawski et al., 2009); and,
4. the use of a semi-empirical modified resistor equation (Woodside and Messmer, 1961; Abuel-Naga et al., 2008).

These approaches can be used to estimate the thermal conductivity of saturated clay, but no rigorous research that evaluates these models has been reported for the thermal conductivity values of saturated clay.

This paper presents carefully controlled laboratory testing data obtained from consolidation tests with thermal conductivity measurement. Further, experimental results are utilized to assess the accuracy of previously developed models.

PREDICTION METHODS

Table 1 summarizes the 4 methods used to estimate thermal conductivity. With the exception of Model 1, all of the models require fluid thermal conductivity (k_w) and solids thermal conductivity (k_s) values. Tested specimens are prepared with distilled water (k_w = 0.57 W/mK) (Ambersland and Ladanyi, 2004). To determine the solids thermal conductivity (k_s), a back-calculation approach can be used to fit experimental data. However, back-calculation is tedious, and k_s becomes little more than a parameter that is adjusted to fit the experimental data.

Simple methods to obtain k_s have been recommended by Gemant (1952) and Cote and Konrad (2005) as follows:

\[ k_s (\text{W/mK}) = 5.84 - 0.033p \]  
\[ k_s (\text{W/mK}) = \prod_{j} k_{m_j}^{x_j} \text{ with } \sum_{j} x_j = 1 \]

where \( p \) is the percentage of clay in the soil, \( k_{m_j} \) is the thermal conductivity of the \( j \)th rock-form mineral, and \( x_j \) is the volumetric fraction of the \( j \)th rock-form mineral. In Eq. 1, the percentage of clay (\( p \)) can be obtained from a grain-size distribution curve. In Eq. 2, the thermal conductivity of common minerals can be found in the literature (Horai, 1971; Maky and Ramadan, 2010). The volumetric fraction (\( x \)) and mass fraction are approximately equal, and the mass fraction can be obtained using X-ray diffraction (XRD) techniques, which are rapid and fairly accurate, to determine the mass fractions of minerals in the soil samples (Cote and Konrad, 2005; Hardy, 1992).

EXPERIMENTAL PROGRAM AND RESULTS

Consolidation tests with measuring thermal conductivity were performed by mixing kaoline with deionized water. Consolidation tests provide continuous changes in dry density (\( \rho_d \)) (i.e., porosity...