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A reliable model to predict thermal conductivity of unsaturated weathered granite soils☆

Gyu-Hyun Go [a], Seung-Rae Lee [b,*], Young-Sang Kim [c]

[a] Convergence Research Planning Division, KICT, Goyang 411-712, Republic of Korea
[b] Department of Civil and Environmental Engineering, KAIST, Daejeon 34141, Republic of Korea
[c] Department of Marine and Civil Engineering, Chonnam National University, Yeosu 59626, Republic of Korea

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ABSTRACT

The aim of this study is to present a new empirical model to predict thermal conductivity, based on experimental databases that might be particularly applicable to unsaturated weathered granite soils. To establish the experimental databases, a number of thermal conductivity tests were conducted using a new probe system combined with a volumetric pressure extractor. Thereby, 162 data were collected and applied to the prediction model. The prediction model has two empirical coefficients that determine the shape of a graph, and it is not easy to determine these coefficients unless experiments are conducted. Thus, in this paper, we propose using an artificial neural network model to obtain these empirical coefficients without experiments, given only information on the soil properties. Moreover, to evaluate the applicability of the trained network model, it was tested for data sets that had not been introduced during the training stage. According to the verification results, the trained network model presents reasonable prediction results ($R^2 = 0.9046$), even for the new testing data. In addition, the model traces the measured data curve with fairly good agreement, depending on a sample's porosity, regional characteristics, and degree of saturation.

1. Introduction

Recently, the depletion of fossil fuel sources and rising energy consumption, have emerged as serious problems for global society. To achieve energy savings and reduce greenhouse gases, the use of renewable energy sources is becoming inevitable all over the world. In particular, Ground Source Heat Pump (GSHP) systems making use of renewable energy stored in the ground have been recognized as a clean, efficient way to enhance space heating and cooling of buildings. They use relatively constant ground temperatures as a heat reservoir: a heat source in winter and a heat sink in summer. Though a vertical loop [1] has often been the choice for GSHP systems, this approach is facing a major obstacle due to its high initial construction cost, which comes from the required drilling operation [2–4]. For this reason, attention is shifting to GSHP systems using shallow grounds. A typical example of a shallow GSHP system is an energy pile and horizontal loop system. The energy pile has been used as part of the ground heat exchangers to overcome the initial cost of conventional vertical loop systems [5–8]. This innovative idea has led to notable progress in the field of GSHP systems and has become particularly attractive to developers in urban areas. This is because it offers the lowest total cost while offering the highest renewable contribution, and the lowest spatial requirements [9]. In addition, horizontal loop systems are often preferred over vertical loop if the site has adequate space. Owing to the lower initial installation costs, the use of horizontal loops can provide a viable alternative solution that reaches a good compromise between efficiency and cost [10–12].

In most cases, all or some parts of the ground heat exchanger in shallow GSHP systems are located above the ground water table (GWT). This means that the shallow ground above the GWT consists of three-phase soils: solid mineral components, water, and air. Because three-phase soils are unsaturated (with water), the thermal properties of the ground relatively near the surface can be affected by unsaturated soil behaviors. Hence, the performance of GSHPs can also be influenced by complex soil behavior at shallow depths [13–14]. Thus, there have been extensive studies on the prediction of thermal conductivity of unsaturated soils, based on empirical or theoretical approaches. For example, Kersten [15] proposed an empirical model in 1949, and it is considered one of the first approaches to predict the thermal conductivity of frozen soils. After that, Johansen [16] suggested another empirical model having a logarithmic form, obtained by regression analysis. Donazzi et al. [17] investigated the thermal and hydrological characteristics of the soil surrounding buried cables and proposed an empirically derived model. Farouki [18] reviewed several methods for prediction of the effective thermal conductivity of frozen soils, and provided an extensive collection of experimental data for unfrozen and frozen soils. Cote and Konrad [19] modified Johansen's model to eliminate the

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* Corresponding author.

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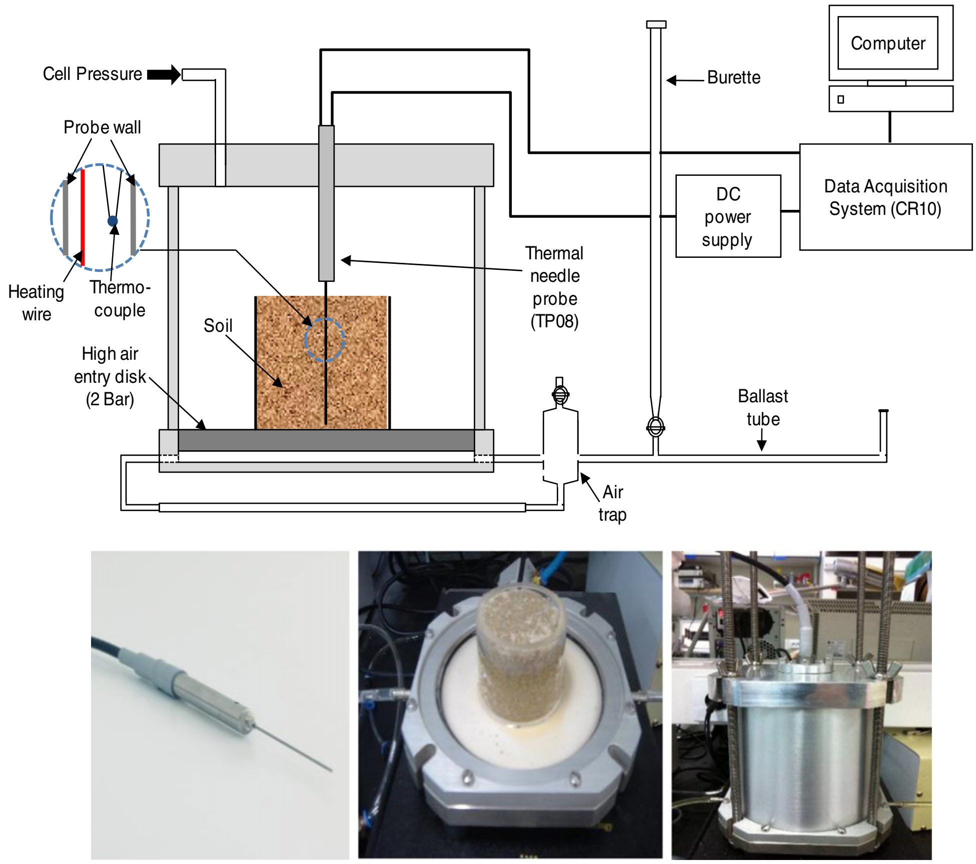

Fig. 1. Schematic diagram of thermal conductivity test for unsaturated soils [36].

logarithmic dependence on the saturation ratio, which distorted predictions at low degrees of saturation. They suggested three empirical parameters that could consider the effect of particle shape and soil texture. Lu et al. [20] also modified Johansen's model and suggested several empirical parameters for sandy soils. Chen [21] proposed an empirical equation, based on 80 needle-probe tests on sands with a wide range of particle sizes, saturation ratios, and void ratios. In addition to above models, there are simpler mixed models based upon such as arithmetic, harmonic, and geometric means. These are statistical models containing both fixed effects and random effects, and are known to be particularly useful in computation of multi-phase thermal conductivity.

An analytical solution was attempted by Germant [22]; he evaluated the thermal conductivity of an array of chipped spherical particles with circular areas of contact between them. After that, De Vries [23] suggested a soil thermal conductivity model based on Maxwell's equations for the electrical conductivity of uniform spheres dispersed within a continuous fluid. A previous model [23] was extended by Penner [24] to accommodate frozen soils after extensive experiments [25]. Gori

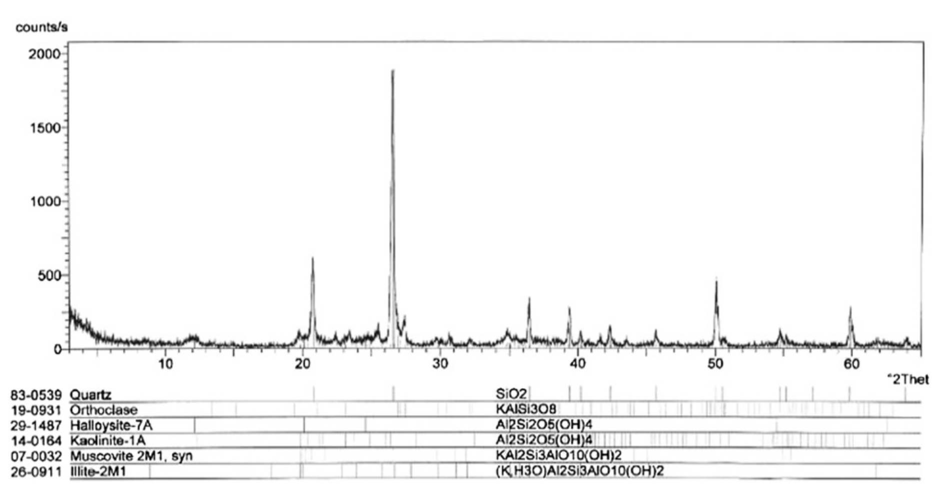

Fig. 2. Results of mineral quantitative analysis using X-ray diffusion (XRD) method.