Soils and Foundations 2014;54(2):116–125

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

Thermal properties of boring core samples from the Kanto area, Japan: Development of predictive models for thermal conductivity and diffusivity

Takeshi Saito[a,g,*], Shoichiro Hamamoto[b,g], Ei Ei Mon[a,g], Takato Takemura[c,g], Hirotaka Saito[d,g], Toshiko Komatsu[a,e,g], Per Moldrup[f,g]

[a]*Graduate School of Science and Engineering, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama, Japan*
[b]*Graduate School of Agricultural and Life Sciences, The University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[c]*Department of Geosystem Sciences, College of Humanities and Sciences, Nihon University, Setagaya-ku, Tokyo, Japan*
[d]*Institute of Agriculture, Tokyo University of Agriculture and Technology, Fuchu City, Tokyo, Japan*
[e]*Institute for Environmental Science and Technology, Saitama University, Sakura-ku, Saitama, Japan*
[f]*Department of Civil Engineering, Aalborg University, Aalborg, Denmark*
[g]*Core Research for Evolutionary Science and Technology, Japan Science and Technology Agency, Kawaguchi City, Saitama, Japan*

Received 4 December 2012; received in revised form 9 September 2013; accepted 2 October 2013
Available online 26 March 2014

Abstract

The subsurface of the Earth is facing evermore thermal impact due to global warming, urban heat islands, and the widespread use of ground source heat pump (GSHP) systems. This potentially causes changes in its physical, mechanical, microbiological, and chemical properties, and in the subsurface water quality. To predict and evaluate this thermal impact (or thermal pollution), a better understanding and improved models for the thermal properties governing heat transport in subsurface sediments are needed. Also, data acquisition in high spatial resolution for the thermal properties and basic physical properties of the subsurface sediments are essential. In this study, the main thermal properties (the thermal conductivity, heat capacity, and thermal diffusivity) together with the basic physical properties (the soil texture, water content, and dry bulk density) were measured on boring core samples representing depths from 0 to 50 or 80 m, at three study sites in the Kanto area of Japan. Based on the measured data, models for thermal conductivity as functions of gravimetric water content, dry bulk density, and volumetric sand content were developed. The new models performed markedly better than presently available models from the literature and, in combination with a modified de Vries type model for heat capacity, the resulting model for thermal diffusivity was capable of describing the measured data well. The usefulness of the newly developed models were validated and illustrated by using data from a two-day thermal response test (TRT) performed at one of the three study sites. The new predictive models for the thermal properties used in a numerical heat transport simulation accurately predicted subsurface (5–50 m) temperature changes during the TRT.

Keywords: Geothermal properties; Thermal conductivity; Thermal diffusivity; Predictive models; Geophysical properties; Subsurface temperature change; Thermal response test (TRT)

*Corresponding author at: Graduate School of Science and Engineering, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama, Japan.
Tel./fax: +81 48 858 9146.
E-mail address: saitou@mail.saitama-u.ac.jp (T. Saito).
Peer review under responsibility of The Japanese Geotechnical Society.

Production and hosting by Elsevier

1. Introduction

While global warming is now widely recognized as one of the major environmental problems facing our planet, the possible analog subsurface warming effect has not received much attention (Taniguchi et al., 2009). It has been shown that subsurface warming is strongly associated with surface warming including the global warming effects (Harris and Chapman,

http://dx.doi.org/10.1016/j.sandf.2014.02.004
0038-0806

1997; Pollack et al., 1998; Huang et al., 2000). Studies have reported a small but significant temperature rise in subsurface environment up to 100–200 m depths below many larger cities in the world (Perrier et al., 2005; Taniguchi et al., 2007; Kooi, 2008). Large underground facilities such as subways and shopping malls along with the rapidly expanding urbanization creating "Urban Heat Islands" (Allen et al., 2003; Taniguchi et al., 2003) may in part explain these changes in subsurface temperatures.

Recently, ground source heat pump (GSHP) systems have become increasingly popular for obtaining energy for heating and cooling with minimal climate impact (Spitler, 2005; Banks, 2008; Dinçer and Rosen, 2011). The GSHP system exchanges heat with the subsurface environment for indoor heating (winter situation) and cooling (summer situation) (Florides and Kalogirou, 2007; Gao et al., 2009). A temperature rise of up to approximately 10 °C in the subsurface monitoring wells in the vicinity of GSHP systems has been observed in several countries (Sowers et al., 2006; Bonte et al., 2011).

Subsurface temperature changes may cause changes in physical, mechanical, microbiological, and chemical properties, as well as in the subsurface water quality. To predict and evaluate the thermal impact (or thermal pollution), a better understanding and improved models for the thermal properties governing heat transport in subsurface sediments are needed. Also, data acquisition in high spatial resolution for both the thermal properties and the basic physical properties (i.e., the soil texture, water content, and dry bulk density) of the subsurface sediment samples are essential since little data is presently available.

The heat transport process in porous media is governed by thermal properties, i.e. thermal conductivity, heat capacity, and thermal diffusivity. Previous studies have investigated the relationships between thermal conductivity and basic physical properties including mineral composition, dry bulk density, and water content, to develop predictive models (de Vries, 1963; Johansen, 1975, Kasubuchi, 1984; Côté and Konard, 2005; Lu et al., 2007). The widely used prediction models currently available for thermal conductivity require several input parameters, each with a marked measurement uncertainty, cost, and time. There is, however, an increasing need for accurate and realistic heat transport models with minimum input parameters requirement for thermal effect and risk assessment calculations, for example in regard to designing GSHP systems with a minimal effect on the subsurface environment and groundwater quality.

The objectives of this study are therefore as follows: (i) to measure the main thermal properties (the thermal conductivity, heat capacity, and thermal diffusivity) as well as the basic physical properties (the soil texture, water content, and dry bulk density) on boring core samples (0 to 50 or 80 m) from three study sites in the Kanto area of Japan, (ii) based on the measured data to develop accurate, low-parameter predictive models for thermal properties of differently-textured water-saturated samples, and (iii) to validate the models and illustrate their possible use by predicting subsurface (5–50 m) temperature changes during a full-scale, short-term thermal response test (TRT) at one of the three study sites.

2. Materials and methods

2.1. Description of sites

The study sites are located at three universities, Saitama University: SU (Saitama city, Saitama; 35°51′44.146″N, 139°36′34.034″E), Nihon University: NU (Setagaya-ku, Tokyo; 35°39′49.385″N, 139°38′4.752″E), and Tokyo University of Agriculture and Technology: TUAT (Fuchu city, Tokyo; 35°41′1.37″N, 139°28′58.44″E), all in the Kanto area of Japan (Fig. 1a). The boring core samples were obtained from all three sites, and the lengths of those samples at SU, NU and TUAT were 50 m, 80 m and 50 m, respectively. For the NU site, the core samples were taken from two boreholes approximately 1 m apart. The groundwater tables are around 1–2 m, 2–4 m, and 10–12 m below the surface at SU, NU, TUAT, respectively.

2.2. Thermal and physical properties measurements

The main thermal and basic physical properties of the core samples were measured by the following procedures. Dry bulk density and wet bulk density were determined on intact subcores (retrieved from the larger columns by a cores sampler) of 7.85 cm^3 (2.0 cm in diameter and 2.5 cm in height). Subsequently, thermal conductivity and heat capacity were measured by a portable KD2 Pro thermal probe (Decagon Devices, Inc.), based on the transient line heat source measurement principle. The probe used has two needles functioning as the heater and temperature sensor, respectively. The temperature sensor monitors the temperature versus time relationship necessary for calculating thermal conductivity and heat capacity (Decagon Devices, 2012). Thermal diffusivity was calculated from the measured thermal conductivity and heat capacity. After the determination of the thermal properties and bulk densities, the gravimetric water content, particle density (AccuPyc 1330 Pycnometer, Micromeritics Instrument Corporation), and particle size distribution (Laser Diffraction Particle Size Analyzer SALD-3100, Shimadzu Corporation) were measured. Following the definition of The Japanese Geotechnical Society, the clay, silt, and sand fractions were defined as < 5 μm, 5–75 μm, and 75–2000 μm, respectively. The total porosity was calculated from the dry bulk density and the particle density.

For the subsurface temperature simulation described below, some values of the basic physical properties were obtained by interpolation between the data for the two nearest depths. This was assumed to be accurate since the data were measured with high spatial resolution (typically 1 m between measurements).

2.3. Thermal response test

At the SU site (Fig. 1b), an in-situ thermal response test (TRT) was performed for two days to estimate the effective thermal conductivity. We note that this will include thermal effects by groundwater flow along the whole length of a U-tube functioning as a heat exchanger. The heat exchanger (a double U-tube) was installed in the borehole at 50 m depth and silica sand was used as backfill material around the U-tube. Resistance-type temperature