Determination of the thermal conductivity of sands under varying moisture, drainage/wetting, and porosity conditions- applications in near-surface soil moisture distribution analysis

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Abstract. A class of problems in hydrology and remote sensing requires improved understanding of how water and heat flux boundary conditions affect the soil moisture processes in the shallow subsurface near the land/atmospheric interface. In these systems, a clear understanding of how variations in water content, soil drainage/wetting and porosity conditions affect the soil's thermal behavior is needed for the accurate detection of buried objects such as landmines, however, very few experimental data showing the effects of these variations are available. In this study, the effect of soil moisture, soil hysteretic behavior and porosity on the thermal conductivity of some sandy soils was investigated. For this experimental investigation, a Tempe cell was modified to have a network of sampling ports, continuously monitoring water saturation, capillary pressure, temperature, and soil thermal properties. The water table was established at mid elevation of the cell and then lowered slowly. The initially saturated soil sample was subjected to slow drainage, wetting, and secondary drainage cycles. After liquid water drainage ceased, evaporation was induced at the surface to remove soil moisture from the sample to obtain thermal conductivity data below the residual saturation. For the test soils studied, thermal conductivity increased with increasing soil density and moisture content while thermal conductivity values were similar for soil drying/wetting behavior. Thermal properties measured in this study were then compared with independent estimates made using empirical models from literature. These soils will be used in a proposed set of experiments in intermediate scale test tanks to obtain data to validate methods and modeling tools used for landmine detection.

1. Introduction

Soil thermal properties to include thermal conductivity and resistivity, specific heat and thermal diffusivity are required to conduct analysis and modeling associated with numerous agricultural, hydrological and industrial applications. In addition to characterizing the soil's physical/hydraulic properties, knowledge of the soil's thermal properties is necessary for proper soil and water management in irrigated agriculture (e.g., Noborio et al. 1996), determining the energy balance at the soil surface, and soil water retention and unsaturated hydraulic conductivity (Hopmans and Dane 1986). The measurement of soil thermal properties is also necessary for the analysis of heat and moisture flow in soils in the vicinity of a buried object in the shallow subsurface affected by the land/atmospheric boundary conditions and understanding the fate and transport of many contaminants and microbes (e.g., bacteria and virus).

Heat and water transfer are strongly coupled processes, creating transient temperature, water content and thermal conductivity distributions/gradients in unsaturated near-surface conditions. Understanding of this coupled process is limited due to a lack of thorough experimental testing thus restricting testing and refinement of coupled heat and water transfer theory (Heitman et al. 2007). Available data is scarce, incomplete and very often limited to specific soils and select moisture content values, partially due to difficult and laborious experiments (Tarnawski and Gori 2002). For example, laboratory data on soil water content has most commonly been obtained through destructive sampling techniques (e.g. Nassar and Horton 1989), preventing the measurement of transient conditions. Heat and water transfer models are usually calibrated against steady state moisture and temperature distributions and attempts at validating the calibrated models or describing transient boundary conditions is lacking (Heitman et al. 2007). The development of complete data sets for transient temperature, soil moisture and thermal properties is needed to validate models.

Thermal conductivity is one of the important thermal properties known to vary as a function of soil water content. Because thermal conductivity of water, dry air, and quartz mineral are typically 0.58 (at 20°C), 0.024 (at 20°C), and 6.15-11.3 W/mK respectively, the apparent thermal conductivity of wet soil as a mixture of the three phases is a function of water and air content (Bristow 2002; Clauser and Huenges 1995). Under different water contents, the apparent thermal conductivity varies as the contributions from the three phases vary. Thermal conductivity data from previous works is scarce and incomplete as thermal conductivity has not been measured in a continuous fashion, utilizing recent technologies based on sensors. In this work, several recent sensor based technologies are compiled into one experimental cell in order to measure thermal conductivity in a continuous manner at varying soil water contents and soil bulk densities.

With the goal of better understanding water/vapor migration behavior in the vicinity of a buried object such as a landmine, this work focuses on identifying thermal properties of soils under the various conditions that can be expected around buried landmines as well as fitting the data to existing models. Potential field conditions include both precipitation and evaporation or seasonal water table fluctuations (when the water table is shallow), causing wetting/drainage/drying in the soil. Mine burial procedures involve digging and backfilling thus altering the bulk density/porosity of the soil. Therefore, the purpose of this work is to: (1) develop a Tempe cell-based apparatus that has the capability of simultaneously/continuously monitoring soil water content, capillary pressure, temperature, and thermal properties, (2) measure thermal conductivity as a function of water content under both transient wetting and drainage/drying conditions for four different laboratory test sands, however, data for only one sand is presented in this paper, (3) determine the effect of porosity on thermal conductivity and (4) compare measured thermal properties with independent estimates (Johansen 1975; Campbell 1985). The effects of water content, wetting/drainage and porosity, and discrepancies between experimental measurements and standard estimates are discussed and the need for reliable data highlighted.

2. Drainage and Wetting Experiments

A Tempe cell (Model no. Cl-029B, *Soil Measurement Systems LLC.*) was modified to contain a network of sampling ports, continuously monitoring water saturation, capillary pressure, temperature and soil thermal properties using a soil moisture sensor (ECH$_2$O EC-5 sensor (length = 5.5 cm, measurement frequency = 70 MHz, *Decagon Devices, Inc.*), tensiometer, temperature probe (EC-T , *Decagon Devices Inc.*) and thermal property analyzer (KD-2 Pro, *Decagon Devices Inc.*,), respectively. Figure 1 shows a schematic of the Tempe cell as well as the placement of sensors within the cell. All of the sensors were installed horizontally through the plexiglass walls of the Tempe cell. Prior to installation in the cell, the EC-5 sensor was calibrated according to Sakaki et al. (2008). The tensiometer consisted of a small porous cup (diameter = 0.64 cm, length = 2 cm, air entry value = 51 kPa, *Soilmoisture Equipment, Inc*.) and brass fitting, that was connected to a differential pressure transducer (Validyne Engineering Co., Model P55D). The KD-2 Pro thermal property analyzer 30 mm dual-needle heat pulse sensor (SH-1) was customized by the manufacturer in order to fit directly into the Tempe cell. The KD2 Pro performance was verified prior to installation according to Decagon Devices, Inc. (2006). At the bottom of the cell, a nylon membrane (Nylaflo, 142mm, pore = 0.2 µm, air entry value = 340 kPa) was cut to fit and used.

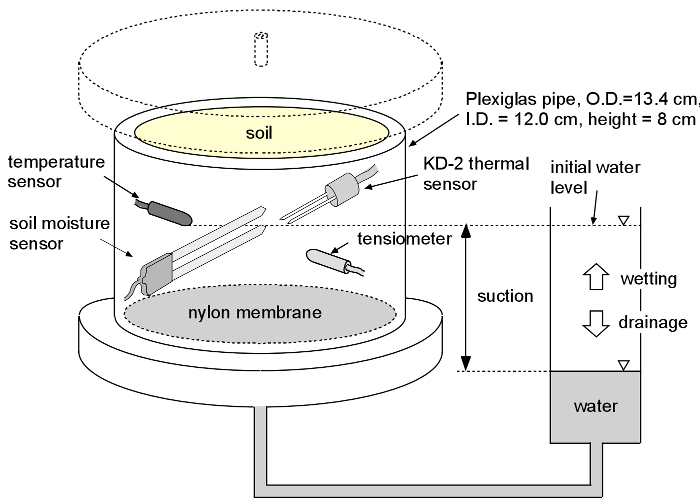

Figure 1: Schematic view of the Tempe cell used in the experiments, shown without insulation. The diagram is not drawn to scale. The dimensions of the acrylic pipe are; 8 (height) × 13.3 (O.D.) cm, wall thickness = 1.27 cm, inside volume excluding the sensors = 909.3 cm^3.

Four relatively uniform specialty silica sands of differing particle size were used in the experiments. The silica sands are identified by the effective sieve numbers; #12/20, #20/30, #30/40, and #40/50 (Accusands, *Unimin Corp.,* Ottawa, MN, 2007). All sands have similar porosity values of 0.33-0.34 when tightly packed. However, in the current investigation, only experimental and theoretical results for sand #20/30 are presented (Table 1). Based on the technical sheet provided by the manufacturer, the mean grain diameter for #20/30 sand is 0.75 mm, the uniformity coefficient is approximately 1.2, the grain density is 2.65 g/cm^3 and the grain shape is classified as rounded.

Table 1: Selected properties of test sand #20/30.

Sand no. 20/30	Saturated hydraulic conductivity [cm/sec]	Dry bulk density [g/cm^3]	Porosity	Air entry pressure [cm of water]
Loosely Packed	0.58	1.62	0.388	7.5
Tightly Packed	0.24	1.80	0.322	10.8

The sand was carefully wet-packed into the Tempe cell, using de-aired water. Sand was poured into the cell in 0.5 cm incremental depths in an effort to achieve a uniform bulk density. Maximum densities were assumed to be achieved by thoroughly tapping the cell wall. In the loose packing case, minimum densities were achieved according to Youd (1973) by slowly pouring sand through a funnel into the cell and minimizing the soil disturbance after packing. In an attempt to create no-heat flux boundary conditions on the cell walls, a 3 cm thick Styrofoam insulation was placed around the Tempe cell. This kept the temperature variations within the cell to ± 0.5 °C (19.5 - 20.5 °C). The water table was established at mid elevation of the cell (Figure 1) and then lowered slowly (0.5 cm/hr), simulating the drainage cycle (primary drainage). Drainage was terminated when capillary pressure reached 16 cm of water at which time the water content was reasonably close to residual water content. The water table was then raised slowly to the original elevation and subsequently lowered again to establish the wetting and secondary drainage cycles. After liquid water drainage ceased, evaporation was induced at the surface using an electric fan to obtain thermal conductivity data below the residual saturation. Capillary pressure, water saturation and temperature were continuously monitored every one minute interval while soil thermal properties were measured every 15 minutes in order to allow ample time for thermal gradients to dissipate. At the end of the experiment, the sand in the vicinity of the soil moisture and thermal property sensors was destructively sampled and weighed to verify soil moisture conditions. In addition, the sand was oven dried and repacked into the cell to verify dry soil moisture and thermal property values.

3. Experimental Results and Discussion

Soil thermal conductivity (λ), of #20/30 sand measured using the KD-2 probe is shown in Figure 2 as a function of volumetric water content (θ) under tightly packed conditions. In general, the measured λ- θ data showed that thermal conductivity increased with an increase in water content with three distinct regimes; I) a very small slope for $\theta > 0.2$ cm^3/cm^3, II) mild change for $0.02 < \theta < 0.2$, and III) abrupt change for $\theta < 0.02$. At high water contents (regime I), the water phase is physically connected and heat is therefore transmitted largely through the grain/water phases and contacts between grains, resulting in higher thermal conductivity values than at lower saturations. The small change in the thermal conductivity indicates that the effect of air is not significant in this water content range. As water content decreases (regime II), water is displaced by air leading to more water in pendular form (i.e. disconnected). As a result, the grain/water paths decrease, heat flows partially through less-conductive air/water/grain or air/grain paths and apparent thermal conductivity decreases. In regime III, where water content is below residual water content ($0.02\,cm^3/cm^3$), thermal conductivity shows an abrupt and very pronounced decrease in water content. In this regime, heat conduction must occur through the air/water/grain, air/grain paths and contacts between grains only, resulting in fewer conductive channels between soil particles and the abrupt decrease. The $\lambda - \theta$ relationships under primary drainage, wetting and secondary drainage/drying conditions at a given water content were nearly identical (Figure 2), demonstrating that the wetting/drainage history of the sand does not affect the λ - θ relationship.

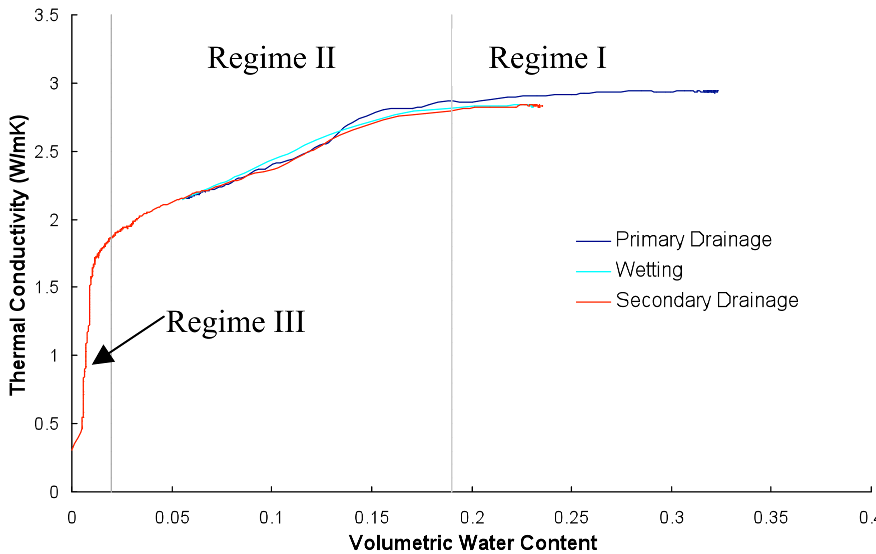

Figure 2: Thermal conductivity as a function of water content for #20/30 sand under tightly packed (porosity = .322, dry bulk density =1.80 g/cm^3) conditions for primary drainage, wetting and secondary drainage cycles.

Thermal conductivity for loosely packed sand is presented in Figure 3 as a function of θ. Thermal conductivity values are obviously sensitive to packing conditions. Consistent with previous experimental investigations (Horn 1994; Usowicz et al. 1996, Abu-Hamdeh 2000; Abu-Hamdeh and Reeded 2000), thermal conductivity increased with increasing density as a result of better particle contact with a decrease in porosity and a greater mass of solids per unit volume. The effect of porosity on thermal properties was more pronounced at higher soil water contents than at lower water contents. However, at soil water contents above the residual water content, the difference in thermal conductivity as a function of porosity at a given water content was very consistent. At full saturation, soil has only two phases; water and soil grains. Therefore, a geometric mean equation based on the thermal conductivity of water ($\lambda_w = 0.58$ W/mK at 20 °C) and effective thermal conductivity of soil solids (λ_s) can be used to estimate the saturated thermal conductivity (λ_{sat}) (Johansen, 1975):

$$\lambda_{sat} = \lambda_s^{1-\phi} \lambda_w^{\phi} \tag{1}$$

where ϕ is the porosity. Johansen (1975) proposed that the value of λ_s could be determined using another geometric mean equation from the quartz content of the total soils content (q) and thermal conductivities of quartz (λ_q = 6.5 W/mK (Clauser and Huenges 1995)), and other minerals (λ_o =2.0 W/mK):

$$\lambda_s = \lambda_q^q \lambda_o^{1-q} \qquad (2)$$

Based on equations 1-2, for tightly packed sand with a porosity of 0.322, λ was 2.9 W/mK whereas for loosely packed sand with porosity of 0.388, λ was 2.5 W/mK. This was very consistent with the values obtained experimentally (2.9 and 2.5 W/mK, respectively).

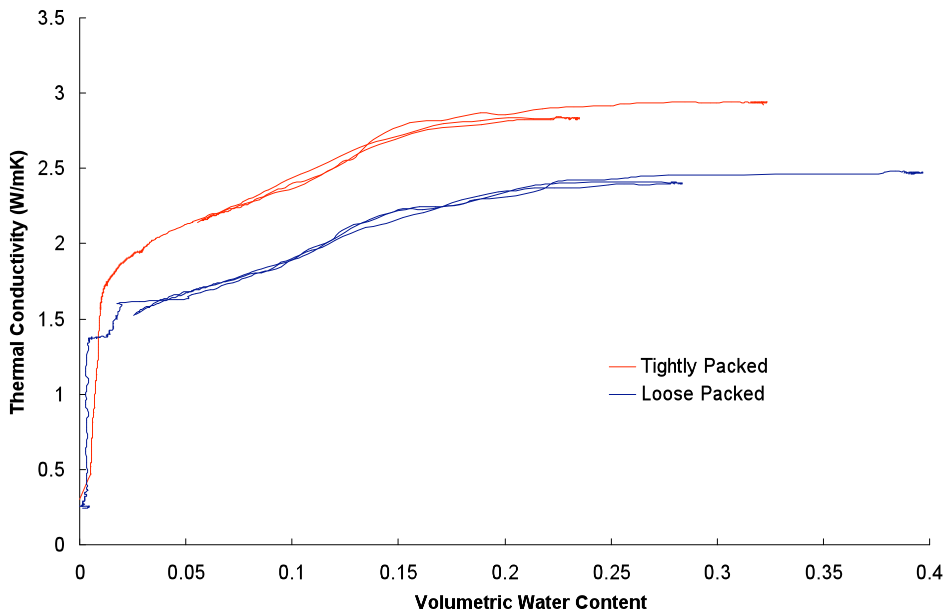

Figure 3: Thermal conductivity as a function of water content for #20/30 sand under tightly packed (porosity = 0.322) and loosely packed (porosity = 0.388) conditions.

Johansen (1975) used a semiempirical relationship to determine λ_{dry}:

$$\lambda_{dry} = \frac{0.135\rho_b + 64.7}{\rho_s - 0.947\rho_b} \qquad (3)$$

where ρ_b is the bulk density of soil (kg/m^3) and ρ_s is the density of soil solids (kg/m^3). Based on equation 3, for tightly packed sand, λ was 0.32 W/mK whereas for loosely packed soil, λ was 0.20 W/mK. This was very close to the values obtained experimentally (0.30 and 0.24 W/mK, respectively).

The thermal conductivity model by Campbell (1985) was then examined to determine if the model supported the experimental data. Thermal conductivity can be calculated using the equation (McInnes 1981; Campbell 1985):

$$\lambda = A + B\theta - (A - D)\exp[-(C\theta)^E] \qquad (4)$$

where A, B, C, D, and E are soil dependent coefficients obtained by curve fitting. These relationships are (Campbell 1985):

$$A = (0.57 + 1.73\phi_q + 0.93\phi_{rm})/(1 - 0.74\phi_q - 0.49\phi_{rm}) - 2.8\phi_s(1 - \phi_s) \qquad (5)$$

$$B = 2.8\phi_s \qquad (6)$$

$$C = 1 + 2.6/(m_c^{0.5}) \qquad (7)$$

$$D = 0.03 + 0.7\phi_s^2 \qquad (8)$$

$$E = 4 \qquad (9)$$

where the subscripts q, rm, and s indicate quartz, minerals other than quartz and total solids and m_c is the clay fraction. Soil minerarology was determined based on the manufacturer's specification sheets. The Campbell (1985) model generally overestimated both the saturated and dry thermal conductivity (Figure 4). However, the model can predict the λ - θ relationship reasonably well when proper coefficients are determined. The Campbell method is highly sensitive to the choice of mineralogy (Bristow 1998) which could have resulted in some of the curve fitting discrepancies. Further analysis is in progress.

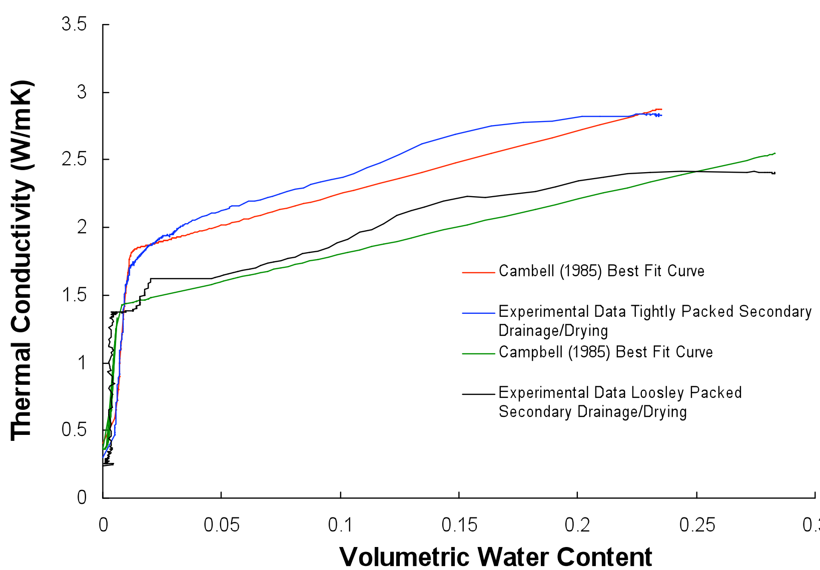

Figure 4: Measured and Campbell model-predicted thermal conductivity values for #20/30 sand under tightly and loosely packed conditions.

4. Summary

This study is a first in a series of experiments on the thermal properties of four sands with different particle size under varying soil moisture, soil wetting and drainage/drying and porosity conditions. In this work, several recent measurement technologies were compiled into an experimental cell, allowing for the measurement of thermal conductivity in a continuous manner at varying soil water contents and soil porosities. For the test sand studied, thermal conductivity increased with increasing moisture content showing three distinct regimes. The tightly-packed sand showed consistently higher thermal conductivity values than loosely packed sand. The difference was well explained by the geometric mean equation. The λ–θ relationships were similar for drying/wetting cycles. A comparison of measured thermal conductivities with thermal conductivitivies estimated using fairly well known models suggest that the model requires calibration for each soil. These sands will be used in a proposed set of experiments in intermediate scale test tanks to obtain data to validate methods and modeling tools used for landmine detection.

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