Journal of Hydrology 510 (2014) 79–91

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Constant energy calibration for permittivity based moisture probes

Sami Arsoy *

Department of Civil Engineering, Kocaeli University, 41380 Kocaeli, Turkey

ARTICLE INFO

Article history:
Received 29 October 2013
Received in revised form 10 December 2013
Accepted 11 December 2013
Available online 20 December 2013
This manuscript was handled by Corrado Corradini, Editor-in-Chief

Keywords:
Soil moisture
Bulk density
TDR
ThetaProbe
WET sensor
Constant energy calibration

SUMMARY

Soil moisture or soil water content (SWC) is an important variable and its determination with an acceptable accuracy is an essential need for a variety of hydrological disciplines. Among the alternatives, permittivity based probes are gaining popularity and becoming established techniques. However, probes are affected by local soil conditions, requiring soil-specific calibrations for accurate and reliable measurements. Measurement errors associated with these probes can be classified in three groups as primary, secondary and tertiary. Primary errors are mostly associated with the underlying operating principles of a probe. Soil density variation is inherently the major source of secondary error as it can create a measurement error as much as 0.030 $m^3\ m^{-3}$. The error associated with the secondary variables can be reduced by up to 0.015 $m^3\ m^{-3}$ by targeting the half range of the density variations. Currently available techniques do not explicitly quantify/minimize the secondary errors. Tertiary errors arise mostly from user dependent factors associated with probe-soil contact discontinuities and unexpected small scale environmental variations in the vicinity of the measurement point.

This study presents a unique approach in considering the natural variations of the dry density by proposing to conduct the soil specific calibrations on repacked samples under constant compaction/compression energy of 350 $kN\ m/m^3$. A simple probe insertion procedure was also employed by using guides and predrilling for probe rods in order to minimize the tertiary variables. A comparative assessment of the proposed calibration approach was conducted, considering a time domain reflectometry (TDR) probe and two relatively affordable moisture probes with different operating principles (ThetaProbe ML2x and Wet-2 sensor). The findings of this study showed that accuracy levels of 0.012 $m^3\ m^{-3}$, 0.015 $m^3\ m^{-3}$ and 0.016 $m^3\ m^{-3}$, through Root Mean Square Error (RMSE), were achieved for TDR, ThetaProbe and WET sensor, respectively, for a wide range of soil types including the clays and silts. It is concluded that the proposed constant energy calibration approach help contain the secondary effects due to density variation in a tight range and that the recommended probe installation procedure help minimize the tertiary effects associated with the probe-soil contact discontinuities.

1. Introduction

Soil moisture or soil water content (SWC) is an essential variable in a variety of hydrological applications. The impact of its variation spans from local to an extended area, and its variation with time and space is of great importance. The soil moisture affects the flux between the soil and the atmosphere, and, hence, subsequently affects the Earth's climate regimes (Kornelsen and Coulibaly, 2013; Seneviratne et al., 2010; Krakauer et al., 2010). The moisture content at the boundary of the ground surface and the atmosphere dictates the physical properties in the troposphere, which plays an important role in determining the time of irrigation, estimating the infiltration rate, minimizing the water loss by drainage and maintaining optimum levels of water for maximum plant growth (Heathman et al., 2012; Blonquist et al., 2006; Hedley and Yule, 2009; Francesca et al., 2010; Haley and Dukes, 2012), and in estimating surface runoff under complex rainfall patterns (Morbidelli et al., 2013, 2011; Crespo et al., 2011; Castillo et al., 2003; Liu et al., 2011; Wei et al., 2007) and the related soil erosion (Western et al., 2004). Water based irrigation management through measuring and monitoring the soil moisture help contribute the sustainable agriculture policies by conserving water. SWC is one of the key geotechnical engineering parameters for both saturated and unsaturated soils (Arsoy et al., 2013b). Soil moisture also plays an essential role in many civil engineering applications such as early detection of landslide risk and compaction quality control in earthwork and highway projects (Berney and Kyzar, 2012; Yu and Drnevich, 2004). Therefore, it is clear that the determination of the SWC is an essential need for a variety of hydrological disciplines.

According to Grayson and Western (1998) the methods used for obtaining the SWC can be divided into three main groups: (1) remote sensing methods, (2) water balance simulation models, and

* Tel.: +90 262 3033269; fax: +90 262 3033003.
E-mail addresses: samiarsoy@yahoo.com, sarsoy@kocaeli.edu.tr

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http://dx.doi.org/10.1016/j.jhydrol.2013.12.024

(3) ground based methods. Reliable determination of soil moisture by remote sensing methods is still a remaining question due to the factors of ground and surface temperature variability (Giraldo et al., 2009) and due to the difficulty arising during the separation of the signal contributions from the vegetation and the soil (Boegh et al., 2004). Obtaining the soil moisture via soil water balance simulation models involves a systematic evaluation of the gains to and losses from the soil reservoir (Panigrahi and Sudhindra, 2003). Adequate number of parameters must be known and used in the model. However, it is a challenging work to quantify the contributions of the errors arising from each parameter employed in the model. Ground based methods are the most accurate and reliable among the three main groups in obtaining the soil moisture, and methods in this group rely on the measurement of an instrument, which is directly in touch with the soil.

Oven-drying method (ASTM D2216) is the standard approach to determine the water content gravimetrically. Infrared oven-drying and calcium carbide gas pressure method can also be used for gravimetric SWC determination (Arsoy, 2008; Arsoy et al., 2013a). However, in most cases volumetric SWC is needed, and as a result, soil coring or additional measures to determine the dry density become necessary. Continuous measurement with oven-drying and other destructive methods is not possible. Radioactive methods such as neutron probe and gamma ray attenuation are widely accepted and established methods but they require special caution and licensing to operate in order to avoid possible health hazards (Noborio, 2001). Hence, the search for a rapid alternative measurement method with acceptable accuracy among the practitioners has been continuous. Additionally, a method allowing the detection of time dependent variations in the SWC would clearly serve better.

Among the alternative methods, electromagnetic reflectometry based methods utilizing apparent permittivity of soils such as time and amplitude domain reflectometry methods (TDR and ADR) are gaining popularity and becoming established methods in lieu of the neutron probe. However, these relatively new methods are significantly affected by temperature, electrical properties, compaction characteristics and texture of soils, requiring soil-specific calibrations for accurate and reliable measurements.

Despite the fact that a great number of publications associated with the use of TDR method and a fair amount of publications (Vienken et al., 2013; Robinson et al., 1999; Nemali et al., 2007; Blonquist et al., 2005; Kaleita et al., 2005; Kargas and Kerkides, 2009; Hamed et al., 2006) on the capacitive/impedance/other moisture probes are available in the literature, a clear and mostly agreed standard approach for soil specific calibration with respect to representativeness of soil samples does not exist. More specifically, calibration approaches focus mostly on moisture variations in the arbitrarily re-compacted or cored samples without taking any systematic measures on the variability of the dry bulk density.

Most of the calibration studies with the TDR equipment are devoted into establishing a better measurement of permittivity, and subsequently the TDR measured/corrected permittivity is linked to SWC through a transfer function (see Topp et al., 1980 and Eq. (2)of this paper). Keng and Topp (1983) reported earlier that the bulk dry density of the soil is another possible source of error for the TDR measured water content due to its effect on the volume fraction of the bound water. Gong et al. (2003) studied the effect of dry density on the permittivity and presented a linear equation, from which one can derive that the variation in dry density from an initial calibration value can result in a variation of about 0.3 in the square root of the relative permittivity. Kaleita et al. (2005) conducted an elaborative study on soil specific calibration methodology for ThetaProbe. For a valid field calibration, they recommended to use 20 samples and concluded that this is a significant limitation of their proposed approach. Hamed et al. (2006) evaluated the WET sensor to investigate the salinization process. The paper focused on the conductivity on the calibration parameters. The literature review for extensive quantification of the dry density effect did not yield a return on the WET sensor.

The importance of the bulk density on the soil water content–dielectric permittivity relationship has been subject of other studies such as Jacobsen and Schjønning (1993), Hook and Livingston (1996), Rothe et al. (1997) and Persson et al. (2002). While they document the effect of the dry density, no practical measure in dealing with the dry density variable was presented in order to alleviate the inherent measurement variations in SWC. A review by Dobriyal et al. (2012) concludes that general calibration for TDR is adequate, which implies that soil specific calibration is not mandatory. On the contrary, Stangl et al. (2009) reports that local soil properties strongly affect the probe responses, which impede data interpretation and require site-specific calibration. It was concluded that the variation in the dry bulk density should be considered during soil specific calibration stage such that an unbiased representation of the dry density variation should be established, which will improve the measurement accuracy of the SWC.

The most desired use of the permittivity based probes would be to estimate the volumetric SWC during the field measurements without retrieval of additional data such as soil coring and bulk density measurements as they would add costs, time-delays, cross error generations and significant restrictions to continuous measurements. Variables affecting the measurements should be considered during the calibration stage of the probes as much as possible for the expected range of operations of the probes, and no additional data collection should be required during field operations for user friendly operations of the probes.

In order to help fill the gap in the literature on unbiased representation of dry bulk density during the calibration stage, a comparative assessment of soil moisture measurements were conducted, considering two relatively affordable moisture probes (ThetaProbe ML2x and Wet-2 sensor) and a TDR probe for a wide range of soil types. This novel approach is able to consider the natural variations in dry bulk density and moisture levels, resulting in unbiased handling of these two variables (density and SWC) and also allowing unbiased comparisons of probes of different operating principles. A probe installation procedure was implemented in order to help minimize the tertiary effects associated with the probe-soil contact discontinuities as a secondary objective. Finally, recommendations for calibration practices and for probe selection are provided.

2. Background on permittivity based probes

When a coaxial line is established in a soil, a dielectric material, an electric field occurs in the soil between the conductors of the coaxial lines. The soil acts like a capacitor and then it shows impedance; the probes specially developed for detecting this phenomenon is usually called capacitance/impedance probes such as ThetaProbe, ECH2O, WET sensor, Hydra probe, CS616, operating at frequencies of 100, 50, 20, 50, 200 MHz, respectively. Time domain reflectometry (TDR) based probes are also used such as TDR100 at 1.45 GHz, MiniTrase and others.

Capacitance/impedance probes monitor the maximum reflected wave amplitude at the probe soil interface. As a result, they are based on the approach called amplitude domain reflectometry (ADR). In simplicity, ADR loosely correlates to the amplitude at the probe soil interface of a TDR waveform, except that the measurement is conducted at a much lower frequency and a sinusoidal incident wave is used, instead of a pulse wave. The majority of the capacitance/impedance probes falls in the ADR category although