Evaluation of TDR measured dielectric constant vs. volumetric water content relationships for different soils

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ABSTRACT: This paper investigates the application of Time Domain Reflectometry (TDR) for either laboratory or field determination of the soil water content measurements. TDR technique uses measurements the soil apparent dielectric permittivity (dielectric constant), by analysing the velocity of propagation of the electric pulse in the tested soil. The apparent dielectric permittivity (K) is converted into the soil volumetric water content (θ) on the basis of a predetermined calibration curve. The success of TDR technique for soil water content measurement depends on the adopted K-θ relationships or calibrations. Several TDR measured K-θ relationships in porous materials have been published, and significant discrepancy exists among them. Additionally, the paper examines the applicability of some previous published TDR measured K-θ relationships for different porous media and water content range. Laboratory and field measurements of two different tropical soils were used for the comparative study. The results show that specific TDR measured K-θ relationships are recommended, principally for tropical soils with clay contents above 30%.

1 INTRODUCTION

Compacted soils are widely used in engineering practice, but the behavior of these soils is not fully understood, mainly because of their unsaturated state. Compacted soils are unsaturated during the construction subsequently the degree of saturation is either increased (e.g., infiltration or loading) or decreased (e.g., evaporation), and the soil properties may change considerably (Bicalho et al. 2000). Understanding these changes in the soil properties, especially the changes in the in-situ soil water content, is important in optimizing the design of earthen landfill covers and in controlling their long-term performance (Bicalho el al., 2015).

Time Domain Reflectometry (TDR) is an indirect technique for measuring soil water content and electrical conductivity. TDR is a non-invasive technique for rapid, reliable, and continuous monitoring of water content of unsaturated soils. This paper investigates the application of TDR for either laboratory or field determination of the soil water content measurements.

TDR technique uses measurements the soil apparent dielectric permittivity (dielectric constant), by analysing the velocity of propagation of the electric pulse in the tested soil. Reviews of dielectric methods for soil water content measurements have been presented by Tarantino et al. (2008). The apparent dielectric permittivity (K) is converted into the soil volumetric water content (θ) on the basis of a predetermined calibration curve. The higher the soil volumetric water content, the higher the soil apparent dielectric permittivity.

Empirical and dielectric mixing models are used to relate volumetric water content to measured apparent dielectric permittivity. Water is the soil component that has the greatest influence on the K of an unsaturated soil, since it has a relative permittivity (about 81) much larger than that of soil solids (from about 3 to 16) and soil air phase (about 1) (Roth et al. 1990, Bittelli et al. 2008). As a result, measurements of the K of an unsaturated soil have been shown to be highly successful in predicting the soil volumetric water content (θ).

The success of TDR technique for soil water content measurement depends on the adopted K-θ relationships or calibrations. Topp et al. (1980) published a called *universal* calibration in which several soils were tested. They assumed that K could directly be related to θ through a polynomial empirical calibration curve. For soils with bulk density values ranging from 1.00 to 1.78 kN/m^3, the soil bulk density or soil porosity did not have a significant influence on the adopted calibration (Topp et al. 1980, Ledieu 1986).

Topp *et al*. (1980) calibration does not require the determination of any other soil property such us: soil bulk density, soil type, particle size distribution, mineralogy and salt content. However studies on TDR calibration curves have obtained different equations especially for high plasticity clayey soils (Dirksen and Dasberg 1993, Blonquist Jr. et al. 2006) and high organic matter content (Roth et al. 1990, Regalo 2004). TDR calibration curves can significantly vary among them (Bittelli et al. 2008).

The objective of this paper is to examine the applicability of some previous published TDR measured K-θ relationships or calibrations for different tropical soils and water content range. The evaluation of the TDR calibration has been necessary for tropical soils due to the physical and chemical properties of these soils. Laboratory and field measurements of two different tropical soils were used for the comparative study.

2 EMPIRICAL K-θ RELATIONSHIPS

Topp et al. (1980) published an empirically-based third-order polynomial function between K and θ obtained by curve fitting to describe experimental data points determined for different soils. The K-θ calibration for soils proposed by Topp et al. (1980) has been widely adopted in geotechnical engineering. Topp *et al*. (1980)´s calibration does not require the determination of any other soil property such us: soil bulk density, soil type, particle size distribution, mineralogy, temperature and salt content. It is thus called "universal" calibration (i.e., K-θ relationship) for soils, and defined as:

$$K = 3.03 + 9.3\theta + 146\theta^2 - 76.7\theta^3 \quad (1a)$$

or

$$\theta = (-530 + 292K - 5.5K^2 + 0.043K^3) / 10^4 \quad (1b)$$

Although empirical K-θ relationships are widely used in the literature, they are based on curve fitting experimental data, and, they may be used only to specific soils. Ponizovsky et al. (1999) recommended the use of fitting models only if the empirical parameters can be related to basic soil properties making possible their estimation from readily available soil data.

Table 1 presents some previous published empirical K-θ relationships representing different soil types and volumetric water content ranges. The differences observed in θ values obtained by the calibrations proposed by Topp et al. (1980), Lidieu (1986) and Jacobsen and Scjonning (1993) are small. The calibrations are essentially coincident for θ range from 5% to 20%. Topp et al. (1980) and Jacobsen and Scjonning (1993) calibrations are proposed for soils with wide moisture range (i.e., from hygroscopic moisture to fully saturation). For high volumetric water contents data dispersion is greater.

Divergence from the Topp et al. (1980) calibration has been observed for clayey soils that contain substantial amount of bound water (Dirksen and Dasberg 1993, Blonquist Jr et al. 2006). It is important to remark that for clayey soils at low moisture content most of the soil water is expected to be adsorbed on soil particle surface and held in micropores, and hence the soil dielectric response would be dominated by that of bound water (Regalado 2004, Blonquist Jr. et al. 2006).

According to Medeiros et al. (2007), Topp et al. (1980) calibration underestimates volumetric water content (about 10%) for Brazilian tropical soils. The high clay and organic matter contents present in these soils reduce soil water content and corresponding apparent permittivity (Figure 1).

Table 1. Some previous published empirical TDR calibrations

Empirical TDR calibrations	References
$\theta = (-530 + 292K - 5.5K^2 + 0.043K^3) /104$	Topp et al. (1980)
$\theta = 0.1138 K^{0.5} - 0.1758$	Ledieu (1986)
$\theta = (-7.01 x 10 -2) + (3.47 x 10 -2 K) - (11.6 \times 10 -4 K^2) + (18.0 \times 10^{-6} K^3)$	Jacobsen and Scjonning (1993)
$\theta = - 0.0194 + 0.0269K - 0.0007K^2 + 8.10 -6 K^3$	Tommaselli and Bacchi (2001)
$\theta = 0.0366 + 0.02698K - 4.8 x 10^{-4}K^2 + 3.6 x10^{-6} K^3$	Medeiros et al. (2007)

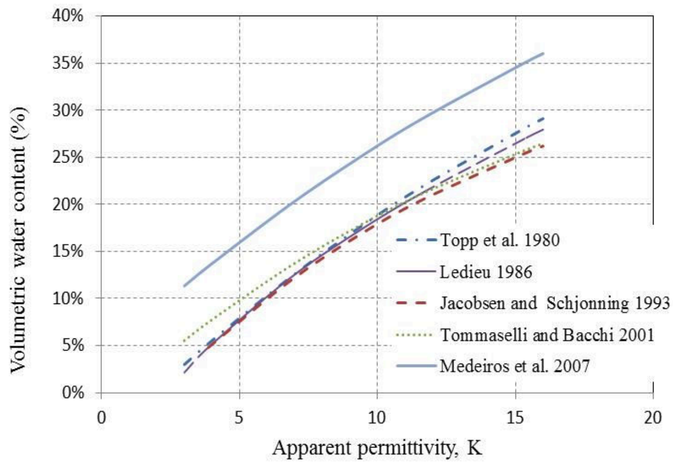

Figure 1. Variation of some previous published empirical TDR calibrations representing different soil types.

3 MATERIALS AND METHODS

3.1 *Soil types and index properties*

The test site location selected for this study is the metropolitan region of Grande Vitoria on the coast of the state of Espírito Santo, ES, in southeast Brazil (Figure 2). Field and laboratory measurements were performed on two different soils from GV-ES. The two tested soils from GV-ES are identified as: Soil 1 (GV-ES) and Soil 2 (GV-ES).

There are two main types of climates at site location tests: tropical rainy and humid mesothermal. The first one is characterized by high temperatures throughout the year and an average temperature above 22°C. The humid mesothermal climate is characterized by an average temperature of the coldest month below 18°C. Vitoria, the capital of the state of ES, is located partially in the continent (Camburi plain) and on an island (Vitoria Island) with several smaller islands, covering a territory of about 87 km^2 divided in two bays.

Table 2 summarizes the particle size distribution and index properties of the two tested soils corresponding to Liquid limit (LL), Plastic limit (LP), Plasticity index (PI) and Specific gravity (G_s). According to the Unified Soil Classification System, USCS, the two tested soils are classified as clayey sand (SC). It is observed that the two soils present more than 30% of fines content (silt and / or clay fraction). The clay fraction is dominated by kaolinite and crystalline iron oxides (Bicalho *et al.* 2015).

Figure 2. Location of test-site: Grande Vitoria, ES, Brazil

Table 2. Summary of measured index properties of the two tested soils from GV-ES, Brazil

Index property	SOIL 1	SOIL 2
Particle size distribution		
Gravel content (> 4.75 mm, %)	0.5	7
Sand content (≤ 4.75 mm, %)	59.5	58
Clay - Silt content (≤ 75 μm, %)	40	35
Specific gravity	2.719	2.702
Atterberg limits		
LL (%)	54	72
PL (%)	21	30
PI (%)	33	42

3.2 *Test setup and arrangement of instruments*

The used sensors to monitor the volumetric soil water content changes at the investigated soils from GV-ES are TRIME-PICO 64, of IMKO Micro GmbH, in Germany, which are capable of simultaneously measuring soil temperature and inferring the volumetric water content. TRIME measuring system operates with a factory calibration (Topp et al., 1980) for mineral soils as a standard. Material-specific calibration is recommended if one needs accuracy to the last digit. Through the equation published by Topp et al. (1980), Eq. 1a, the dielectric constant of each point was calculated in order to obtain specific calibration equations for the tested soils.

Approximately twelve continuous measurements were carried out to determine the mean values of the TDR volumetric water determinations. A comparison of the volumetric water content inferred from the TDR measurements (θ_{TDR}) with those obtained from the specific gravity and gravimetric water content (θ_{REF}) of the tested soils are made using the universal Topp et al. (1980)´s equation (Eq. 1a).

The TDR can be installed in the field in different ways. The in-situ measurements were performed using the TDR horizontally to facilitate the pre-drilled holes and inserting of the TDR probes. The TDR setup horizontally avoids possible heterogeneities between the soil layers (Hugh 1999) in the field.

4 RESULTS AND DISCUSSIONS

Topp et al. (1980) calibration function was evaluated for the two tested soils through the comparisons between θ values determined by the TDR using Topp et al. (1980) calibration, θ_{TDR}, and reference θ values determined by the specific gravity and gravimetric water content of the tested soils, θ_{REF}. The soil specimens for laboratory tests were compacted in predefined soil conditions into a PVC cylinder. A single TDR probe was inserted by hand into the compacted soil using the same procedure used in the field. At least 20 TDR measurements were made on each soil sample in the tube. In general, the obtained results were consistent for a given soil specimen, varying within a range of about 1% in any set of reading. Table 3 summarizes the volumetric water content (i.e., θ_{TDR} and θ_{REF}) and soil apparent dielectric permittivity (dielectric constant, K) values of the two tested soils. Topp et al. (1980) calibration significantly underestimates volumetric water content and its use should be avoid. The variation was less prominent in the soils with higher volumetric water content values.

Table 3. Summary of measured θ (average) values of the two tested soils from GV-ES, Brazil

θ REF	θ TDR	K
SOIL 1		
16%	6%	4.12
21%	10%	5.38
27%	23%	11.64
SOIL 2		
16%	9%	5.10
21%	13%	6.58
27%	28%	15.40

Figure 3 presents the calibration proposed by Topp et al. (1980) and the experimental results (mean values of the TDR volumetric water determinations) obtained for the two soils of GV-ES, Brazil. It can be noticed that the results obtained for the two tested soils show slight variations despite the differences observed in the index properties of the tested soils. Although the experimental results found in both field and laboratory tests analyzed in this paper do not fit the calibration proposed by Topp et al. (1980), measurents in both laboratory and field show that a single calibration could be used for diferent tropical soils from the same local.

The empirical calibration published by Medeiros et al. (2007) for tropical tested soils from South of Brazil is also shown in Figure 3. For practical purposes, the calibration proposed by Medeiros et al. (2007) for soils from different region is applicable to the measured data (i.e., the apparent permittivity and volumetric water content values) for the tested soils from GV-ES, Southeast Brazil. Ideally, however, independent calibration curves should be obtained using specific experimental data for the particular soil type.

Topp et al. (1980) equation significantly underestimates water content for the investigated soils from GV-ES for θ values between 15% and 30%. These results confirm the tendency observed by Medeiros et al. (2007) for a Brazilian Latosol soil. It may be due to the amount of clay and organic matter of the tested soil, which reduces the soil volumetric water content and therefore reduces the value of the corresponding apparent permittivity. Tommaselli and Bacchi (2001) mention that the called universal equation proposed by Topp et al. (1980) is not applicable to the Brazilian soils studied. Roth et al. (1990) and Yu et al. (1997) state that the Topp et al. (1980)´s equation overestimates volumetric water content values. One explanation for this behavior is that water is not so uniformly distributed (Topp et al., 1980). The observed errors of estimate θ values depend on the measured range of water contents.

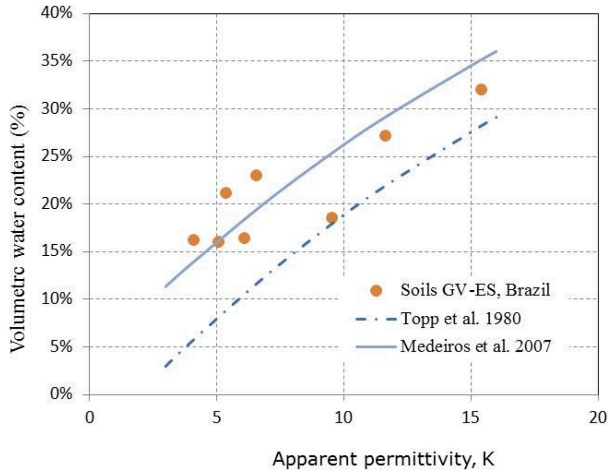

Figure 3. Comparison between different calibrations curves (Toll et al. 1980 and Medeiros et al. 2007) and the experimental data for the investigated soils from GV-ES, Brazil

5 CONCLUSIONS

The field and laboratory tests results show that the referred "universal" calibration (i.e., K-θ relationship) introduced by Topp et al., (1980) is not applicable for Brazilian condition tested soils and for the volumetric water content range between 15% and 30%. A soil- specific calibration is recommended for Brazilian tropical soils specially the clayey soils subject to a large range of moisture content variation in the field.

The tested soils are from the barrier group of the coastal region of the Grande Vitoria located in the state of ES, Brazil, with clay contents above 30%. It is observed that there is a general tendency fit between the results (θ TDR) for the two different tested soils. From measurements and observations taken during this study, it was possible to notice that the values of K are not significantly different for different types of soils from the same local, in spite of the differences observed in the index properties of the tested soils.

Although the experimental results do not fit well the calibration proposed by Topp et al. (1980), laboratory and field measurents show that a single calibration could be used for different soils from the same local in the state of ES, Southest of Brazil. The observed measured variation of the apparent permittivity with volumetric water content (%) for the investigated soils is consistent with the results of other studies (Medeiros et al. 2007) on tropical soils from different regions of Brazil.

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