Development of a new TDR probe for assessing the soil water content at different depths

Développement d'une nouvelle sonde TDR pour estimer le niveau d'humidité des sols à différentes profondeurs

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ABSTRACT
A system capable of measuring both gravimetric and volumetric water content of unsaturated soils, at different soil depths, is presented. This system, based on the Time Domain Reflectometry (TDR), uses a new probe with helical electrodes assembled to a cylindrical core. The new probe was designed to work in conjunction with CPTU equipment. Tests performed in the field have demonstrated that the use of the proposed technique is perfectly feasible and could be of great usefulness in geotechnical applications.

RÉSUMÉ
On présente un système capable de mesurer la teneur en eau, à la fois gravimétrique et volumétrique, des sols non saturés à différentes profondeurs. Ce système, fondé sur la technique de Time Domain Reflectometry (TDR), utilise une nouvelle sonde d'électrodes hélicoïdales montées sur une base cylindrique. La nouvelle sonde a été conçue pour fonctionner ensemble avec les équipements pour les essais CPTU. Les essais réalisés sur chantier ont montré que cette technique est parfaitement viable et peut être d'une grande utilité dans des applications géotechniques.

1 INTRODUCTION

Soil water content and dry density are two important properties required for engineered earthwork constructions, such as foundations, embankments, dams, retaining walls and slopes. Soil mechanics properties, including strength and deformability, are also dependent on water content.

Failure of unsaturated collapsible soils can be caused by water infiltration or water content variation. Thus, the study of problems concerning these issues requires information about the moisture conditions and hydraulic conductivity of the soil. These two factors have a direct influence on the total and matric suction which in turn have influence on the shear strength, compressibility and permeability.

These and many other problems require prompt information about the soil water content. Commonly used methods for determining water content in the field are either inaccurate or time consuming. As an alternative, the Time Domain Reflectometry (TDR) technique has been used in the determination of the soil water content. However, most of the TDR systems have been developed for agricultural purposes. The probes are suitable for water content measurements only at superficial layers of soil.

The present paper is intended to show a system capable of measuring both gravimetric and volumetric water content of unsaturated soils, at different soil depths. The proposed probe has been designed to work in conjunction with CPTU equipment. Tests performed in the field have demonstrated that the use of the proposed technique, using a probe with helical electrodes assembled on a cylindrical core and associated to Time Domain Reflectometry (TDR) technique is perfectly feasible and could be of great usefulness in geotechnical applications.

2 THEORETICAL BACKGROUND

In the telecommunications area TDR is used to identify locations of discontinuities in cables. The cable tester has a pulse generator that sends a high frequency electromagnetic signal along a cable. When the wave reaches a discontinuity, the signal is reflected back to the cable tester. The TDR instrument can be equipped with an oscilloscope that shows and records the signal waveform. The signal propagation elapsed time associated with the reflected signal allows the determination of the line break location.

Using a similar principle, it is possible to determine the travel time of electromagnetic pulses traveling along a probe of known length (L), buried into the soil.

Since the signal travel time depends on the relative permissivity or apparent dielectric constant (denoted Ka in this paper) of the soil surrounding the probe, from the waveform and travel time analysis, K_a can be computed.

The value of K_a is determined from (Jones et al. 2002):

$$K_a = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2 \quad (1)$$

where c = speed of light in vacuum (3×10^8 m s^{-1}); v = velocity of propagation; L = length of the probe; and t = travel time through the wave-guide (down and back = $2L$). The travel time is evaluated from the electromagnetic or apparent length (L_a) of the probe, which is equal to the scaled horizontal distance between the reflection from the soil surface and the reflection from the end of the probe (Figure 1).

The apparent dielectric constant of the soil is considerably affected by the dielectric constant of the water present in the

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soil, which is equal to 81 for a temperature of 20°C. The dielectric constants of other soil constituents are much smaller, ranging from 3 to 5. The large difference of dielectric constant values makes the soil apparent dielectric constant strongly dependent on the soil water content and relatively insensitive to soil composition and texture (Figure 1). Thus, it is possible to correlate the measured soil apparent dielectric constant to its water content. The correlations are referred to as calibration equations.

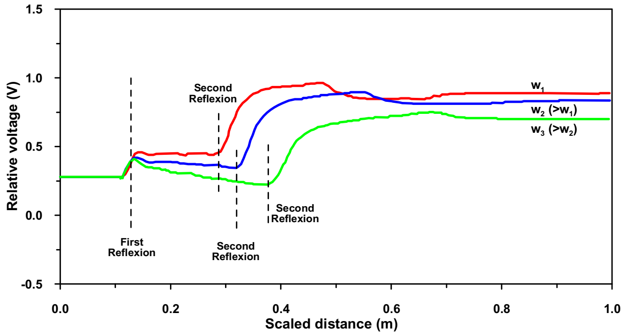

Figure 1. Sample of a TDR waveform (Esquivel & Giacheti, 2007).

3 SHAFT-MOUNTED TDR PROBE DESIGN

The majority of the conventional TDR probes uses a set of parallel rods that are inserted into the soil. TDR Probe length generally varies between 10 and 30 cm long and its use in deep soil profile implies in digging the soil for probe installation.

The basic concept of the shaft-mounted probe is to coil the transmission wires around a cylindrical core. The physical length of the probe can be reduced without compromising the travel time of the electromagnetic wave. Based on this concept, Nissen et al. (1998), Vaz & Hopmans (2001) and Persson & Wraith (2002) presented probe designs for agricultural purposes. In this research field, there is an interest in the determination of the soil water content at shallow depths only.

Based on this idea, the authors developed a probe for geotechnical engineering purposes capable of determining both water content and bulk density, at different depths. The transmission electrodes of this probe are coiled on a nylon sleeve, which in turn is mounted on a steel core. The diameter of the new probe was chosen to be the same of a standard 10 cm^2 CPTU probe. This makes it possible to use the CPTU penetrometer and rods to penetrate the probe into the soil. Each transmission electrode is 280 mm long and has a rectangular cross section with an area of 10 mm^2. The ground and conductor electrodes, separated by 30 mm, are fixed in place with epoxy resin. A 50 Ω coaxial cable connects the probe to the cable tester (Figures 2 and 3).

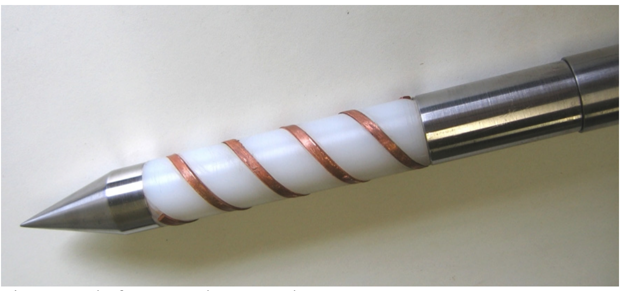
Figure 2. Shaft-mounted TDR probe.

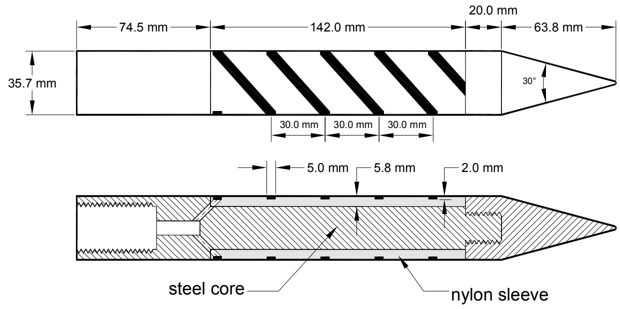

Figure 3. Schematics of the shaft-mounted TDR probe.

4 PROBE LABORATORY CALIBRATION

All TDR measurements were performed using a Tektronix 1502C Metallic TDR Cable Tester. Assessments of apparent dielectric constant (K_a) were made using WinTDR software, Version 6.1 (Or et al. 2004). The laboratory calibration process relies on performing TDR measurements on a particular soil, which is compacted in a cylindrical mold, at different moisture contents. The used PVC mold had an internal diameter of 202 mm and a height of 285 mm.

In the first calibration step, the soil is naturally dried in the air. Then, the soil is compacted in the mold and TDR measurements are performed. At this time, soil samples are collected to determine the gravimetric water content. The gravimetric water content (w) is evaluated by the oven-dry procedure (ASTM D2216). In the subsequent steps, water is gradually added to the soil in order to make the water content 5% higher than the previous one. Then, the soil is placed in plastic bags that are subsequently sealed and left to rest for a couple of hours, to ensure that an appropriate homogenization has occurred. After that, the soil is compacted in the mold and its mass is measured in order to assess the natural density of the soil. Following, the TDR measurements are performed and a small amount of soil is collected for oven-dry determination of water content.

The apparent dielectric constant (K_a) of the soil, for each value of moisture content, is assessed as output from the TDR measurement. The soil density (ρ) can be easily evaluated since the natural density of the soil is known a priori. The dry density can be calculated as $\rho_d = \rho / (1+w)$.

Topp et al. (1980) suggested that for conventional TDR probes, a single calibration equation was suitable for soils with a wide range of mineral content, and practically independent of soil density, salt content and environment temperature. This extensively used calibration equation, known as Topp's equation, correlates volumetric water content (denoted by θ in this paper) to apparent dielectric constant:

$$\theta = 4.3\times10^{-6} K_a^3 - 5.5\times10^{-4} K_a^2 + 2.92\times10^{-2} K_a - 5.3\times10^{-2} \qquad (2)$$

5 RESULTS AND DISCUSSION

Calibrations have been performed with soil samples collected from ten different sites. Tables 1 and 2 show some geotechnical characteristics of investigated soils.

Table 1 Grain size distribution.

Soil	Clay (%)	Silt (%)	Sand (%)	Gravel (%)
1	22	14	62	2
2	60	32	8	0
3	28	23	48	1
4	22	13	61	4
5	57	28	15	0
6	3	49	48	0
7	22	8	70	0
8	31	9	60	0
9	36	10	54	0
10	34	7	59	0

Figure 4 shows the response of the soil relative permissivity (K_a) with the volumetric (θ) and gravimetric (w) water content for the ten different soils studied. The well known and typical non linear variation of K_a with the θ is observed, as shown by Vaz e Hopmans (2001) using a similar coiled TDR probe. The variation observed among soils is probably due to their composition and particle size distribution (Table 1). The relationship between K_a and w (Figure 5) is more scattered than the one between K_a and θ (Figure 4), but it also shows the direct dependence between the soil relative permissivity and the water content.

Table 2 Soil densities.

Soil	Solid density	Bulky density		Dry density	
		AVG(1)	STD(2)	AVG(3)	STD(4)
	($g\ cm^{-3}$)	($g\ cm^{-3}$)	($g\ cm^{-3}$)	($g\ cm^{-3}$)	($g\ cm^{-3}$)
1	2.80	1.55	0.14	1.13	0.10
2	2.67	1.33	0.13	0.96	0.11
3	2.86	1.36	0.15	1.04	0.06
4	2.91	1.71	0.16	1.35	0.15
5	3.09	1.57	0.20	1.19	0.09
6	2.72	1.45	0.23	1.07	0.09
7	2.70	1.80	0.20	1.44	0.17
8	2.68	1.70	0.17	1.30	0.11
9	2.94	1.65	0.18	1.30	0.10
10	2.69	1.61	0.24	1.30	0.12

(1) average of densities corresponding to each water content level.
(2) standard deviation of densities corresponding to each water content level.
(3) average of dry densities corresponding to each water content level.
(4) standard deviation of dry densities corresponding to each water content level.

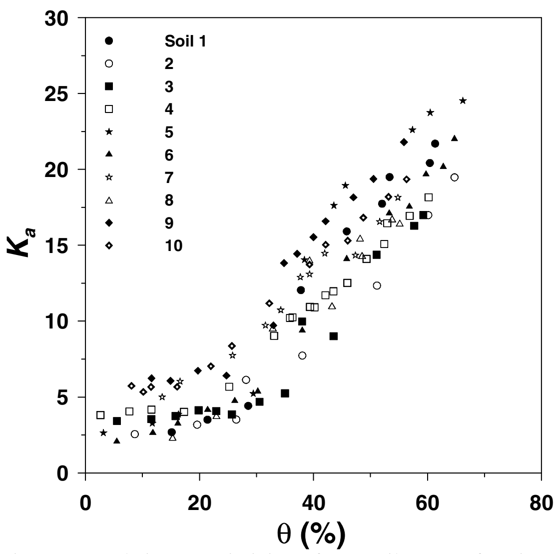

Figure 4. Relative permissivity of 10 soils as a function of the volumetric water content.

Calibration curves for individual soils were obtained with third order polynomial equations in w versus $\sqrt{K_a}$ plot and are presented in Table 3. Such calibration curves were used for estimating the gravimetric water content in the soil profile of four sites with 4 points each (16 sampling points). Figure 6 shows an example of the gravimetric water content estimated and measured (disturbed soil samples collected by drilling) in Site 1 (Campus I of EESC/USP), Soil 7, from 1.5 to 5 meters deep.

Figure 7 presents the correlation between the estimated and measured gravimetric soil water content at the four field sites. The root mean square deviation (RMSD) obtained were 1.3 %, 3.7 %, 3.8 % and 2.3 % for Site 1 (Soil 7), Site 2 (Soil 8), Site 3 (Soil 9) and Site 4 (Soil 10), respectively. The average RMSD was 2.8 %, which can be considered very accurate for field determination of water content with the TDR technique and consistent with most TDR measurements in the literature using conventional TDR probes (Topp et al. 1980).

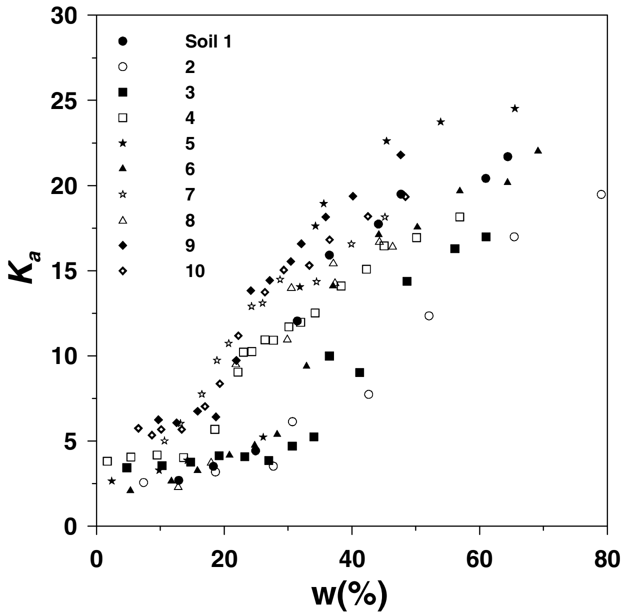

Figure 5. Relative permissivity of 10 soils as a function of gravimetric water content.

Table 3 Calibration constants corresponding to $\sqrt{K_a}$ versus w correlations

Soil	*a*	*b*	*c*	*d*
1	7.42	-66.18	196.62	165.20
2	6.17	-55.09	176.00	-155.34
3	22.82	-208.39	628.45	-585.42
4	7.18	-61.73	188.22	-179.30
5	7.50	-73.95	240.36	-226.94
6	5.69	-50.11	152.16	-127.80
7	4.33	-34.37	99.25	-87.52
8	4.81	-36.49	95.82	-65.76
9	5.69	-56.24	193.00	-206.21
10	9.68	-92.38	301.81	-315.31

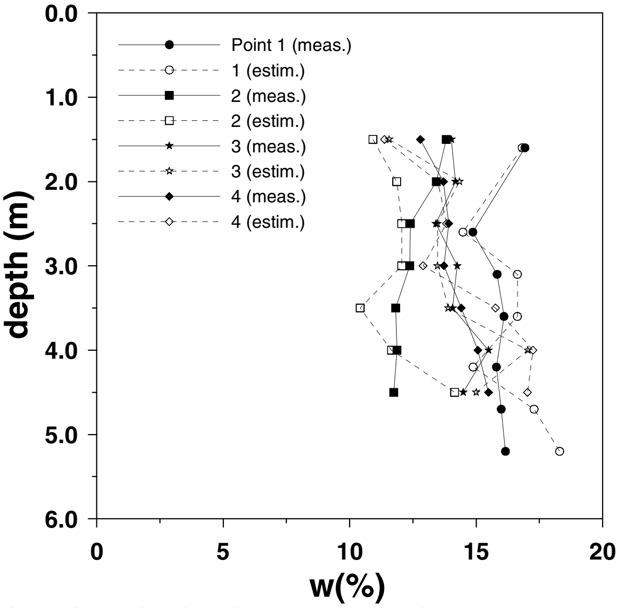

Figure 6. Gravimetric soil water content estimated by TDR and measured at four different points at Site 1 (Campus I of EESC/USP), Soil 7.

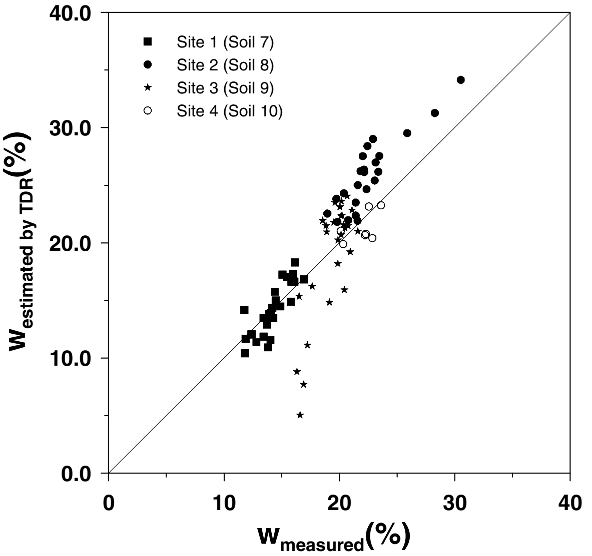

Figure 7. Comparison between gravimetric soil water content values estimated by TDR and measured (disturbed soil samples collected by drilling).

6 CONCLUSIONS

A new TDR probe design, for geotechnical purposes, was developed and evaluated. The key advantage of this probe is that it can be used to determine both gravimetric and volumetric water content of soils, at different soil depths. Differently from the standard TDR probes with straight rods, the new probe consists of two parallel copper stripes coiled around a PVC-steel core.

Test results obtained with the new coiled TDR probe in ten different soils with different granulometry confirm the usefulness of such design and its accuracy in determining the gravimetric soil water content in field. Further effort should be done to model the calibration data (Figure 1 and 2) in terms of the dielectric mixing model (Dobson et al. 1995) and the fitting parameter interpretation for the 10 soils considering their composition and granulometry.

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