Use of a Combined Penetrometer-TDR Moisture Probe for Soil Compaction Studies

Carlos Manoel Pedro Vaz[1]

Embrapa Agricultural Instrumentation, São Carlos, Brazil

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[1] vaz@cnpdia.embrapa.br

Introduction

Soil mechanical strength is an important soil parameter that affects root growth and water movement, and controls nutrient and contaminant transport below the rooting zone. The most common way to assess soil strength is by using a soil penetrometer, which characterizes the force needed to drive a cone of specific size into the soil (Bradford, 1986). The measured penetration resistance (PR) depends on such soil properties as bulk density, water content and potential, texture, aggregation, cementation and mineralogy.

Soil scientists have related changes in PR as caused by tillage, traffic or soil genetic pans to root growth, crop yields and soil physical properties. For example, correlation between PR and crop root growth and water and nutrient exploration have been obtained (Stelluti et al. 1998), and cone penetrometers have been used extensively in soil science studies to identify natural and induced compacted layers (Henderson, 1989) or to predict related soil properties (Ayers and Bowen, 1987).

Many studies have been conducted to understand the influence of bulk density (ρ) and water content (θ) on PR in the laboratory (Taylor and Gardner, 1963; Mirreh and Ketcheson, 1972; Ayers and Perumpal, 1982; Ayers and Bowen, 1987; Ohu et al. 1988) and field (Simmons and Cassel, 1989; Vasquez et al. 1991, Busscher et al. 1997), from which both empirical and theoretical relationships were obtained. From the many different models that have been introduced to test these relationships (polynomial, exponential, power and linear equations), Busscher et al. (1997) suggested that either the power or exponential equations are the most adequate. Using dimensional analysis techniques, Upadhyaya et al. (1982) suggested a power-exponential equation for prediction of the PR as a function of ρ and θ for a silt loam soil, but also suggested additional experimental work for its validation.

However, many referenced studies lack accurate and representative data, because PR is a highly variable soil property, whereas it is usually determined from local small-scale measurements. Hence, difficulties in relating PR with other soil parameters can be attributed mostly to soil spatial variability, because available measurement techniques prevent determination of the different soil attributes (PR, ρ, θ, organic matter, texture) at the same spatial location.

To improve on the measurement technique, we have developed a combined cone penetrometer-TDR moisture probe by wrapping two TDR wires around the penetrometer rod (combined rod TDR) as a double helix, so that both soil water content and penetration resistance can be measured simultaneously and at approximately the same location within the soil profile (Vaz and Hopmans, 2001). The main advantage of the coiled design is that relative long travel times can be obtained, allowing accurate water content measurements for small-sized TDR probes.

The objective of this lecture is to present the combined penetrometer-TDR probe as a new tool to study soil compaction. The presentation will cover the following topics:

- Theory of the dynamic cone penetrometer;
- Laboratory calibration of a coiled TDR moisture probe and application of the mixing model;
- Field calibration and use of the combined penetrometer-coiled TDR moisture probe;
- Penetration resistance, bulk density, water content and potential relationships;
- Practical applications of the combined penetrometer-coiled TDR moisture probe.

Coiled TDR probe design

The basic configuration of the combined penetrometer coiled TDR moisture probe is shown in Figure 1. The coiled TDR probe consists of 2 parallel copper wires (ground and conductor wire), each 0.8 mm diameter and 30 cm long, coiled around a 5 cm long PVC core, with a 3 mm separation distance between the two wires. The coil is constructed at the bottom of the penetrometer rod, immediately above the cone of the penetrometer. A 2.5 m long 50 Ω coaxial cable is passed through the hollow steel shaft of the penetrometer probe and connected to a cable tester (Tektronix 1502C).

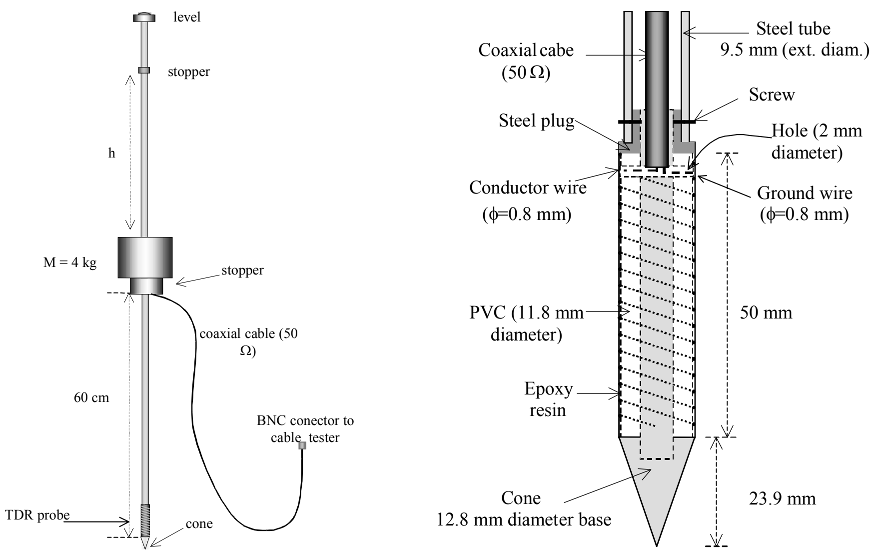

Figure 1. Combined penetrometer – coiled TDR moisture probe.

Laboratory calibration

The waveform or trace is transferred from the cable tester to a personal computer through the RS232 serial port and analyzed. The trace (Figure 2) is a visualization of the amplitude of a reflected pulsed electromagnetic wave as a function of propagation or travel time along the TDR probe. The trace can be regarded as a signature of the physical status of the soil, and it can be shown that knowledge of the travel time is sufficient to determine the bulk material dielectric constant of the soil (Topp et al., 1980).

Using a mixing model approach, the dielectric constant measured by the coiled TDR probe (ε_{coil}) can be related to the soil dielectric constant as determined by the conventional probe (ε_{soil}):

$$\varepsilon_{coil} = \left[w\varepsilon^{n}_{probe} + (1 - w)\varepsilon^{n}_{soil} \right]^{1/n} \quad [1]$$

In Eq. [1], w is a weighting factor that partitions the measured dielectric by the coiled TDR probe between contributions by the epoxy and PVC of the probe (ε_{probe}) and the bulk soil (ε_{soil}) and the parameter n defines the probe's geometry and ε_{probe} is the dielectric constant of the PVC and epoxy material in which the wire coils are imbedded. The dielectric constant of the soil (ε_{soil}) as determined by a conventional probe is written in terms of the fractional bulk volume of each of the 3 soil phases (1-ϕ, ϕ-θ, and θ, for the solid, gas and water phase, respectively). Hence,

$$\varepsilon_{soil} = \left[(1 - \phi)\varepsilon^{\alpha}_{s} + (\phi - \theta)\varepsilon^{\alpha}_{a} + \theta\varepsilon^{\alpha}_{w} \right]^{1/\alpha} \quad [2]$$

where ϕ (cm^3cm^{-3}) and θ (cm^3cm^{-3}) denote the soil porosity and volumetric water content, respectively, and ε_s, ε_a and ε_w are the dielectric constant of the soil solid material, air and water, respectively, with assumed values of ε_a =1.0; ε_w = 80 and ε_s=3.9 (Dasberg and Hopmans, 1992).

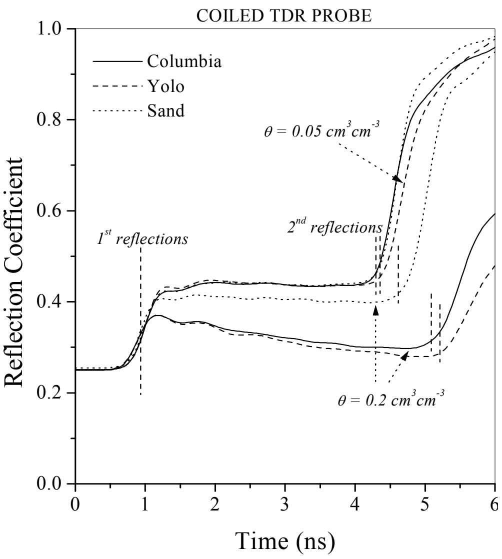

Figure 2. Waveforms for the coiled TDR probe designs for three soils at water contents values of 0.05 and 0.20 cm^3cm^{-3}.

The ε_s-value varies slightly with mineralogical composition of the soil solid material (Yu et al. 1999). For instance, the dielectric constant of quartz can vary between 3.75 and 4.1 (Lide, 1996), whereas an aluminum silicate has a dielectric constant of 4.8 (Fink,1978). Also, the presence of organic matter increases the dielectric constant of organic soils to values as high as 5.0. For the mineral soils studied here, an ε_s-value of 3.9 appears to be a good estimation for the investigated mineral soils. The exponent α depends on the geometry of the soil solid phase and the soil's orientation with respect to the applied electric field and must be $-1 < \alpha < 1$ (Roth et al. 1990).

After substitution of Eq. [2] into [1], the dielectric constant as measured with the coiled TDR probe (ε_{coil}) can be written as:

$$\varepsilon_{coil} = \left\{ w\varepsilon_{probe}^{n} + (1-w)\left[(1-\phi)\varepsilon_s^{\alpha} + (\phi-\theta)\varepsilon_a^{\alpha} + \theta\varepsilon_w^{\alpha}\right]^{n/\alpha} \right\}^{1/n} \quad [3]$$

The presented mixing model approach is preferred to allow for a meaningful physical interpretation of the calibration results (Roth et al., 1990), rather than the model fitting of an arbitrary empirical functional relationship. Moreover, the application of Eq. [3] inherently corrects for the influence of bulk soil density on the bulk soil dieletric constant. Alternatively, one can simply use a polynomial to substitute for Eq. [3], writing ε_{coil} as a function of water content, and fit the data to estimate the regression coefficients as was done in Topp et al. (1980), and later for the field calibration results.

The calibration data of the coiled TDR probe for three soils are presented in Figure 3. Calibration curves (lines in Figure 3) for the coiled probe were obtained substituting the fitted parameters n, w and α in Eq. [3] and using average values of bulk density and porosity.

Influence of soil water content and bulk density on penetration resistance

The combined penetrometer-cone TDR data are averaged and presented in Figure 5 for both the dry and wet soil treatments. PR is presented as a function of θ, with different symbols indicating ranges in magnitude of depth-averaged dry bulk soil density (ρ). As expected, there is a tendency of PR to increase as ρ increases at equal θ values. Moreover, the fitted curves demonstrate the intuitive–correct results that (1) the bulk density effect on PR decreases as the water content increases and (2) PR increases exponentially with decreasing water content.

Depth distribution of penetration resistance (a) and volumetric water content (b) as determined from measurements with the combined penetrometer-coiled cone TDR probe are presented in Figure 4 for a dry (before irrigation) and wet soil condition.

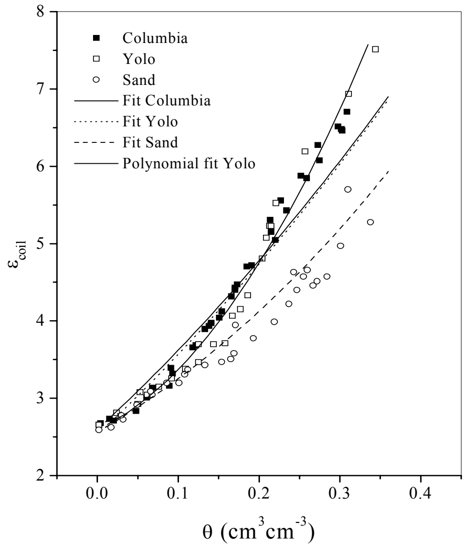

Figure 3. Calibration data for the coiled TDR probe using Eq. [3] for 3 soils, using parameters n, w, ε_{probe} fitted to Eq. [1] and soil specific α–values fitted to Eq. [2].

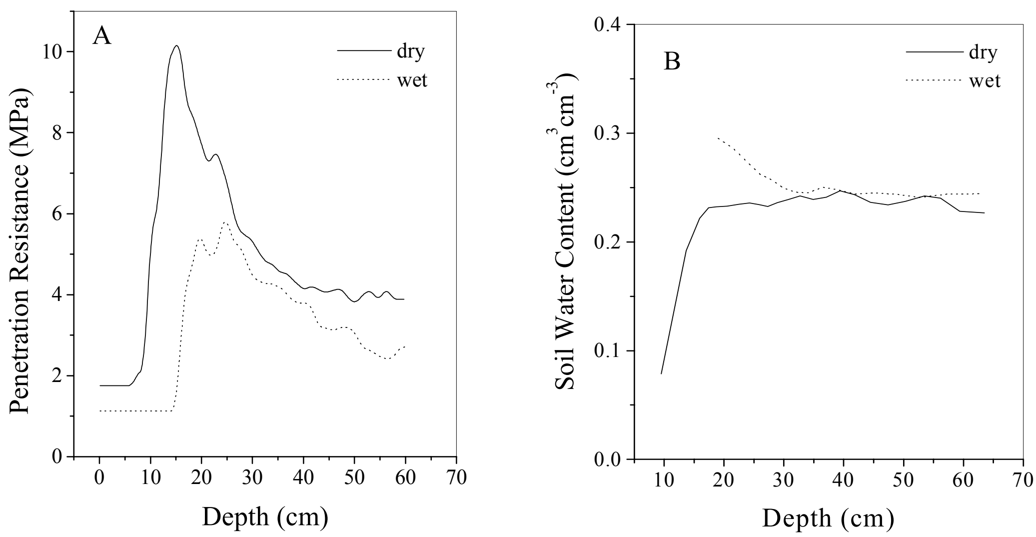

Figure 4. Combined field measurement results of penetration resistance (PR) and water content (θ) obtained with the combined coiled TDR-cone penetrometer probe

Using the model-fitting software of Wraith and Or (1998), the PR, θ, and ρ data in Figure 5 were fitted to Equation [3], yielding soil-specific parameter values of a =170.15, n = 3.22, and b = 5.99, and a r^2-value of 0.72 and RMSE = 0.98. We conclude that Eq. [3] of Upadhyaya et al. (1982) described the experimental data fairly well within the water content range of 0.15 – 0.30 cm^3 cm^{-3}. Scattering of data presented in Figure 5 was caused by a combination of factors such as the relatively narrow range of water content; different sampling locations of combined probe

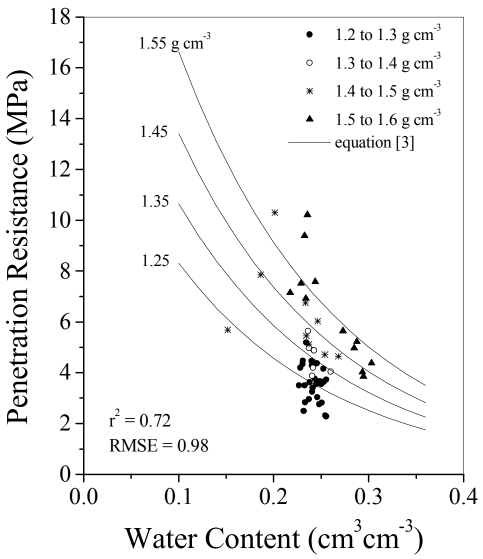

Figure 5. Correlation between water content measured by the coiled TDR probe (ε_{coil}) and gravimetric data from collected soil cores

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