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Geoelectrical Measurements by TDR Penetrometer

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Abstract

Electrical properties of a bulk soil include its electrical conductivity and dielectric permittivity. Conventional electrical probes measure only the resistivity (the reciprocal of the electric conductivity) profile of a soil deposit. Interpretation of the resistivity alone for soil physical properties is difficult because it is sensitive to many factors, such as water content, soil type and soil solution characteristics. To better characterize a bulk soil electrically, both the electrical conductivity and dielectric permittivity should be measured. This paper introduces a Time Domain Reflectometry (TDR) penetrometer to allow simultaneous measurements of dielectric permittivity and electrical conductivity during cone penetration. A TDR penetrometer is formed by placing a multiple-conductor waveguide around a non-conducting shaft. A homogenization model is proposed to determine the effective electrical properties in terms of the electrical properties of the shaft and surrounding soil. A TDR wave propagation model based on the transmission line theory is derived to provide a theoretical relationship between the electrical properties of surrounding soil and the TDR response. The wave propagation model accounts for all wave phenomena including multiple reflection, dielectric dispersion, and cable resistance. Inverse analysis based on the TDR wave propagation model is proposed to calibrate the TDR system parameters. The calibration parameters involved in the homogenization model are shown to be easily determined by calibration tests with several materials of different and known electrical properties. A prototype TDR penetrometer was fabricated and used to perform simulated penetration tests in a calibration chamber. The effect of penetration disturbance is quantitatively reported and explained. The implications of the data that can be measured by the TDR penetrometer are also discussed.

Key Words TDR penetrometer, dielectric constant, electrical conductivity

Introduction

The soil physical properties, such as water content, void ratio, and physical chemistry of pore water, are of great interest in geo-environmental and hydro-geological problems. Furthermore, soil-water interaction and soil microstructure are important to the renewed focus on the fundamentals of soil behavior. These physical properties of soils are usually investigated using laboratory techniques on samples retrieved from a borehole. Hence, questions arise as to how representative laboratory samples are of the actual field conditions. In particular, it is relatively difficult to obtain undisturbed sample in sand deposits. It is also costly and time consuming to obtain soil physical properties using traditional drilling and laboratory techniques. Conventional in situ testing methods, be it standard penetration test (SPT), cone penetration test (CPT), or Dilatometer test (DMT), focuses on mechanical response of the soil under test. Field tests for characterizing soil physical parameters are more likely to be implemented by electrical methods, since electrical properties are related to the soil composition and less affected by the stress state.

Electrical properties of a soil include its electrical conductivity and frequency-dependent dielectric permittivity. Much laboratory and theoretical work has been done on the relation between soil electrical and physical parameters (Santamarina et al. 2001[1]). These results encourage further development of field measurement techniques and more effective homogenization model for electrical properties of porous media. While laboratory and theoretical development continues to advance, electrical characterization in situ lags behind. Campanella and Weemees (1990[2]) developed an electrical resistivity module in CPT using the four-electrode array under low frequency excitation. Several similar modules are now commercially available. However, interpretation of the resistivity alone for soil properties is difficult because it is sensitive to many factors, such as water content, soil type and soil solution characteristics. CPT dielectric modules have been reported more recently for soil moisture measurements based on resonant frequency modulation or time domain reflectometry (Knowlton et al. 1995[3]; Singh et al. 1997[4]; Young et al. 1999[5]; Vaz and Hopmans 2001[6]). On the contrary, these probes measure only the dielectric constant in a certain frequency range. To better characterize the soil electrically, both the resistivity (reciprocal of electrical conductivity) and dielectric permittivity in a wide band are desired. The spatial sensitivity and penetration effect of both resistivity and dielectric penetrometer should also be studied.

The Time Domain Reflectometry (TDR) is a geophysical method based on electromagnetic waves. It can be used to make simultaneous measurements of apparent dielectric constant ,electrical conductivity, , and dielectric constant at different frequencies of a soil (Topp et al. 1980[7]; Topp et al. 1988[8]; Heimovaara 1994[9]). Much work has been published in soil science regarding the measurements of soil water content and salinity using apparent dielectric constant and electrical conductivity.

A four-phase research project was undertaken at National Chiao Tung University in Taiwan to develop an efficient field method for estimating various physical properties of soils using time domain reflectometry. The four-phase steps of the research was (1) development of field probes suitable for TDR measurements of soils at various depths, (2) construction of homogenization models for soil electrical properties as functions of soil compositions, (3) development of dielectric spectroscopy of soils using the new field probe, and (4) development of theoretical or semi-empirical relationships to extract soil physical properties from electrical properties. As part of the phase one, a TDR probe was developed to be used in conjunction with the Cone Penetration Test (CPT) or deployed as a permanent sensor. The probe was specifically designed to be directly inserted into soils without the need for digging, drilling, or other types of soil preparation. The present paper describes details of the probe design and calibration methods for dielectric constant and electrical conductivity measurements. The laboratory investigations of the spatial sensitivity and penetration effect of the TDR penetrometer are also reported.

Theoretical Development of TDR Penetrometer

Probe Design

Standard waveguides or probes for TDR measurements are primarily of two types: coaxial type and multi-conductor type, as shown in Fig. 1(a) and 1(b). The coaxial type of probe is composed of a cylinder acting as the outer conductor and a rod along the centerline of the cylinder acting as a central conductor. The multi-conductor type of probe is composed of one or more rods acting as the outer conductors and a center rod as the inner conductor. The coaxial type of probe is adopted for laboratory measurements such as in the compaction mold or in a Shelby tube, using the cylinder as the outer conductor with the inner conductor being a steel rod inserted along the centerline of the soil in the mold. The multi-conductor probes can be used for in-place measurements. Conventional multi-conductor probes are 30 cm long and therefore difficult to insert at depths below one meter. In order to adapt the TDR technique to a cone penetrometer application, a new design is required for the probe. The multiple conductors are placed around a non-conducting shaft to form a TDR probe as shown in Fig. 1(c).

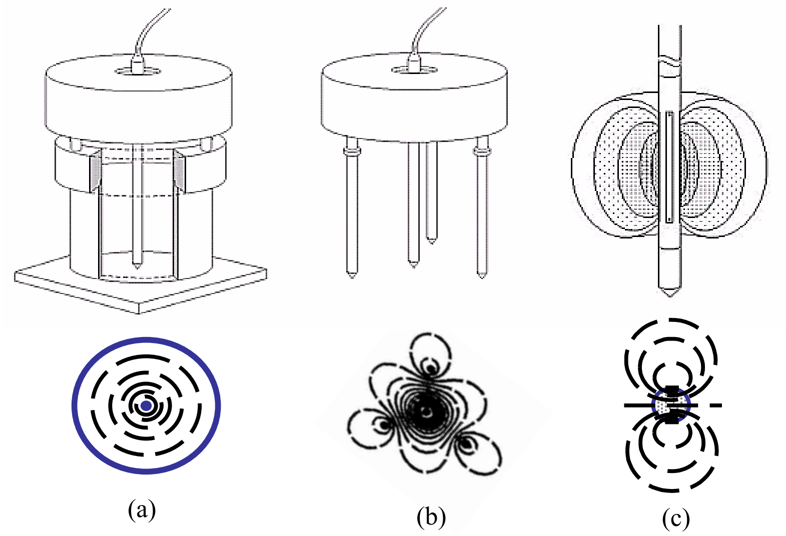
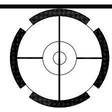
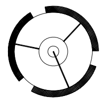
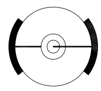
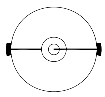
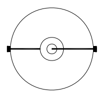


Fig. 1. Configurations of types of transmission lines and illustrations of their associated electrical potential distribution.

Also shown in Fig. 1 are the electrical potential distributions corresponding to the cross-sections of different probe types. The electrical field is contained in the cylinder for a coaxial probe while it is open in a multi-conductor probe. Placing multiple conductors around a non-conducting shaft allows the waveguide to sense the material around the shaft. It should be noted that the material inside the shaft of the TDR cone penetrometer is different from the surrounding material to be measured by the probe design. Therefore, a new calibration procedure is required for measurements of the apparent dielectric constant and electrical conductivity using the TDR penetrometer. Previous studies on two-conductor probe have shown that the non-uniform spatial weighting in the plane transverse to the probe is inherent in the TDR measurement and cannot be eliminated (Baker and Lascano 1989[10]; Knight 1992[11]). Hence, the probe should be designed to minimize the effect of the material inside the shaft and maximize the influence zone in the surrounding medium. A series of trial probes were constructed in the laboratory to determine the optimal configuration for the waveguide. The variables considered included the number of conductors and conductor width (or spacing). The PVC tubes were used as the shaft and copper strips as the waveguide conductors. The configurations of the trial probes are summarized in Table 1. A later section will present the performance of these probes through laboratory investigations.

Table 1. Probe types with different conductor configurations.

Type No.	Copper width (mm)	Copper length (mm)	No. of copper strips	Probe type*
T1	20	200	4	
T2	30	146	3	
T3	20	200	2	
T4	10	200	2	
T5	3	200	2	

*: bold lines represent copper strips

Calibration Methods for Measuring K_a and σ

The dielectric constant measured by the penetrometer probe is a weighted average of the soil-water medium dielectric constant and the dielectric constant of the probe material (Derlin® and air) between the conductors. We formulate a new calibration equation was formulated to determine the dielectric constant of the surrounding soil from travel time analysis of the waveform measured by TDR penetrometer. The derivation of the new calibration equation is based on a homogenization model proposed by Birchak et al. (1974[12]). Using Birchak's exponential model, the effective (or measured) apparent dielectric constant ($K_{a,eff}$) may be written as a function of the soil dielectric constant ($K_{a,soil}$) and probe dielectric constant ($K_{a,probe}$). We have

$$\left(K_{a,eff}\right)^n = a\left(K_{a,soil}\right)^n + (1-a)\left(K_{a,probe}\right)^n \tag{1}$$

where n is an empirical constant that summarizes the geometry of the medium with respect to the applied electric field and a is a weighting factor of the surrounding soil. The last term in Eq 1 can be lumped as an empirical parameter b, since the dielectric permittivity of the probe is a constant. Hence, the soil dielectric constant may be determined from the TDR penetrometer measurement as

$$K_{a,soil} = \left(\frac{(K_{a,eff})^n - b}{a} \right)^{1/n} = \left(\frac{\left(\frac{cT}{2L} \right)^{2n} - b}{a} \right)^{1/n} \quad (2)$$

where n, a and b are calibration parameters for the measurement of apparent dielectric constant using the TDR penetrometer. T and L are travel time and probe length, respectively. Similarly, the probe material between the conductors affects the effective electrical conductivity. Following the same homogenization formulation, the effective (measured) electrical conductivity (σ_{eff}) is related to the soil electrical conductivity (σ_{soil}) and probe electrical conductivity (σ_{probe}) as

$$(\sigma_{eff})^n = a(\sigma_{soil})^n + (1-a)(\sigma_{probe})^n \quad (3)$$

where weight factor a in Eq 3 may or may not be identical to that in Eq 1. Consider that the probe material between the conductors is not conductive ($\sigma_{probe} \approx 0$), the soil electrical conductivity based on Giese and Timman method (Topp et al. 1988[8]) may be determined from the TDR penetrometer measurement as

$$\sigma_{soil} = \frac{(\sigma_{eff})}{a^{1/n}} = \frac{\alpha\left(\frac{2}{V_{r,\infty}} - 1 \right)}{a^{1/n}} = \beta\left(\frac{2}{V_{r,\infty}} - 1 \right) \quad (4)$$

where $V_{r,\infty}=V_\infty/V_0$, α is the calibration parameter for the measurement of electrical conductivity using the TDR penetrometer. The new calibration equations (Eq 2 and Eq 4) will be verified by experimental data.

Experimental Evaluation of Probe Performance

The multi-conductor penetrometer waveguides may have different features in the TDR response depending on the number of conductors and conductor width. The optimum probe configuration should result in TDR waveforms in which travel time analysis can be easily performed. In addition, the effective dielectric constant should be as close to the soil-water medium dielectric constant as possible, and the probe have an influence zone around it as far as possible. The efficiency and accuracy of each type of probe was evaluated.

TDR Waveforms and Effective Measurement

Time domain reflectometry measurements were made by attaching the TDR probe to a Tektronix 1502C via 2 m of 50-ohm coaxial cable fitted with 50-ohm BNC connectors at each end. The multi-conductor penetrometer waveguides were submerged in a large tank (100cm*100cm*50cm) filled with tap water. Figure 2a shows the TDR waveforms in water for waveguides with different numbers of conductors. Similarly, the waveforms in water for 2-conductor waveguides with different conductor width are shown in Fig. 2b. The waveform of a coaxial probe is also shown in Fig. 2a and Fig. 2b for comparison. The length of the coaxial probe was 116 mm and the length of T2 was 146mm. All other probes were 200 mm. The TDR sends a step pulse down the cable and some of the wave energy is reflected from both the beginning and end of the probe as shown in Fig. 2a and Fig. 2b. From a practical perspective, the data shown in Fig. 2a and Fig. 2b suggest any of the 5 probe configurations can be used in terms of identifying reflection points. However, as the number of conductors and conductor width increases, the impedance of the probe decreases and the negative reflection at the beginning of the probe increases, causing the waveform to drop down to a lower level. Hence, the reflection points in probe T1 are clearest. This becomes more obvious especially when the dielectric constant of the surrounding medium decreases (e.g. soils with low water contents).

The traveltime T of the penetrometer probe is about 70% of that of the coaxial probe with the same length. All penetrometer probes perform similarly in this aspect. The effective dielectric constants measured by the probes listed in Table 1 are all near 41, which is approximately equal to $(K_{a,water} + K_{a,probe})/2$, in which $K_{a,water}$ = 80 and $K_{a,probe} \approx 2$. Considering the theoretical value n = 1.0, Eq 1 can be simplified as

$$K_{a,eff} \cong \frac{K_{a,soil} + K_{a,probe}}{2} \tag{5}$$

for all probe configurations. Regardless of the waveguide configuration, the material, Derlin® and air, inside the probe weights the same as the material surrounding the probe in K_a measurements.

Unlike the traveltime measurement, the asymptotic value of the reflection coefficient $V_{r,\infty}$ depends on the impedance of the probe. As the number of conductors and conductor width increases, the impedance of the probe decreases and $V_{r,\infty}$ decreases. Therefore, the effective electrical conductivity (σ_{eff}) can not be determined unless the constant α in Eq 4 is known for the multi-conductor probe with conductor arrangement identical to the TDR penetrometer but without the cone shaft. However, the relationship between the effective electrical conductivity and electrical conductivity of the surrounding medium can be revealed by comparing the σ value of the TDR penetrometer with that of the probe with the same conductor arrangement but without the cone shaft. The measurements in tap water showed that $\sigma_{eff} = 0.5\ \sigma_{Tap\ water}$ and $\sigma_{probe} = 0$ (Derlin® and air are nonconductive) for all probe types listed in Table 1. Considering the theoretical value n = 1.0, Eq 3 can be simplified as

$$\sigma_{eff} \cong \frac{\sigma_{soil} + \sigma_{probe}}{2} \tag{6}$$

Regardless of the waveguide configuration, the material inside the probe also weights the same as the material surrounding the probe in σ measurements.

The material surrounding the TDR penetrometer contributes 50% to the effective dielectric constant and electrical conductivity. This percentage can not be increased by changing the conductor configuration. Placing multiple conductors around a non-conducting shaft allows the waveguide to sense the material around the shaft at depths, but decreases the sensitivity of dielectric and conductivity measurements. The measurement sensitivity is defined here as the derivative of the TDR response (i.e. the T or $V_{r,\infty}$) with respect to the dielectric constant or electrical conductivity of the material under test. The sensitivity of the TDR penetrometer is about 70% of the coaxial or conventional multi-conductor probes. This reduction in sensitivity is acceptable in practice.

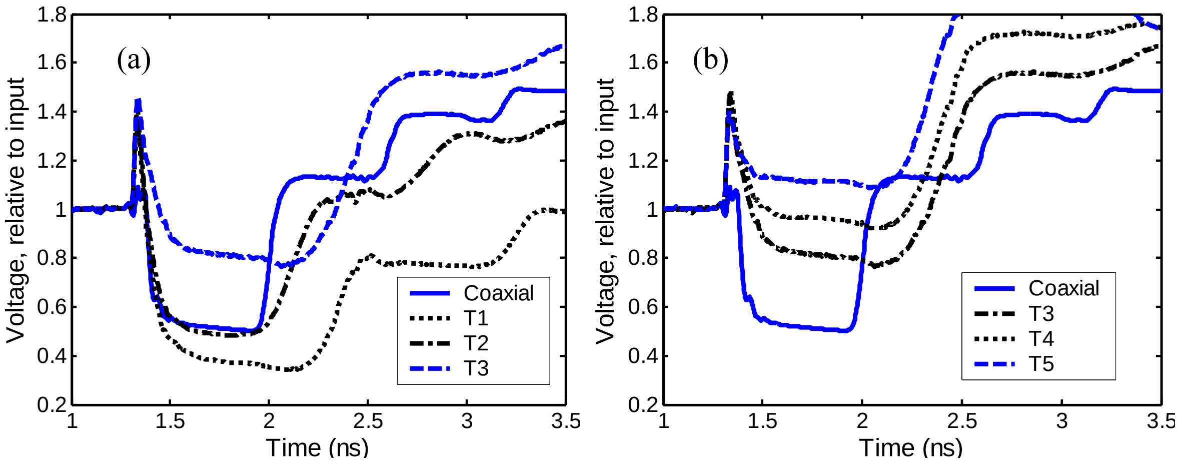


Fig. 2. The TDR waveforms of probes with different number of conductors (a) and spacing (b).

Radial sampling

The radial sampling of TDR measurements using the TDR penetrometer may be investigated using electromagnetic field theory. Alternatively, an experimental approach was taken since the theoretical derivation is complicated and also needs to be verified experimentally. In order to investigate the radial sampling of the TDR penetrometer, the trial probes were submerged in water-filled PVC tubes of different diameters. Figure 3 illustrates the cross section of the testing arrangement in the plane transverse to the probe. The material surrounding the TDR penetrometer is a composite medium with tap water located concentrically around the center rod and air outside the PVC pipe. The dielectric constant of the PVC material is close to that of air, so the internal side of the PVC tube can be considered as the boundary between tap water and air. Since the dielectric constants of water and air lie in the two opposite extremes ($K_{a,water}$ = 80 and $K_{a,air}$ = 1.0) the 'spatial weighting function' for K_a may be defined experimentally as

$$F(r) = \frac{K_{a,r}}{K_{a,eff}} \times 100\% \tag{7}$$

where $K_{a,r}$ is the effective dielectric constant measured in a water-filled PVC tube with r defined as the distance between the external side of the probe and the internal PVC wall, and $K_{a,eff}$ is the effective dielectric constant measured in a large water-filled tank. $K_{a,eff}$ is representative of the effective dielectric constant measured in a water-filled PVC tube with $r = \infty$.

The K_a spatial weighting functions for different probe configurations are also shown in Fig. 3. The effective dielectric constant approaches an asymptotic value at a distance of 100 mm and greater. The majority of the electromagnetic response occurs within the first several centimeters in the radial direction. The four-conductor probe (T1) and three-conductor probe (T2) have similar spatial weighting functions; and the spatial weighting appears to be insensitive to the conductor width for the two-conductor configuration (see T3, T4, and T5). In K_a measurements, the radial sampling of the four-conductor probe (T1) and three-conductor probe (T2) is more focused on the vicinity of the probe than that of the two-conductor probes (T3, T4, and T5). Observations from Fig. 3 raise the concern for the penetration (disturbance) effect on K_a in soil measurements. The soil displaced by the penetrometer may change the density of the soil adjacent to the penetrometer, and hence the dielectric constant.

Unlike dielectric permittivity, effective electrical conductivity is a directional and conductive parameter that depends on current flow paths and distribution of conductivity variation. Defining a unique spatial sampling function for the electrical conductivity measurement is not possible. To compare the radial sampling of different probes, a spatial weighting function for electrical conductivity analogous to Eq 7 was experimentally defined using the same PVC-tube experiments depicted in Fig. 3. The tap water inside the PVC tube was conductive with $\sigma = 0.67$ dS/m and the PVC material and air were considered non-conductive ($\sigma = 0$ dS/m). To compare the radial sampling of different probes, a spatial weighting function for electrical conductivity was experimentally defined as

$$F(r) = \frac{\sigma_r}{\sigma_{eff}} \times 100\% \tag{8}$$

where σ_r is the effective electrical conductivity measured in a water-filled PVC tube with r and σ_{eff} is the effective electrical conductivity measured in a large water-filled tank (100 cm × 100 cm × 50 cm). σ_{eff} is representative of the effective electrical conductivity measured in a water-filled PVC tube with $r = \infty$.

The σ spatial weighting functions for different probe configurations are shown in Fig. 4. It appears that the radial sampling of probes with higher probe impedance (e.g. T4 and T5) is more focused on the vicinity of the probe than probe with lower impedance. However, all trial probes show a very biased radial sampling characteristic. The radial sampling is even more biased towards the probe for σ measurements than for K_a measurements. The majority of the current flow in the cross section occurs within the first two centimeters in the radial direction. This behavior is of great concern as to the disturbance effect that may induced by the cone penetration. The soil displaced by the penetrometer may change the density of soil adjacent to the penetrometer, and hence the electrical conductivity. The penetration effect appears to be a common problem to all resistivity probes, and the degree of its influence should be quantified.

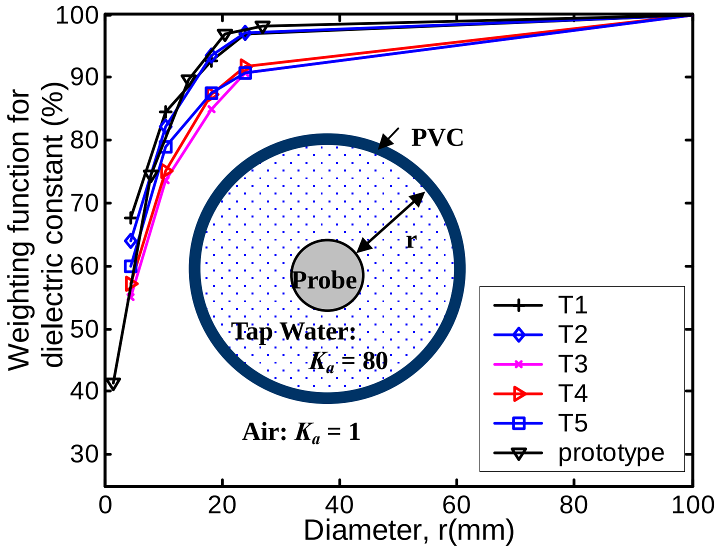


Fig. 3. Spatial weighting function for dielectric constant.

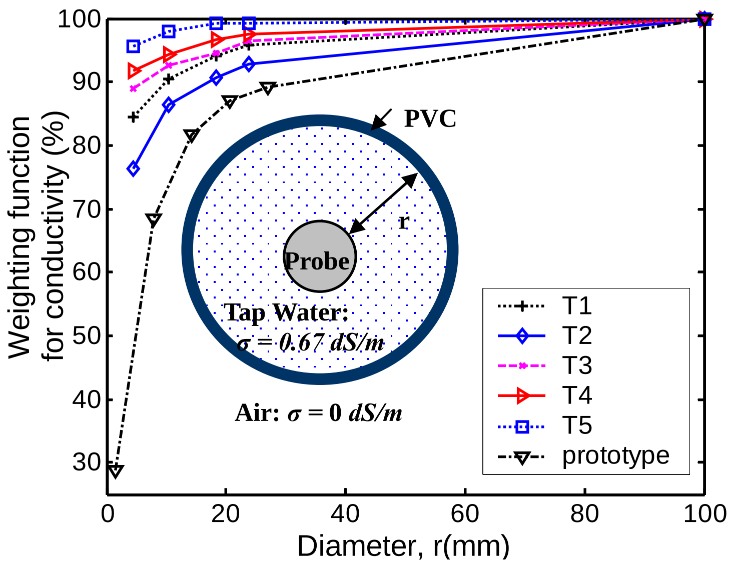


Fig. 4. Spatial weighting function for electrical conductivity.

Prototype TDR penetrometer

The spatial weighting functions of different probe types have different trends in dielectric constant and conductivity measurements, as shown in Fig. 3 and Fig. 4. There is a tradeoff between selecting an optimum probe design for dielectric measurements and that for conductivity measurements. A TDR dielectric penetrometer was actually fabricated using the design similar to probe T1. It was selected at the time when the major concern was to have TDR reflection that can be identified most easily for all cases (i.e. from dry to wet soils). Figure 5 shows the design and a photo of the probe. The diameter of the prototype is the same as a standard CPT module (35 mm) and the sensing waveguide is 20 cm long. The probe consists of four arc-shape stainless steel plates and a Delrin® shaft. The thickness of the stainless steel was maximized to increase the axial strength of the probe. The stainless steel plates were fit into four grooves in the Delrin® shaft and fastened with screws. This probe was used to perform simulated penetration tests in a calibration chamber.

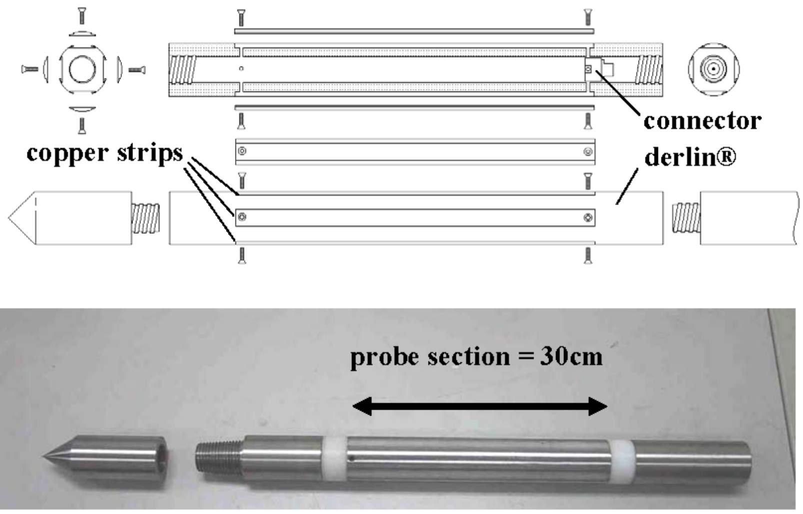


Fig. 5. Prototype of the TDR penetrometer.

Calibration of the Prototype

The TDR penetrometer shown in Fig. 5 differs slightly from probe T1 in that thick conductors are embedded in a dielectric shaft instead of thin conductors bonded to the surface of the dielectric shaft. Calibration tests need to be carried out before it can be put into used for measurements of dielectric constant and electrical conductivity. Several liquids of known dielectric constants and electrical conductivities were used for calibrating the probe using Eqs 2 and 4. The materials used for calibrating dielectric measurements were air, butanol, ethanol, and water; while NaCl solutions of different concentrations were used for calibrating electrical conductivity measurements. According to Birchak et al. (1974[12]), the theoretical value of n is 1.0 for the probe design. Assuming theoretical value n = 1.0, the calibrated parameters a = 0.34 and b = 1.91 were obtained through linear regression. If n remained unknown during calibration, the calibrated parameters are a = 0.35, b = 1.78, and optimal n = 0.96. Note that the a value is smaller than 0.5 (suggested by Eq 5), because the prototype used thick conductor plates fit into Delrin® grooves rather than thin conductor plates stick on the surface of a dielectric shaft. Using the calibrated parameters, the apparent dielectric constants of the calibrating liquids are plotted against their known values in Fig. 6a. Both calibrated results provide fairly good fit. The theoretical value n = 1.0 is verified, as can be inferred from Fig. 6a. For simplicity, n = 1.0, a = 0.34, and b = 1.91 are used. Similarly, the calibration constants for electrical conductivity were obtained as β = 0.0362. The estimated electrical conductivities using the calibrated parameters are shown in Fig. 6b to fit the known values very well. These results prove the new calibration equations (Eqs 2 and 4) to be extremely accurate.

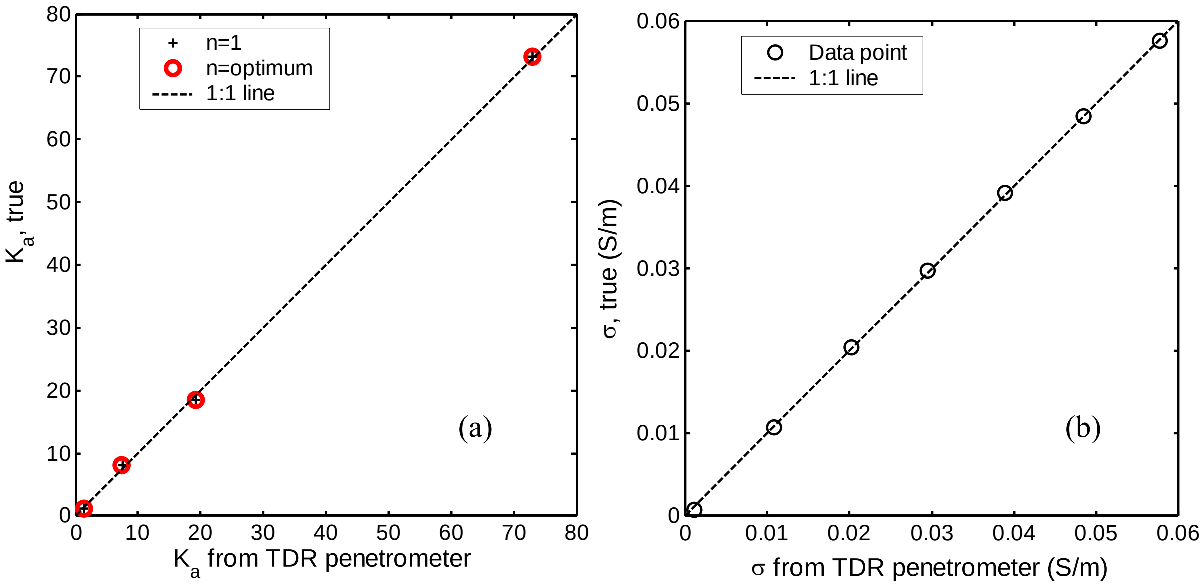


Fig. 6. (a) Dielectric constant and (b) Electrical conductivity measured by TDR penetrometer compared to actual dielectric constant in calibration tests.

Spatial Weighting Function of the Prototype

To quantify the spatial weighting function of the prototype, the aforementioned radial sampling experiment was carried out on the prototype. The spatial weighting function of the prototype is also shown in Fig. 3 for K_a measurements and in Fig. 4 for σ measurements. The K_a radial sampling characteristic of the prototype is similar to that of the trial probes T1 and T2. However, the σ radial sampling of the prototype is much less focused on the vicinity of the probe than that of all trial probes (T1-T5). This may be attributed to the fact that the prototype used thick conductor plates fit into grooves of a dielectric shaft rather than thin conductor plates stick on the surface of a dielectric shaft. This configuration alters the distribution of the electromagnetic response, further decreasing the measurement sensitivity but making the σ radial sampling less biased towards the probe.

Simulated Penetration Tests

To test the penetrometer and study the penetration effect, simulated penetration tests were performed in the laboratory using a calibration chamber and hydraulic loading frame. The chamber was 45 cm in inner diameter and 40 cm in height. A silty sand (SM) was used for the simulated penetration tests. Seven different gravimetric water contents were used to prepare samples in the chamber. The soil and water were mixed thoroughly to obtain the desired water content. The mixed soil was sealed with plastic wrap and allowed to equilibrate for more than 24 h, to yield a uniform soil specimen. The soil was then compacted in the calibration chamber in layers and the total mass of the soil and chamber was measured. The gravimetric water content of the soil specimen ranged from 2% to 10% and the dry density ranged from 1.58 to 1.67 g/cm^3.

Two TDR measurements were taken. Simulated penetration test was first conducted by penetrating the TDR penetrometer at the center of the chamber. No surcharge was applied to the soil specimen but a cap was placed on top of the chamber to prevent the soil from heaving during penetration. Hence, the soil around the penetrometer was slightly densified during penetration. After the penetrometer was retracted, another TDR measurement was taken at the location between the penetrated hole and the chamber cylinder using a conventional multi-rod probe (MRP) similar to Fig. 1b. The diameter of the multiple rods is 9.5 mm and the spacing between the center conductor and outer conductors is 65 mm. The MRP mimics a coaxial probe in which the electromagnetic field is concentrated around the central rod. The effect of penetration on TDR measurements using the MRP is considered negligible (Siddiqui et al. 2000[13]). Comparing the measurements of TDR penetrometer with that of MRP can reveal the effect of penetration. After all the TDR measurements were taken, samples of the soil were oven-dried to determine the gravimetric water content. The volumetric water content (θ) of each soil sample was determined from the total density and gravimetric water content.

$\sqrt{K_a}$-θ and $\sqrt{\sigma}$-θ relationship

TDR measurements show that both dielectric constant and electrical conductivity increase with water content. A good linear relationship between measured by the TDR penetrometer and the volumetric water content (θ) exists as Fig. 7 shows. The $\sqrt{K_a}$-θ relationship was shown by Topp et al. (1980[8]) to be relatively independent of soil type and electrical conductivity of pore water. The correlation between $\sqrt{\sigma}$ and θ also shows great linearity. Unlike the $\sqrt{K_a}$-θ relationship, the intercept and slope of the $\sqrt{\sigma}$-θ relationship depend on the soil type and electrical conductivity of pore water. Soil water content can be estimated by the K_a measurement alone, electrical conductivity and future study on dielectric dispersion can provide extra information for characterizing soil type and pore water.

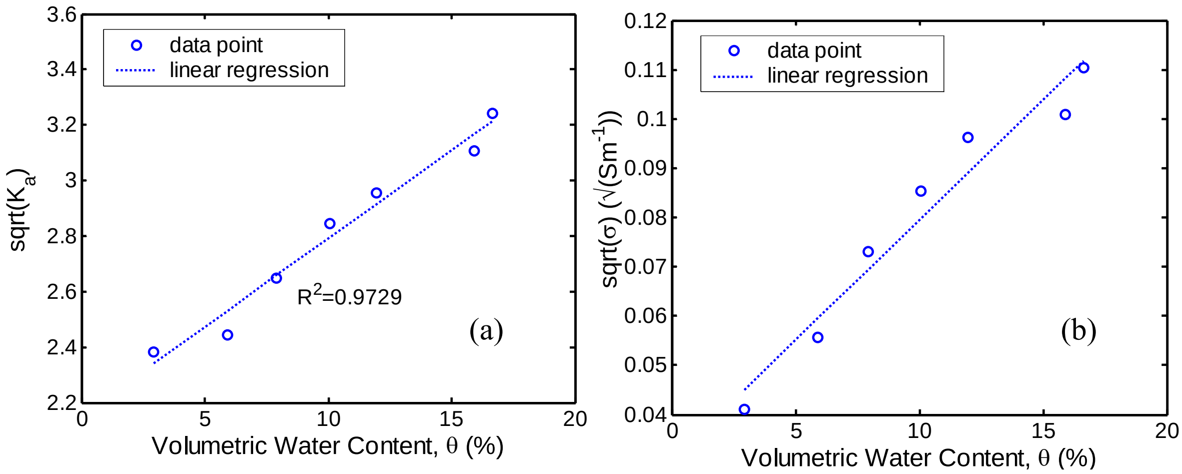


Fig. 7. Correlation between (a) $\sqrt{K_a}$ and θ, and (b) $\sqrt{\sigma}$ and θ

Penetration Effect

In addition to measurements using the TDR penetrometer, TDR measurements were also performed using a 4-rod MRP probe (measurements which were much less disturbed). Figure 8a shows the comparison for K_a measurements. The effect of penetration can be noticed in K_a measurements as expected. K_a increases as soil density increases due to penetration because the volumetric water content increases with density when gravimetric water content remained unchanged. This increase in apparent dielectric constant depends on the degree and extent of the soil densification. As the original soil density increases, the disturbed zone becomes larger and the soil near the conductors is less densified. Therefore, the K_a measurement is less affected by the penetration effect for dense soil than for loose soil. This can explain the effect of penetration shown in Fig. 8a. The soil samples prepared for the simulated penetration tests were compacted at dry side. At dry side, the density increases as gravimetric water content, and hence the apparent dielectric constant, increases. Therefore, the penetration effect is more pronounced for the soil with lower K_a, as Fig. 8a shows. In summary, the penetration effect induces a coherent K_a error which increases with decreasing soil density. For the soils tested (dry density ranging from 1.58 to 1.67 g/cm^3), this error is within the uncertainty associated with the $\sqrt{K_a}$-θ correlation. But caution should be taken when performing tests in looser soils.

Figure 8b compares electrical conductivity measured by the prototype TDR penetrometer with that by the MRP probe. Unexpectedly, coherent errors due to penetration effect are not noticeable in σ measurements. The radial sampling is less focused on the vicinity of the probe for σ measurements, as shown by comparing Fig. 3 to Fig. 4. However, this difference can only partly explain the unnoticeable penetration effect. The σ spatial weighting function was experimentally defined by the PVC-tube experiment. This spatial weighting function was valid strictly only for the condition shown in Fig. 4. In actual soil measurements, the conductivity variation due to penetration is smooth. It is believed that the actual radial sampling is much greater than that shown in Fig. 4, resulting in an unnoticeable penetration effect.

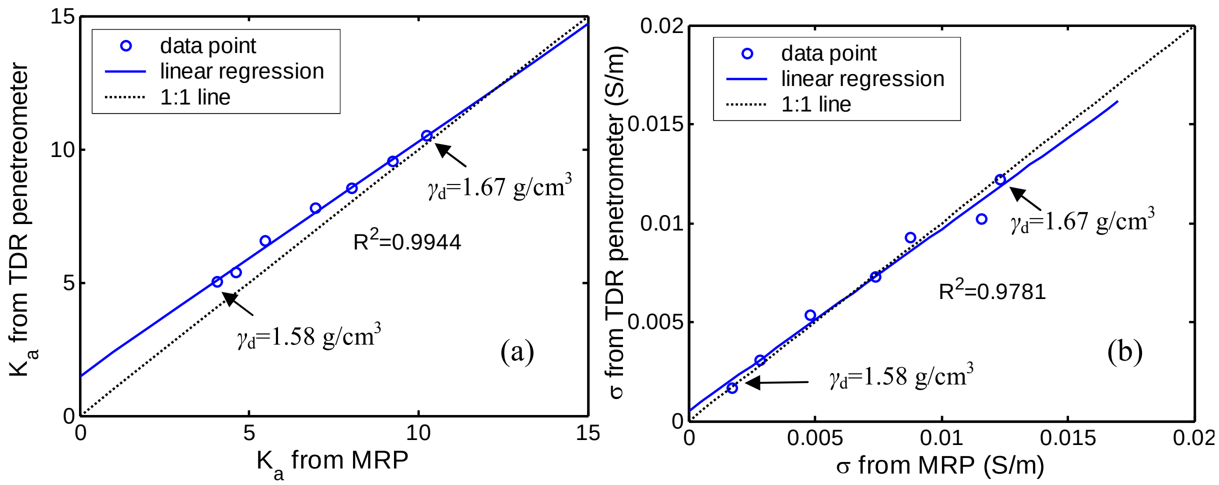


Fig. 8. The (a) apparent dielectric constant and (b) electrical conductivity obtained from TDR penetrometer vs. those from MRP.

Summary and Suggestion

The paper has presented the development of a TDR penetrometer for simultaneously measuring dielectric constant (K_a) and electrical conductivity (σ) during cone penetration. A TDR penetrometer can be formed by placing a multiple-conductor waveguide around a non-conducting shaft. The theoretical relationship between the electrical properties (K_a and σ) of the surrounding material and the TDR responses (travel time T and reflection coefficient ρ_∞) may be formulated by the Birchak's exponential mixing model. The calibration parameters involved in the theoretical relationship can be easily determined by calibration tests with several liquids of known K_a and σ. TDR penetrometer allows the waveguide to sense the surrounding soils at depths, but the sensitivity of K_a and σ measurements is decreased by about 30% compared with the conventional TDR probes. Changing the conductor configuration seems unable to improve the measurement sensitivity but could change the characteristic impedance and radial sampling characteristics. The majority of the electromagnetic response occurs within the first several centimeters measured from the probe surface. Experimental results indicate that the penetration disturbance induces a coherent K_a error which increases with decreasing soil density, but σ measurement is not affected by penetration disturbance. The TDR penetrometer provides both K_a and σ measurements. Soil water content can be estimated by the K_a measurement alone, the soil water content and electrical conductivity can then provide extra information for determining the characteristic of the pore water.

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