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Time Domain Reflectometry Tests of Multilayered Soil

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Abstract

Time Domain Reflectometry (TDR) is an established technology for measuring the volumetric water content. It has been recently extended to measure the gravimetric water content and dry density for geotechnical applications for earthwork compaction control. Commonly used information from a TDR signal is the dielectric constant and electrical conductivity of the bulk soil specimen. Subsequent analyses generally assume that the soil properties are uniformly distributed. The soil properties obtained are believed to be the average values over the measurement probe length. Under certain circumstances, for example immediate after raining or soil being dried up, the properties of soil near surface might change with depth. This could potentially induce errors in the measurement results.

This study was designed to evaluate the influence of the non-uniform soils on TDR measurement accuracy. A series of tests were conducted on specimens with different layers. Layers were designed to have different water content, density, orders, and thickness. The TDR measured bulk dielectric constants were used to calculate the bulk volumetric soil water content using Topp's equation and the bulk gravimetric water content and dry density using Siddiqui-Drnevich equation. The results were compared with the measured bulk values from oven-dried water content and physically measured soil densities of each layers. The comparison indicated that both equations gave results of bulk volumetric water content or gravimetric water content and dry density with sufficient accuracy. Thus the non-uniform soil properties should not induce significant errors for TDR measured bulk soil water content and/or density.

Investigations were also conducted to evaluate the performance of mixing formulas for layered soil conditions. The dielectric constant for each layer was estimated using Topp's equation or Siddiqui-Drnevich equation together with the measured water content and density of that layer. The predicted bulk dielectric constants by mixing formulas were compared with measured bulk values from TDR. Mixing formulas considered include that of arithmetic average and refractive index. The results indicated both mixing formulas had similar performance to relate the measured bulk dielectric constant to dielectric constants of constitutive layers.

Key words Time Domain Reflectometry, layered soils, mixing formula

Introduction

Time Domain Reflectometry (TDR) is routinely used for field measurement of soil water content. In most applications Topp's equation is used to calculate soil volumetric water content from TDR measured soil apparent dielectric constant. Siddiqui and Drnevich (1995) [1] pioneered the efforts to extend the application of TDR to measure the soil dry density in addition to the water content, essential quantities for geotechnical engineering applications. It is possible to estimate the water content from TDR measured apparent dielectric constant because water has a much larger dielectric constant (around 81 at 20^{o}C) than that of soil solid (around 3 to 5) or air (1). The typical TDR system (Figure 1) includes a TDR apparatus, a coaxial cable, a probe, and a coaxial head used to connect the coaxial cable and the probe. Figure 2 shows the test system used in this study. Probe made of four spikes is generally used for TDR testing in the field. Probe made of the mold with a center probe is used for laboratory investigation.

A fast rising pulse is generated by the TDR electronics. This causes an electromagnetic wave to propagate along the TDR system. The propagation of the electromagnetic wave along the TDR measurement system can be accurately described by the transmission line equations. Simplified approaches directly interpret the phenomena (signal reflections and characteristic signal levels) in the measured TDR signals.

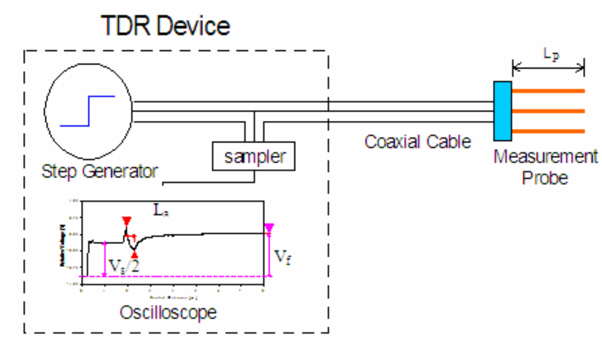

Figure 1. Schema of an example TDR system and output signal (Drnevich et al., 2001[2])

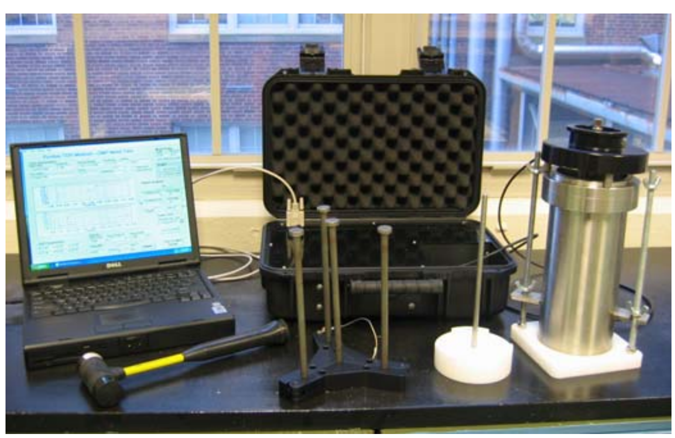

Figure 2. TDR test equipments

Most methods currently used for TDR signal analyses assume that soil properties within the measurement probe are uniformly distributed. That is, reflections only take place when pulse signal enters the soil and when the pulse arrives at the end of the measurement probe. However, under certain conditions, for example after raining or soils being dried up at the surface, the soil properties can change significantly with depth. The existing analyses procedures might produce errors under these circumstances. Compared with the extensive application of TDR technology, research on the influence of non-uniform soil properties distribution on its measurement accuracy are very limited. On the theoretical end, Feng and Lin (1999) [3] presented a multi-section transmission line model to simulate the unmatched probe system and a layered soil system. The simulated waveforms in a two-layer soil system were compared with the measured waveforms. It was shown that the apparent dielectric constant was appropriate to obtain the average water content of the layered soil system. Schaap et al. (2003) [4] studied a multilayered dielectric system using both a broadband TDR signal source and a narrow band signal source. The bulk dielectric constant along the TDR probe was determined as a function of the layer thickness and the probe orientation. The study also found that the mixing formula based on arithmetic average is more accurate than that using refractive index when large number of thin layers exist.

In this study TDR tests were performed on soils with two or three layers. The experimental program carried out in this investigation serves two purposes: 1) to evaluate the performance of different mixing formula for layered soils; 2) to quantize the potential errors by conventional analyses for layered soil conditions. The experimental data will also be incorporated for validating and further developing numerical models for TDR measurement in layered soils.

Background

The principle of TDR measurement has been widely explored. A few fundamentals needed for this research are briefly summarized below. The travel velocity, v, of an electromagnetic wave through media can be calculated as follows:

$$v = \frac{c}{\sqrt{K_a}} \qquad (1)$$

Where c is the velocity of an electromagnetic wave in free space (2.988×10^8 m/s) and K_a is the dielectric constant (for TDR measurement in soils, this quantity is generally called apparent dielectric constant). The time for the electromagnetic wave traveling down and back in a media with length, L, is given by:

$$t = \frac{2L}{v} \qquad (2)$$

Substituting equation (1) to (2) yields

$$K_a = \left(\frac{ct}{2L}\right)^2 \qquad (3)$$

By defining $\frac{ct}{2}$ as apparent length l_a, the apparent dielectric constant can be calculated as

$$K_a = \left(\frac{l_a}{L}\right)^2 \quad (4)$$

In the TDR signal, the apparent length is determined from analyzing the time elapse between reflections. The determination of the apparent length l_a is illustrated in Figure 3.

The volumetric water content, θ, is defined as the volume of water as a percentage of the total volume of the soil. This concept is frequently used by agronomists. Gravimetric water content, w, is defined as the mass percentage of water to the dry soil solid. The gravimetric water content is preferred by geotechnical engineers. These two types of water contents are related by the following equation:

$$\theta = w\frac{\rho_d}{\rho_w} \quad (5)$$

Where ρ_d is the dry density of soil, ρ_w is the density of water.

Many relationships have been established by researchers in soil science and civil engineering to related the TDR measured apparent dielectric constant to the soil water content. One of the most frequently used calibration equations include that by Topp et al. (1980)[5] as presented in equation (6). This equation was developed to relate the apparent dielectric constant of soils to the volumetric water content.

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

Where θ is the volumetric water content and K_a is the apparent dielectric constant.

Siddiqui and Drnevich (1995) [1] developed an equation that relate the TDR measured dielectric constant to the gravimetric water content. The equation accounts for the effects of soil type and density by incorporating two calibration constants. This equation is shown below.

$$w = \frac{1}{b}\left[\frac{\rho_w}{\rho_d}\sqrt{K_a} - a\right] \quad (7)$$

Where ρ_d is the dry density of soil, ρ_w is the density of water, a and b are soil-dependent calibration constants, typically a is assumed to be 1, b is assumed to be 8, a set of parameters a=0.985 and b=9.35 are used in this study.

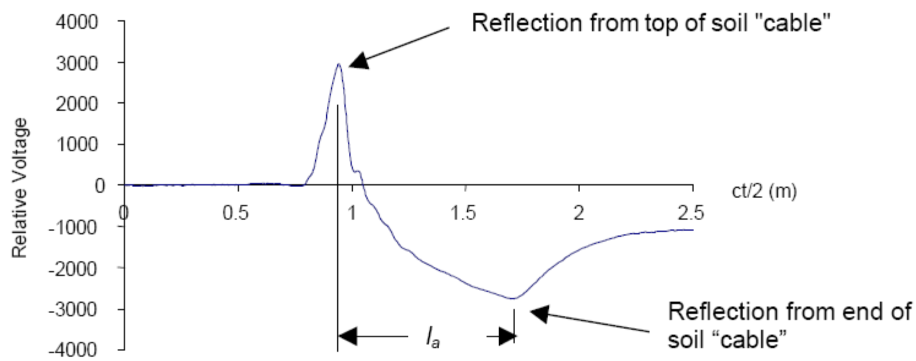

Figure 3. A typical TDR curve for soil and measurement of apparent length l_a (Drnevich et. al, 2001[6])

The apparent dielectric constant obtained from travel time analyses of the TDR signal is an average value for materials along the probe. Therefore, the derived values of water content and dry density are also averages. However soil profile might be non-uniform under certain conditions. This will deviate from the uniform soil assumptions.

For a mixture made up of different components, each with its own dielectric constant and shape characteristics, numerous dielectric mixing models have been developed to study the bulk dielectric behaviors and its relationship to the constitutive components. In physics and engineering, there are two major categories of mixing models: theoretical polarization models and semi-empirical volumetric mixing models (Drnevich et al. 2001) [7].

In theoretical model, the bulk dielectric constant of a mixture is found to be dependent on the volume fraction and "pure" permittivity of the components, the shape of components, their orientation to the applied field and the effect of interaction of the component permittivities on the local field (Sihvola and Lindell, 1992)[8]. Dobson et al. (1985)[9] presented a formula (equation 8) to calculate the dielectric constant of the soil mixture.

$$\varepsilon_m = \frac{3\varepsilon_2 + 2\nu_{fw}\left(\varepsilon_{fw} - \varepsilon_s\right) + 2\nu_{bw}\left(\varepsilon_{bw} - \varepsilon_s\right) + 2\nu_a\left(\varepsilon_a - \varepsilon_s\right)}{3 + \nu_{fw}\left(\frac{\varepsilon_s}{\varepsilon_{fw}} - 1\right) + \nu_{bw}\left(\frac{\varepsilon_s}{\varepsilon_{bw}} - 1\right) + \nu_a\left(\frac{\varepsilon_s}{\varepsilon_a} - 1\right)} \qquad (8)$$

where *v* is the volumetric fraction of the soil component, the subscripts *bw*, *fw*, *a* and *s* refer to bound water, free water, air, and soil solid, respectively. This formula is only valid at high frequency (>1.45 GHz). Drnevich et al. 2001[7] presents detailed discussion on this relationship.

Birchak et al. (1974[10]) presented a semi-empirical volumetric mixing model (equation 9) to relate the bulk dielectric constant of a mixture to its components.

$$\left(K_m\right)^\alpha = \sum_{i=1}^{n} v_i \left(K_i\right)^\alpha \qquad (9)$$

Where v_i and K_i are the volumetric fraction and permittivity (dielectric constant) of each component. The exponent α is an empirical constant that summarizes the geometry of the medium with respect to the applied electric field. The value of α=0.5 is suggested for homogenous and isotropic soils (Birchak et al., 1974[10]; Ledieu et al., 1986[11]).

However difficulties were encountered in some cases when using equation 9 to interpret experimental data in layered media (Nadler et al., 1991[12], and Dasberg and Hopmans, 1992[13]). Chan and Knight (1999) [14] presented a model considering traveling velocity changes with the ratio of effective wavelength (λ) to layer thickness (t). According to this method, the average apparent dielectric constant can be calculated as:

$$\sqrt{K_a} = \sum f_i \sqrt{K_i} \qquad \lambda / t < 4 \qquad (10)$$

$$K_a = \sum f_i K_i \qquad \lambda / t > 4 \qquad (11)$$

Where f_i is the length fraction of soil layer i, λ is the TDR signal wavelength, and t is the layer thickness.

Equation (10) is called dielectric mixing formula with refraction index (square root type) and equation (11) is called dielectric mixing formula with arithmetic average.

TDR experiments on Layered soils

Soil samples were prepared and tested in a compaction mold. The mold has a length of 232.9 mm and a diameter of 101.4 mm. A probe with a length 261.0 mm was used as the center pin for TDR measurement. A ASTM uniform fine sand was used in this study. The natural water content of the sand was measured by oven dry method. The sand was considered as "dry" since the moisture content (gravimetric water content) was close to 0.5%. Wet sand with target moisture content of 12% was prepared by adding water and mixing the soil and water uniformly. Prepared wet or dry sand were poured into the compaction mold and gently compacted to the desired height as scheduled in Table 1. A thin layer of plastic film was placed on the surface when one layer is compacted. The plastics separate these layers from interacting with each other. A hole with a diameter slightly larger than that of the pin was in the center of the plastic film. This way, the pin can penetrate through the soils without distorting the plastic film. After the plastic separation film was in place, another layer of soil was compacted on top of the bottom layer. For soils with three layers, an additional layer of soil was placed following similar procedures. After the mold was completely filled up, extra soil was removed and the surface was flattened. A probe was then driven into the sample through the guide plate. A coaxial head was placed on the compaction mold and the signal was then acquired. The mass of soil added for each layer and layer thickness were recorded. From this, the densities of soils in each layer were determined. After the TDR tests the representative samples from each layer were obtained to measure the moisture content by oven dry method. The experiments design is summarized in Table 2.

Table 1. Summary of experimental program for testing on layered soils

<table>
<tr><td>Test No.</td><td>A-1</td><td>A-2</td><td>B-1</td><td>B-2</td><td>C-1</td><td>C-2</td><td>D</td><td>E</td></tr>
<tr><td rowspan="2">Top Layer</td><td rowspan="2">1/2 H Dry Sand</td><td rowspan="2">1/2 H Wet Sand</td><td rowspan="2">1/3 H Dry Sand</td><td rowspan="2">1/3 H Wet Sand</td><td rowspan="2">3/4 H Dry Sand</td><td rowspan="2">3/4 H Wet Sand</td><td>100mm Dry sand</td><td>100mm Wet sand</td></tr>
<tr><td rowspan="2">32.90mm Wet sand</td><td rowspan="2">32.90mm Dry sand</td></tr>
<tr><td rowspan="2">Bottom Layer</td><td rowspan="2">1/2 H Wet Sand</td><td rowspan="2">1/2 H Dry Sand</td><td rowspan="2">2/3 H Wet Sand</td><td rowspan="2">2/3 H Dry Sand</td><td rowspan="2">1/4 H Wet Sand</td><td rowspan="2">1/4 H Dry Sand</td></tr>
<tr><td>100mm Dry sand</td><td>100mm Wet sand</td></tr>
</table>

Typical TDR Signals

The typical TDR signals under different experimental settings are presented in Figures 4 to 6. Figure 4 shows the TDR signals for dry/wet (top/bottom) samples. The reflection indicative of the interface from dry soil to wet soil layers are noted in this plot. Reflections can be clearly observed at the top and bottom surfaces of the dry soil layer. As the thickness of dry layer increases, the position of the reflection at the bottom of the dry soil layer moves backward. Figure 5 shows the TDR signals of acquired on wet/dry (top/bottom) soil samples. In this case, the reflection at the soil interface is not as clear but can still be identified by zooming in the corresponding signal section. The reduced pronounce of this interfacial reflection is possibly due to the fact that both the interface reflection and the reflection at the end of the probe are superposed to each other. Figure 6 shows TDR signals acquired on soils with three interlacing layers. The existence of a middle layer can be easily identified from the TDR signals. Embedment of a wet soil layer in the dry soil causes a downward concave in the signal. The embedment of a dry soil layer in the wet soil, on the other hand, causes an upward concave in the signal. These fine details provide important information on the soil properties distribution. A rugged approach could be potentially developed to obtain these information.

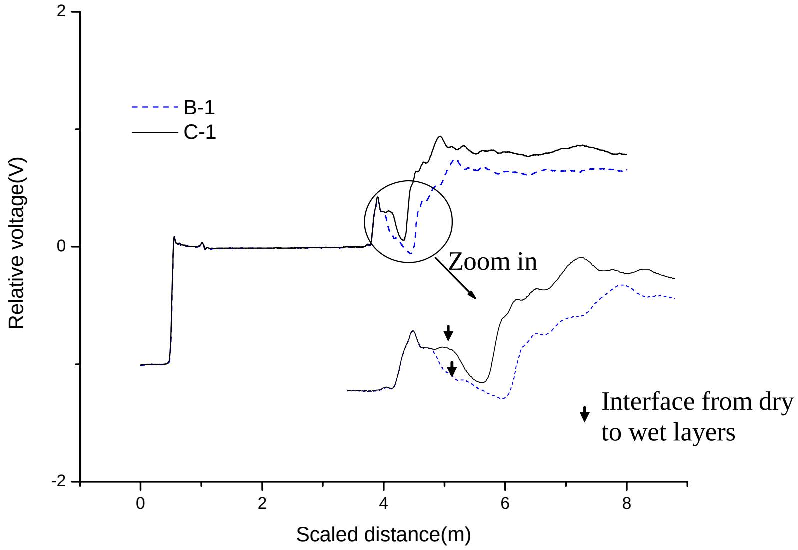

Figure 4. Measured signals of dry/wet samples

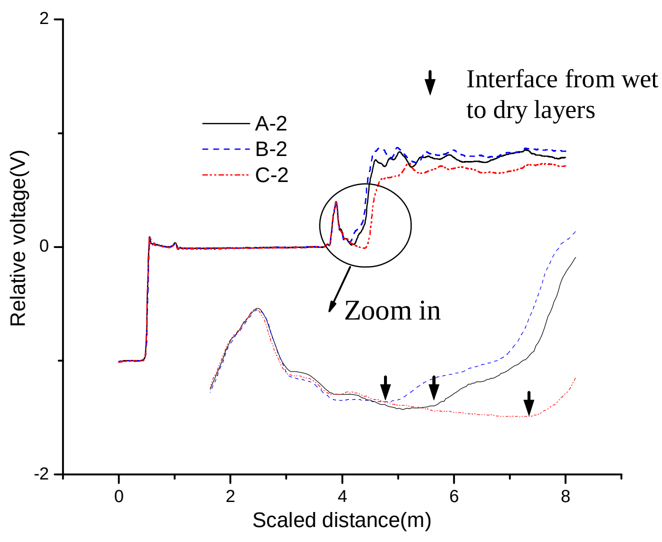

Figure 5. Measured signals of wet / dry samples

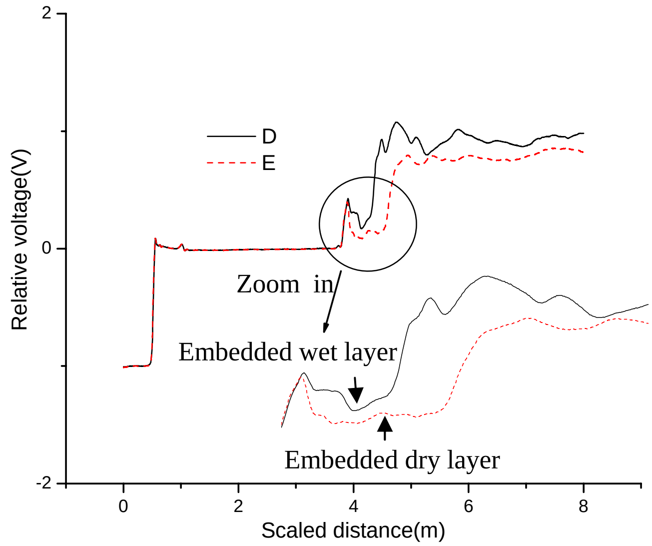

Figure 6. Measured signals of three layer samples

Comparison of mixing formulas for layered soils

The apparent dielectric constant of the soil (K_a) is one of the most important parameter obtained from a TDR signal. It is related to both soil water content and density. For most applications, it is assumed that the water content calculated from the TDR measured apparent dielectric constant is the average along the probe length. This is due to the fact that the measured apparent dielectric constant, K_a, from a TDR signal is believed to be the average value along the probe length. As mentioned in the previous context of this paper, the relationship between the bulk dielectric constant and those of constituent layers of a layered system has been described by different types of dielectric mixing formulas (for example, the mixing formula based on refraction index and the formula based on arithmetic average). A natural question that can be brought up is which formula is more appropriate to use for layered soils.

In this experimental program, the moisture content and dry density of each soil layer were obtained. For each layer, the soil properties are reasonably uniform. The empirical relationships such as Topp's equation or Siddiqui-Drnevich equation are therefore applicable. From these, the dielectric constants of the constituent layers are determined. The apparent dielectric constants of the bulk layered soil samples can be obtained directly from the TDR signal. It can also be obtained from the empirical relationships (Topp's equation and Siddiqui-Drnevich equation) from the measured bulk soil water content and density. This provides an opportunity to examine the relative performance of the different types of mixing formula (including the mixing formula based on the refraction index and that based on the arithmetic average) as well as the performance of the empirical relationships for layered soil conditions.

Table 2. Summary of the actual experimental conditions for TDR testing on layered soil

Test No.		A-1	A-2	B-1	B-2	C-1	C-2	D	E
Top Layer	Length(mm)	116.45	116.5	77.6	77.6	174.7	174.7	100.0	100.0
	Mass(g)	1600.0	1614.0	1046.0	961.0	2277.0	2100.0	1371.0	1195.0
Middle Layer	Length(mm)							32.9	32.9
	Mass(g)							412.0	514.0
Bottom Layer	Length(mm)	116.45	116.5	155.3	155.3	58.2	58.2	100.0	100.0
	Mass(g)	1472.0	1586.0	1999.0	2120.0	779.0	810.0	1409.0	1250.0
Moisture content	Top		0.1174	0.005	0.0935	0.005	0.1009	0.005	0.0857
	Middle							0.0794	0.005
	Bottom	0.1214	0.005	0.1185	0.005	0.1090	0.005	0.005	0.1022
Density (g/cm^3)	Top	1.70	1.72	1.67	1.53	1.62	1.49	1.70	1.48
	Middle							1.55	1.94
	Bottom	1.57	1.69	1.60	1.69	1.66	1.72	1.75	1.55
Dry Density (g/cm^3)	Top	1.70	1.54	1.67	1.40	1.62	1.35	1.70	1.36
	Middle							1.44	1.94
	Bottom	1.40	1.69	1.43	1.69	1.49	1.72	1.75	1.41
Description of tests		Dry/ Wet	Dry/wet	Dry/ wet	Wet/ dry	Dry/ wet	Wet/ dry	Dry/wet /dry	Wet/dry /Wet

Table 3 summarizes the results of data analyses. In this table, the apparent dielectric constants of each individual layer are estimated using Topp's equation (equation 2) or Saddiqui and Drnevich equation (equation 3) from the measured soil water content and dry density of that layer. The bulk apparent dielectric constant is calculated using the mixing formula with either the refraction index or the arithmetic average of the apparent dielectric constant of the constituent layers. The measured bulk apparent dielectric constants from the TDR signals are also presented for comparison.

Table 3. Apparent dielectric constants of constituent layers and bulk samples

Test No.		A-1	A-2	B-1	B-2	C-1	C-2	D	E
Calculated K_a of each layer	Topp	2.19	7.70	2.19	7.23	2.18	7.47	2.19	7.80
								6.48	2.22
		9.08	2.20	9.05	2.19	8.71	2.20	2.20	8.98
Calculated K_a of each layer	Siddiqui	3.05	7.13	2.94	6.80	2.75	6.81	3.04	7.54
								6.17	3.60
		8.77	3.15	8.91	3.02	8.98	3.13	3.21	8.78
Measured ave. K_a		5.32	4.73	6.58	4.3	4.09	6.65	2.94	7.80
Ka (Refractive index)	Topp	5.05	4.53	6.56	4.11	3.97	5.76	3.49	6.24
K_a (Arithmetic Ave.)		5.64	5.14	6.92	4.28	4.31	5.89	3.56	6.30
K_a (Refractive index)	Siddiqui	5.54	4.94	6.56	4.11	3.97	5.76	3.49	7.40
K_a (Arithmetic Ave.)		5.91	5.14	6.92	4.28	4.31	5.89	3.56	7.52
Description of tests		Dry/ wet	Dry/we t	Dry/ wet	Wet/ dry	Dry/ wet	Wet/ dry	Dry/we t/dry	Wet/dr y/Wet

Figure 7 compares the TDR measured bulk apparent dielectric constant and those calculated from dielectric mixing formulas. For each dielectric mixing formula, the dielectric constants of the constituent layers are estimated either with Topp's equation or Siddiqui-Drnevich equation. Results of four different combinations are presented. An error bar of 5% is also plotted in this figure.

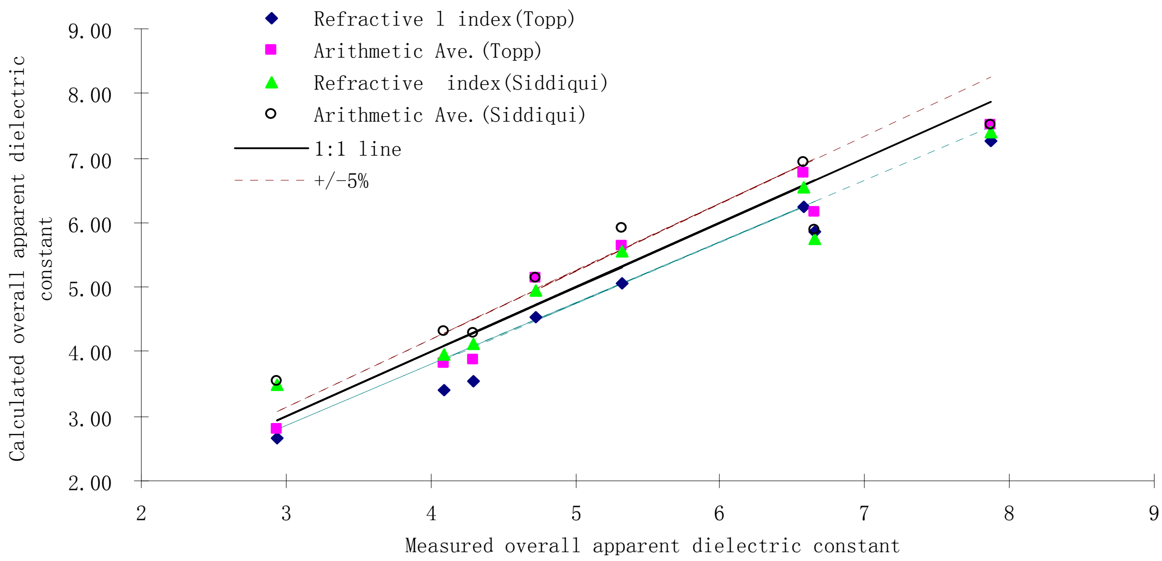

Figure 7. Measured bulk apparent dielectric constant versus those calculated using dielectric mixing formula

Table 3 and Figure 7 indicate that Topp's equation and Siddiqui-Drnevich equation seems to be comparable for determining the apparent dielectric constant of the constituent layers. The Siddiqui-Drnevich equation seems to predict slightly larger apparent dielectric constant than Topp's equation. For the same equation (Topp or Siqqui-Drnevich), the dielectric mixing formula using refraction index predict smaller values of the bulk dielectric constant of layered soils. Nevertheless, the differences are relatively small. The dielectric mixing formula based on refraction index and the arithmetic average are thus believed to be suitable to obtain overall apparent dielectric constant of a layered soil with reasonable accuracy. Comparing the four different data set, the mixing formula using the arithmetic average with the dielectric constant of constituent layers estimated by Topp's equation or Siddiqui-Drnevich equation appears to be more accurate.

Under practical settings, it is typical that the only the bulk information are obtained. For example, it might be only the bulk apparent dielectric constant and the total density of soils are directly measured because of the unawareness of the existence of soil layers. With the known total density of the soil, the dry density of soil can be calculated from the estimated water content using either Topp's equation or Siddiqui-Drnevich equation. A question that needs to be answered is that which formula is more accurate in terms of determining the bulk water content and density of layered soils.

For Topp's equation, which obtains the volumetric water content, the bulk soil dry density and gravimetric water content can be calculated with the following equations (12) to (14):

$$\rho_d = \rho_t - \theta\rho_w \tag{12}$$

$$w = \frac{\theta\rho_w}{\rho_d} \tag{13}$$

$$\rho_d = \frac{\rho_t}{1+w} \tag{14}$$

where ρ_d is dry density of soil; ρ_t is soil density; θ is volumetric water content; ρ_w is water density; and w is gravity water content.

For using the Siddiqui-Drnevich equation, the gravimetric water content (w), volumetric water content (θ) and dry density (ρ_d) of soils can also be calculated. The dry density, ρ_d, is obtained by equation (14). The water content can be obtained from the following equation (Drnevich et al., 2001[7]):

$$w = \frac{\frac{\rho_w}{\rho_t}\sqrt{K_a} - a}{b - \frac{\rho_w}{\rho_t}\sqrt{K_a}} \tag{15}$$

Notations in this equation are the same as in the previous context. Equation 15 can be used to calculate the bulk gravimetric water content and subsequently the bulk dry density and volumetric water content can be calculated.

The calculated bulk soil water content and density for the layered soils using Topp's equation and Siddiqui-Drnevich equation are listed in Table 4. The measured bulk soil water content and dry densities are also presented in this table as comparison basis. The measured bulk quantities are calculated from the basic definitions. Examination of this table indicates that the calculated bulk soil water contents and dry density are generally reasonably close to the actual values.

Table 4. Comparison of water contents and dry density

Test No.		A-1	A-2	B-1	B-2	C-1	C-2	D	E
Total Density (g/cm^3)		1.620	1.639	1.626	1.548	1.698	1.634	1.623	1.609
Total Dry density(g/cm^3)		1.545	1.548	1.505	1.590	1.579	1.444	1.675	1.474
Measured w		0.058	0.048	0.077	0.031	0.030	0.072	0.014	0.092
Measured θ		0.089	0.075	0.115	0.049	0.047	0.104	0.023	0.145
Topp's	Calculated θ	0.087	0.073	0.117	0.063	0.058	0.118	0.028	0.145
	Calculated ρ_d	1.547	1.549	1.503	1.576	1.568	1.430	1.670	1.465
	Calculated w	0.057	0.047	0.078	0.040	0.037	0.083	0.017	0.099
Siddiqui	Calculated w	0.054	0.044	0.077	0.035	0.032	0.089	0.003	0.100
	Calculated ρ_d	1.551	1.554	1.504	1.584	1.576	1.422	1.693	1.463
	Calculated θ	0.083	0.069	0.116	0.055	0.050	0.126	0.005	0.146

To visualize the data presented in Table 4, plots are generated from the data presented in this table. Figures 8 to 10 compares the measured bulk quantities of layered soils and those estimated from Topp's equation or Siddiqui-Drnevich equation. The plots show that bulk gravimetric water content, volumetric water content and dry density calculated from these two equations match reasonably well those from direct measurement. Thus TDR provides reasonably accurate measurement of the average soil properties (water content (volumetric or gravimetric) and dry density) of layered soils. From sands used in this study, Topp's equation appears to provide a better approximation. However, it needs to be pointed out that an empirical set of parameters were used in the Siddiqui-Drnevich equation for this study. The performance of this equation could be further improved by using the parameters more appropriate for this material.

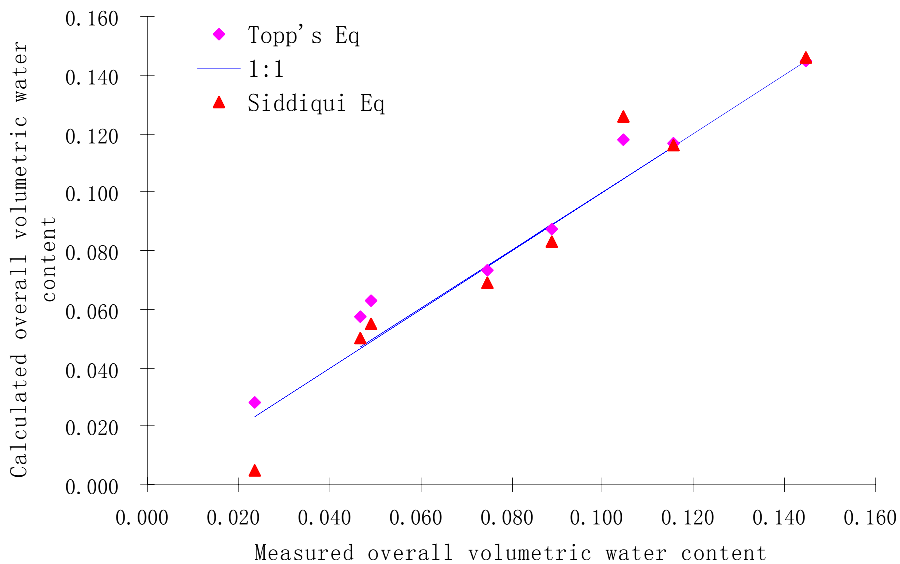

Figure 8. Calculated versus measured volumetric water content of layered soils

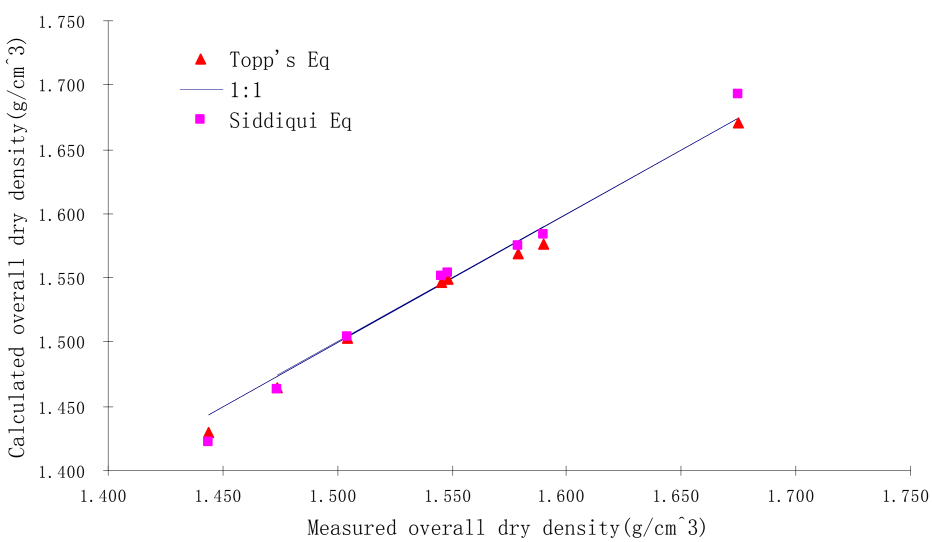

Figure 9. Calculated versus measured soil dry density of layered soils

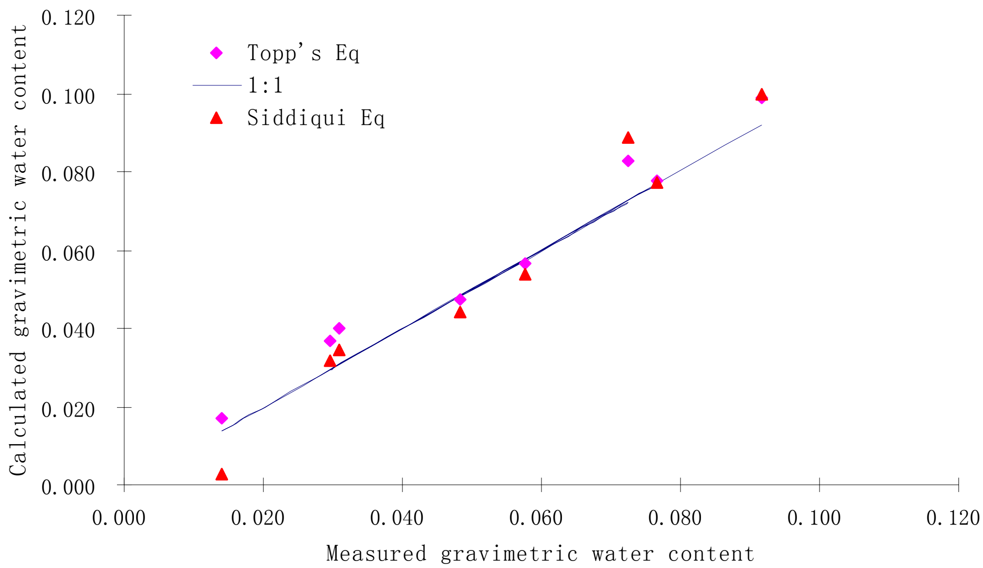

Figure 10. Calculated versus measured gravimetric water content of layered soils

ANOVA analyses were conducted to present more objective and quantified comparison of the performance of different formulas. The calculated values in Table 3 and Table 4 are compared with the measured values (assumed to be reference values). The standard deviations of the error between calculated values and actual (measured) values are calculated and summarized in Table 5. The mean values of the errors are also presented in this table. The analyses show that estimated bulk apparent dielectric constant using the dielectric mixing formula with arithmetic average has better resolution (standard deviation) and accuracy (mean value). Topp's equation is found to have slightly better performance to predict soil properties of a layered soil, such as its bulk water content and bulk dry density. These analyses are consistent with the conclusions from subjectively observing the plots and tables. It needs to be pointed out that the performance of Siddiqui-Drnevich equation could be further improved by using the parameters more appropriate for the material used in this study.

Table 5. Standard deviation of calculated values

	Topp's					Siddiqui				
quantities	θ	ρ_d	w	K_a (Refractive)	K_a (Arith-metic)	w	ρ_d	θ	K_a (Refractive)	K_a (Arith-metic)
standard deviation	6.58 $\times 10^{-3}$	6.4$\times 10^{-3}$	4.50$\times 10^{-3}$	0.234	0.354	8.28$\times 10^{-3}$	1.20$\times 10^{-2}$	1.14$\times 10^{-2}$	0.450	0.483
Mean of absolute errors	5.8$\times 10^{-3}$	7.0$\times 10^{-3}$	4.9$\times 10^{-3}$	0.489	0.326	6.2$\times 10^{-3}$	9.0$\times 10^{-3}$	7.8$\times 10^{-3}$	0.336	0.414

Conclusion and discussion

This study conducted a preliminary evaluation on the influence of non-uniform soil conditions on the TDR measurement accuracy using the common types of relationships originally developed for uniform soils. An experimental program was performed on soil with various specified layers and layer characteristics. TDR signals were found to contain information on the layerness and layer characteristics. However, more advanced analyses will be needed to extract these information. Analyses of the experimental data indicate that the commonly used Topp's equation and Siddiqui-Drnevich equation provide reasonably accurate estimation of the bulk soil water contents and dry density for a layered soil. Topp's equation was found to have slightly better performance for the soil used in this study. The results indicate that the measured soil water contents and dry density by TDR on a layered soil are reasonably close to the actual bulk values. The commonly used TDR technique can thus be used to determine the bulk properties of layered soils without significantly compromising the accuracy. However, it needs to be pointed out that due to the limited scope of this experimental study the conclusion might not be inclusive for special types of soils showing high heterogeneities. This needs to be further investigated.

The study also evaluated the performance of the dielectric mixing formulas (refraction index and arithmetic average) for layered soil conditions. The results indicated both types of mixing formulas had similar accuracy in relating the measured bulk dielectric constant of layered soils to the dielectric constants of the constituent layers. The estimated bulk apparent dielectric constant using the dielectric mixing formula with arithmetic average has better resolution and accuracy. The underlying mechanism needs to be further investigated.

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