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ABSTRACT

Time domain reflectometry (TDR) is a fast, accurate, and safe technology for field monitoring of soil moisture. Commonly used information in TDR signals includes the apparent dielectric constant and electrical conductivity. Because general TDR principles are not available for apparent dielectric constant measurements by travel time methods in soils with high electrical conductivities caused by the significant signal attenuation, the conventional commercial probes lose their purposes. For this reason, a new probe has been designed for measuring dielectric constants in highly conductive soils on the basis of the surface reflection coefficients method. This new probe can make the reflection at the soil surface more distinct. Experiments were conducted to verify the accuracy of measuring dielectric constants in different soils using this new probe. Finally, the probe was used to measure water content and dry density in the field. The results show that the probe has good integrity and high strength. This probe is capable of obtaining the dielectric constant in soils with high electrical conductivities using surface reflection coefficients methods with reasonable accuracy. In addition, it indicates that the dielectric constant measured by this approach matches well with that determined by travel time methods in the relative error range of 10 % in lowly conductive soils. Compared to oven-dry methods, the relative errors of water content and dry density determined using this new probe are less than 10 % and 3 %, respectively.

Keywords

new probe, surface reflection coefficients, TDR, high electrical conductivity

Introduction

Time domain reflectometry (TDR) has become a standard technology for the measurement of water content and dry density with advantages of safety, reliability, and convenience. The main sections of TDR include the step generator, data-acquisition system, coaxial cable, and the measurement probe. The step generator sends a step voltage to the coaxial cable. The input signal and the reflected signal are recorded by the data-acquisition system. Then the apparent dielectric constant and the DC electrical conductivity are estimated from the recorded signal.

Topp et al. (1980) established a relationship between soil volumetric water content and soil apparent dielectric constant. Dalton et al. (1984) found that it is possible to obtain bulk electrical conductivity from TDR waveforms, which could be used to estimate soil pore-fluid conductivity for the purpose of land evaluation and environmental management. Siddiqui and Drnevich (1995) and Yu and Drnevich (2004) made efforts to extend the application of TDR to measure the gravimetric water content and the dry density of soils for geotechnical engineering. Because TDR could measure the soil water content and dry density quickly, easily, and accurately, it had been widely used in practice.

Generally, the conventional travel time method is used to measure the dielectric constant by analyzing the travel time of electromagnetic waves reflected from the end of the probe in soils. Nevertheless, as the electrical conductivity of the soil increases quickly, the reflection from the end of the probe cannot be recognized because of attenuation of the signal. Then the application in these materials with high electrical conductivity will be limited.

In consideration of this problem, Ferre et al. (1996) insulated the TDR probes with electrically resistive dielectric coatings to minimize conductive losses. But the coatings broke easily in the process of inserting and pulling out the probe, and also the undesirable effects of reduced accuracy could be inevitable. Jones and Or (2004) used scatter function fitting (SFF) and resonant frequency analysis (RFA) in frequency domain for bulk permittivity measurements in saline soils, which extended the application range of TDR methods. It was found that probes as short as 3 cm would be optimal for highly lossy conditions, but short probes were likely to result in reduced accuracy.

Chen et al. (2007) proposed surface reflection method that utilized a two-parameter frequency-independent dielectric model to invert the dielectric constant by matching the predicted surface reflection versus the measured signal. This approach showed that the dielectric constant could be measured with satisfactory accuracy for saline soils. Chen et al. (2009) described a new approach based on surface reflection coefficients for measuring dielectric constants in highly conductive soils and established a relationship between the reflection coefficient at the soil surface and the dielectric constant of the soil. Extension rods with a 375-mm-long air gap were used to eliminate the overlap of the reflections along the probe and to get the true reflection coefficient of the soil surface. Laboratory experiments indicated that this method was competent to measure the dielectric constant even for soils with high electrical conductivities, whereas the conventional travel time method failed. However, the limitation of the special probe was that it cannot be used in situ.

Based on the surface-reflection coefficients method, this paper introduces a new probe for highly conductive soils, which could be embedded into soils in the laboratory and in situ tests. This newly designed probe replaces the extension air gap shown by Chen et al. (2009) with the material Delrin whose permittivity corresponds to that of air. In addition, Delrin has good integrity and high strength as well so that this new probe can be used in rough conditions. The other main parts of this new probe contain a coaxial head, a 0.8-cm-diameter, 42.6-cm-long steel rod as the center conductor and three 0.8-cm-diameter, 38.6-cm-long steel rods as the outer conductors. A calibration experiment has been performed to determine the probe-dependent constant ψ. Experiments were conducted to verify the accuracy of measuring dielectric constants in different soils using this new probe. The results show that the probe succeeds in obtaining the dielectric constant in soils with high electrical conductivities using surface reflection coefficients methods with reasonable precision. The newly designed probe can be utilized to accurately determine the water content and dry density in highly conductive soils with reasonable accuracy. It makes further progress in extending the applications of TDR in highly conductive soils, for example, municipal solid wastes, polluted soils, and salty soils.

Fundamental Principles of Surface Reflection Coefficients Method

The surface reflection coefficients method utilizes information about the electromagnetic wave reflection at the soil surface (Chen et al. 2009). The relationship between the reflection coefficient at the soil surface and the soil apparent dielectric constant was established theoretically by Chen et al. (2009). From this relationship, the soil apparent dielectric constant can be estimated from the surface reflection coefficient. Results indicate that the dielectric constant can be determined with reasonable accuracy with this new method even for soils with high electrical conductivity, whereas the conventional travel time method fails because of significant signal attenuation.

A TDR waveform measured in deionized water using the probe with a long air gap is shown in **Fig. 1**. According to **Fig. 1**, the apparent dielectric constant K_a, obtained by the travel time method, can be written as:

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

where c is the velocity of electromagnetic waves in free space, L is the length of the rod inserted in the water, and Δt is travel time of the electromagnetic wave propagating back and forth.

The surface reflection coefficients method measures the reflection coefficient at the junction of the air gap and the test sample (Point C in **Fig. 1**). Chen et al. (2009) stated that the small step C in **Fig. 1** was the end of the reflection at the soil surface and the difference of the reflection coefficients between point B and point C depended on the soil dielectric constant in the mold. The apparent dielectric constant, K_{asc}, obtained by the surface reflection coefficients method can be expressed as (Chen et al. 2009):

$$K_{\text{asc}} = k^2\left(\frac{\psi + \Delta\rho}{\psi - \Delta\rho}\right)^2 \quad (2)$$

where $\Delta\rho = \rho_{t\text{II}} - \rho_{t\text{III}}$, depends on the dielectric constant of the soil. $\rho_{t\text{II}}$ and $\rho_{t\text{III}}$ are total reflection coefficients at the interfaces of the coaxial head section to the Delrin section and the Delrin section to soil samples, respectively, which can be estimated with the waveform. k is a constant related to the geometry of the probe. ψ is a probe constant associated with the material and geometry of the probe, which can be measured by calibration experiments before tests.

Design of the Probe

STRUCTURE OF THE PROBE

The whole probe consists of three parts: the coaxial head, the extension section, and the rods section. As mentioned above, the special probe designed by Chen et al. (2009) with a 375-mm-long air gap cannot be embedded in the soil, so it is necessary to find a kind of new material with a low dielectric constant to substitute for the air gap. The Delrin turns out to be optimal with good integrity and high strength. Above all, it has the dielectric constant of 3.7, which is quite close to that of air. Stainless steel is chosen for the coaxial head and four rods to ensure that they have high stiffness, abrasive resistance, and corrosion resistance.

The structure of this new probe is shown schematically in **Fig. 2**. On the whole, the 20-cm-long Delrin section is the most important part in the whole design of the probe. The height of the coaxial head is 8 cm and the rod that could be embedded into the soil is 15 cm long. The 0.8-cm-diameter inner rod is located at the centroid, whereas three 0.8-cm-diameter outer rods are equally spaced around the inner rod and connected to the coaxial head. The spacing of rods is 4 cm.

DESIGN OF THE COAXIAL HEAD AND DELRIN SECTION

Because the excited TDR pulse has a certain rising time, if the propagation time of the TDR signal in a section of transmission line is less than the pulse width, the two sequent reflected waves will be overlapped. It is difficult to separate the reflection wave at different interfaces accurately because of overlapping, which causes errors of the surface reflection coefficients method (Chen et al. 2009). Therefore, it is necessary to design lengths of different sections of the probe to eliminate the influence of wave overlapping.

FIG. 1 TDR waveforms measured in deionized water using the probe having the extended rods with a long air gap. (a) Reflection at the interface of the coaxial head and the air gap, (b) the start of reflection at the interface of the air gap and test sample. (c) the end of reflection at the interface of the air gap and test sample, and (d) first reflection from the probe end.

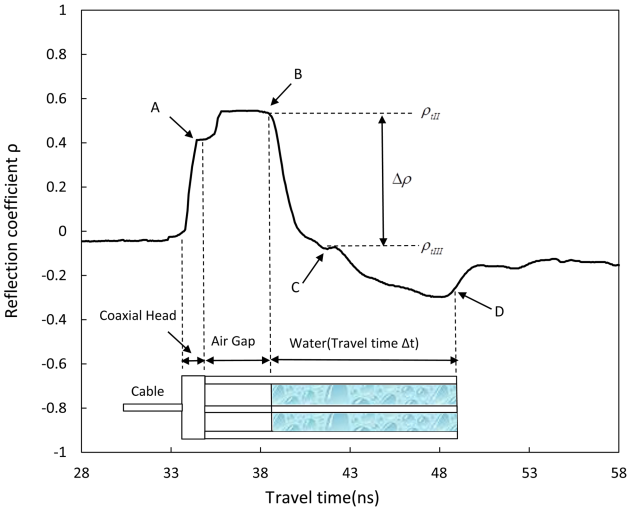
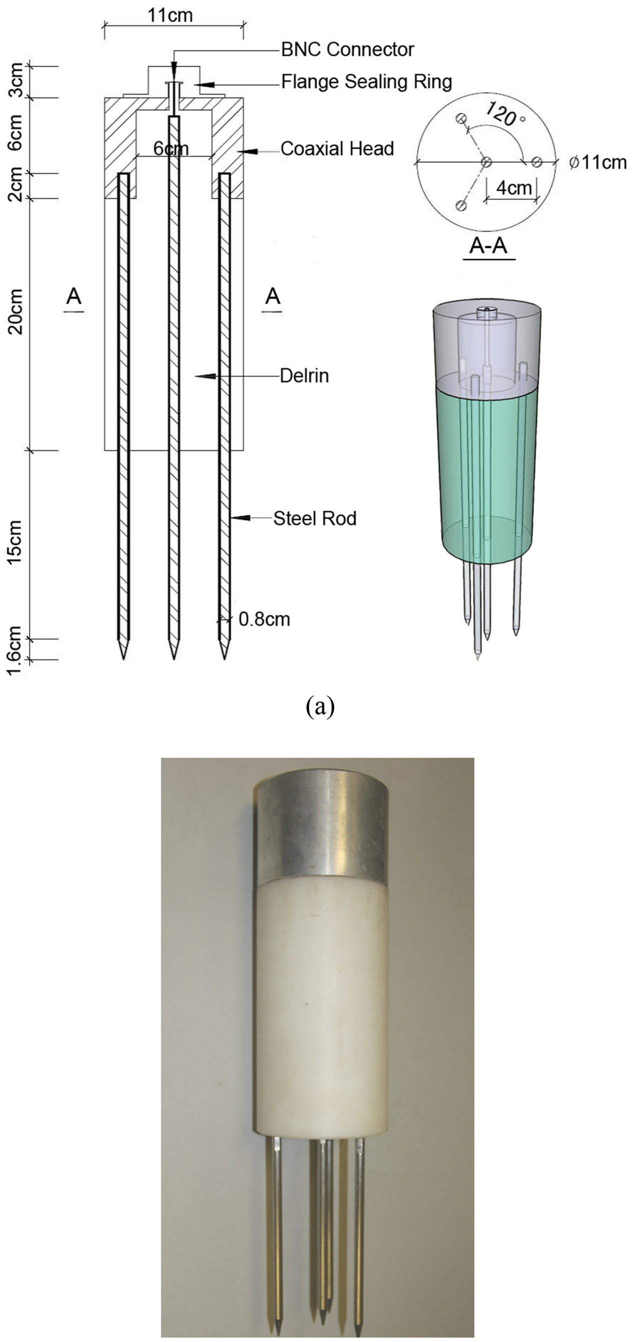


Figure 3 shows multiple reflections of the TDR pulse V_0 in the process of propagating in the non-uniform transmission line. V_{f1}, V_{f2}, V_{f3}, and V_{f4} are reflection signals received by the TDR receiver experiencing only one reflection at $\text{I}-\text{I}, \text{II}-\text{II}, \text{III}-\text{III}$, and $\text{IV}-\text{IV}$ interfaces, respectively. V' and V'' are reflection signals of V_{f2} and V_{f3} through multiple reflections, respectively. t_1, t_2, t_3, t_4, t', and t'' are the arriving time of each reflection signal. Δt_1, Δt_2, and Δt_3 are time intervals between the adjacent interfaces. $\Delta t'$ is the width of the excited pulse. When the pulse arrived in the probe experiencing the filtering effect of the transmission line, the width of the pulse measured by the Campbell Scientific TDR 100 device is: $\Delta t' = 0.8\text{ns}$. If the latest arrival time of the front reflection wave is earlier than the earliest arrival time of the later reflection wave, there is no overlapping of these two types of waves. When it meets the condition that $\Delta t_1 > \Delta t'$ and $\Delta t_2 > \Delta t'$, the reflection waves V_{f1}, V_{f2}, and V_{f3} at three different interfaces will not be overlapped. Consequently, the design of the probe must obey the following rules.

The length of the Delrin section must meet this condition:

$$L_{\text{Delrin}} > \frac{1}{2}c\Delta t'/\sqrt{K_{\text{Delrin}}} = \frac{1}{2} \times 0.3 \times 0.8 \times 100/\sqrt{3.7} = 6.24\,\text{cm} \quad (3)$$

FIG. 2 (a) Schematic diagram of the new probe, and (b) photo of the new probe.



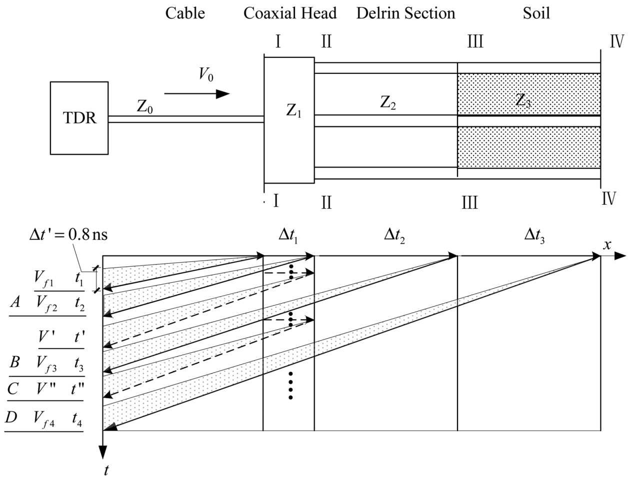
(a)

(b)

And the length of the coaxial head must meet this condition:

$$L_{\text{Head}} > \frac{1}{2} c\Delta t'/\sqrt{K_1^*} = \frac{1}{2} \times 0.3 \times 0.8 \times 100/\sqrt{3.07} = 6.8\,5\text{cm} \qquad (4)$$

FIG. 3 Multiple reflections. (a) Reflection at the interface of the coaxial head and the Delrin section, (b) the start of reflection at the interface of the Delrin section and test sample, (c) the end of reflection at the interface of the Delrin section and test sample, and (d) first reflection from the probe end.



in which K_{Delrin} and K_1^* are dielectric constants of the Delrin section and the coaxial head, respectively. In **Fig. 3**, the reflection wave V_{f2} and V_{f3} are not overlapped. Equations 3 and 4 can calculate the shortest length of the Delrin section and the coaxial head. On the basis of analysis of probe configuration, 8 cm is chosen as the length of the coaxial head. To ensure the full separation of the reflection wave and considering the whole design of the probe, 20 cm is chosen as the length of the Delrin section.

DESIGN OF THE RODS

In general, the shorter the probe is, the greater the error will be, especially for dry soils with low dielectric constants (Robinson and Friedman 2000). Topp and Davis (1985) and Dalton and Vangenuchten (1986) pointed out that the probe length should be greater than 10 cm. The main purpose of designing this new probe is that it can be used to determine the dielectric constant by the surface reflection coefficients method in highly conductive soils. And at the same time, it can also be used to measure the dielectric constant by both the travel time method and surface reflection coefficients method simultaneously in lowly conductive soils. A shorter probe can be designed if the measurement is only taken by the surface reflection coefficients method. But for the sake of measurements by the travel time method, the equation proposed by Heimovaara (1993) based on the travel time approach is used to determine the length of the rods. Heimovaara (1993) developed an equation about volumetric water content measurement error of the three-rods probe as follows:

$$\Delta\theta = \frac{d\theta}{d\sqrt{K_a}}\frac{c}{L}\Delta t_\delta \qquad (5)$$

where θ is the volumetric water content and Δt_δ is the time resolution with a default magnitude of 0.026 ns. θ and K_a has a relationship of $d\theta/d\sqrt{K_a}$=0.103 (Topp et al. 1980). The error can be estimated with Eq 5:

$$\begin{aligned}\Delta\theta &= \frac{d\theta}{d\sqrt{K_a}}\frac{c}{L}\Delta t_\delta = 0.103 \times \frac{3\times10^8}{L}\times 0.026\times10^{-9}\\ &= 8.034\times10^{-4}/L\end{aligned} \tag{6}$$

It can be found that when the rod lengths are 10 cm, 15 cm, and 20 cm, the errors of θ will be 0.8 %, 0.5 %, and 0.4 %, respectively. On the other hand, Suwansawat and Benson (1999) indicated that increasing of the rod length may lead to greater loss and attenuation of the TDR signal. Therefore, 15 cm is chosen as the length of the rods into the soil.

Spacing and diameter of the rods have a great influence on the energy distribution around the probe directly so as to affect the probe accuracy. For the rod diameter, 0.8 cm is chosen to ensure that the rods have enough stiffness to resist buckling during installation. Increasing the spacing can make it easy to insert the probe, but it may produce skin effects to concentrate more energy around the probe. Knight (1992) suggested that $d/s > 0.1$ to avoid this effect. As a result, 4 cm is chosen as the rod spacing.

CALIBRATION OF THE PROBE

Chen et al. (2009) indicated that $k = Z_m/Z_a$, where Z_m and Z_a were the geometric impedance of the testing sample and the extension section, respectively. These two parameters are only related to the geometry of the probe and are independent of the dielectric constant of the sample and the Delrin section. For this newly designed probe, the geometric rod structures of these two sections are the same. So, theoretically, $k = 1$.

Another probe-dependent constant ψ can be obtained by calibration experiments. The dielectric constant of ethanol is about 20. So solutions with different dielectric constants can be obtained by mixing ethanol with different amounts of water. For these solution samples, the dielectric constant K_a could be measured by the conventional travel time method. **Figure 4** presents the waveforms measured by TDR in solutions with different dielectric constants.

Rewrite Eq 2, and ψ can be expressed as

$$\psi = \Delta\rho\left(\frac{\sqrt{K_a}+1}{\sqrt{K_a}-1}\right) \tag{7}$$

Figure 5 shows that the value of ψ is almost a constant with increasing dielectric constants. Therefore, ψ is calibrated as $\psi = 0.70$.

INFLUENCE OF EC ON K_A

It was found by Chen et al. (2009) that electrical conductivity had little effect on the small step by surface reflection coefficients method. However, this influence can be ignored only when electrical conductivity is low. In highly conductive soils, the value of the step will be affected by the electrical conductivity. Experiments were conducted to find out the extent of influence of electrical conductivity on the value of the step with the surface reflection coefficients method. Mixed solutions of alcohol and deionized water with three volume ratios (alcohol: water = 2:1, 1:1, and 1:2) and deionized water were prepared for the experiments. Different amounts of calcium chloride ($CaCl_2$) were added to these solutions gradually to obtain different electrical conductivities. The electrical conductivities of the solutions with different amounts of calcium chloride were measured using an electrical conductivity tester. Then the new probe was utilized to measure the value of the step in these solutions. The experimental results indicate that increasing electrical conductivities lead to decrease of the step value and the waveforms of the aqueous solution are shown in **Fig. 6**. **Figure 7** presents the relationship between the change of the step value and electrical

FIG. 4 Waveforms measured by TDR in ethanol and water solutions with different dielectric constants.

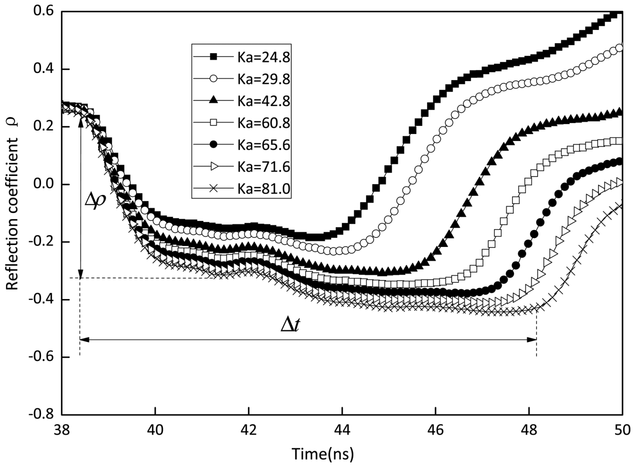


FIG. 5 Calibration of ψ.

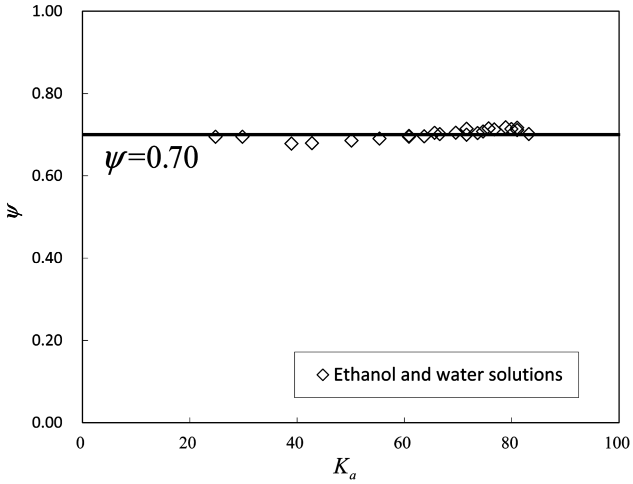
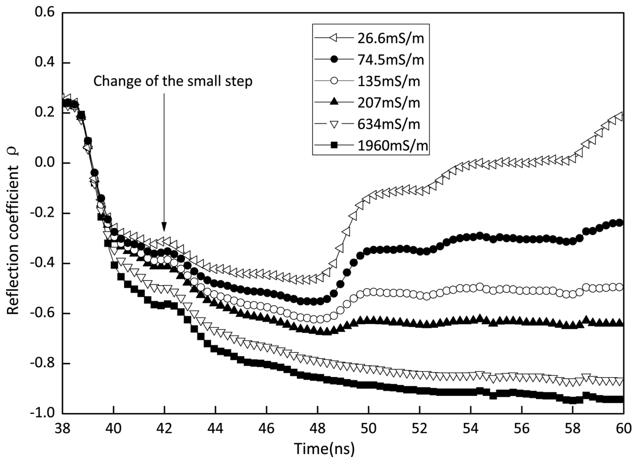


FIG. 6 The change of the step value verses the change of EC in aqueous solutions.



conductivity when the dielectric constant can be regarded as a constant for each solution.

The correction for the change of step value can be written as:

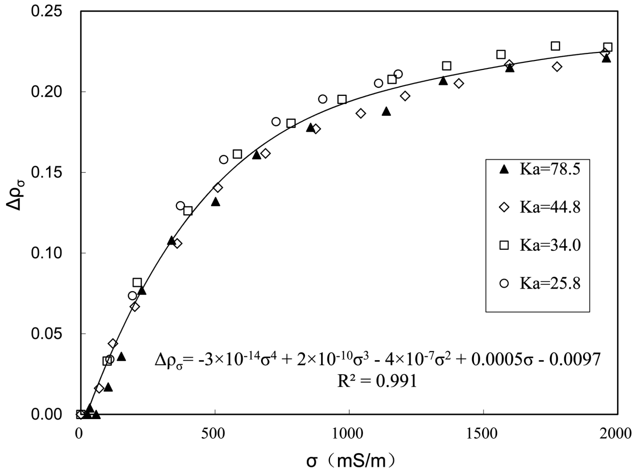
$$\Delta\rho_\sigma = -3\times10^{-14}\sigma^4 + 2\times10^{-10}\sigma^3 - 4\times10^{-7}\sigma^2 + 0.0005\sigma - 0.0097 \quad (8)$$

Then Eq 2 can be changed to:

$$K_{asc} = k^2\left[\frac{\psi + (\Delta\rho - \Delta\rho_\sigma)}{\psi - (\Delta\rho - \Delta\rho_\sigma)}\right]^2 \quad (9)$$

The results of measurements of the dielectric constant calculated by Eqs 2 and 9 are almost the same in lowly conductive soils. But in soils with extremely high conductivities, there exist some errors calculated by Eq 2 because it does not consider the influence of electrical conductivity.

FIG. 7 The formula of electrical conductivity correction.



Experiments and Results

LABORATORY TESTS

This new probe can measure the dielectric constant by the travel time method and surface reflection coefficients method simultaneously. Experiments were conducted to verify the accuracy of the measurement. Three types of soils including sand, silt, and clay were prepared in the experiments. These soils were collected from three excavations in Hangzhou city. They can be classified as SW (sand), ML (silt), and CL (clay) in accordance with ASTM D2487-11. These soils were named group A. At first, soils were washed with deionized water several times until the pore-water conductivities of the soils were less than 20 mS/m. Then the soils were dried and put into sieves to obtain clean soil samples. Different amounts of calcium chloride ($CaCl_2$) solutions were used to mix the soil samples to reach the target water content. Afterward, the soil samples were sealed in big plastic bags and placed in a room with a constant temperature of 20°C for 24 h. The TDR measurements were taken with the Campbell Scientific TDR 100 device and PCTDR software. The experimental procedure was as follows:

1. Compact the soil samples into the test cylinder (diameter = 20 cm, height = 20 cm). The compaction process and compaction energy are in accordance with ASTM D698-00a. Level the soil surface with a scraper and measure the volume and mass of the sample. Then obtain the density of the sample.
2. Put the new probe on the soil surface and then embed the rods of the probe into the soil sample completely. Make sure that there is no air gap between the soil surface and the bottom of the Delrin section.
3. Take TDR readings for each specimen. Then obtain Δt and $\Delta\rho$ for each specimen.
4. After the TDR measurement, measure the water content of the sample by the oven-dry method. Calculate dry density of the sample using water content and density.
5. Calculate K_a and K_{asc} using Eqs 1 and 9, respectively, for all specimens.

FIELD TESTS

Field tests were conducted to verify the accuracy of measurements of water content and dry density using the new probe. A series of experiments were conducted on different types of soils including silt, clay, and mucky soil. They can be classified as ML (silt), CL (clay), and CH (mucky soil) in accordance with ASTM D2487-11. These soils were named group B. A one-step method (ASTM D6780-05) was used to calculate the water content and dry density. Before tests, six parameters of calibration should be obtained in a one-step method. Three different types of soil samples were first delivered into the laboratory.

TABLE 1 Summary of experimental results of group A

			Dielectric Constant		TDR Measurements				
Specimen Name	w By Oven-Dry Method	ρ_d (g/cm^3)	K_a	K_{asc}	w_a	w_{asc}	ρ_{da}	ρ_{dasc}	σ_{DC} (ms/m)
A1-1 (SW)	5.59 %	1.590	7.1	6.5	6.19 %	5.16 %	1.573	1.573	40.3
A1-2 (SW)	12.76 %	1.577	12.1	11.4	13.46 %	12.55 %	1.569	1.570	80.5
A1-3 (SW)	15.40 %	1.580	16.5	15.7	18.70 %	17.80 %	1.567	1.567	131.2
A1-4 (SW)	19.44 %	1.537	NA	18.3	NA	20.64 %	NA	1.566	168.7
A1-5 (SW)	24.37 %	1.608	NA	21.6	NA	23.97 %	NA	1.564	220.4
A1-6 (SW)	27.85 %	1.526	NA	24.9	NA	27.05 %	NA	1.563	255.8
A2-1 (ML)	8.20 %	1.550	7.1	6.9	7.52 %	7.26 %	1.562	1.561	55
A2-2 (ML)	13.50 %	1.573	13.2	12.1	14.13 %	13.09 %	1.590	1.586	91
A2-3 (ML)	15.59 %	1.571	17.01	16.32	17.40 %	16.84 %	1.604	1.602	122.3
A2-4 (ML)	20.22 %	1.596	NA	19.3	NA	19.16 %	NA	1.612	175
A2-5 (ML)	20.87 %	1.583	NA	22.5	NA	21.44 %	NA	1.622	215
A2-6 (ML)	22.06 %	1.651	NA	25	NA	23.08 %	NA	1.630	265
A2-7 (ML)	26.80 %	1.677	NA	28.7	NA	25.35 %	NA	1.640	307
A3-1 (CL)	7.55 %	1.409	7.9	8.3	8.12 %	8.75 %	1.398	1.400	88.5
A3-2 (CL)	14.20 %	1.403	12.4	11.8	14.34 %	13.59 %	1.420	1.418	101.5
A3-3 (CL)	19.37 %	1.476	17.2	16.9	20.18 %	19.87 %	1.442	1.441	138.5
A3-4 (CL)	24.36 %	1.481	NA	20.6	NA	23.47 %	NA	1.455	184
A3-5 (CL)	28.46 %	1.448	NA	24.5	NA	26.86 %	NA	1.468	225.3
A3-6 (CL)	31.56 %	1.467	NA	28.04	NA	29.66 %	NA	1.479	307.1
A3-7 (CL)	34.58 %	1.480	NA	31.95	NA	32.52 %	NA	1.490	399.5

Note: The first number in the specimen name is the soil type: number 1, sand A; number 2, silt A; number 3, clay A. The second number indicates the sample number. SW, ML, and CL are soil classification symbols in accordance with ASTM D2487-11. K_a, w_a, and ρ_{da} = measured by the travel time method; K_{asc}, w_{asc}, and ρ_{dasc} = measured by the surface reflection coefficients method. NA, not applicable.

Experiments were conducted at a room temperature of 20°C. Tap water was used in preparing the soil samples. These soil samples were mixed with different amounts of tap water to obtain samples with a target water content. The soil samples were then sealed in plastic bags for 24 h. The TDR measurements were conducted after the compaction tests and the TDR measurements were taken with a TDR100 device. The procedure of the field test was as follows:

(1) Prepare the soil surface by leveling an area approximately 40 cm by 40 cm. If the soil surface has been exposed for some time such that it was dried out or wet from a recent rain, it was suggested that the top 2.5 cm of the soil be removed and the fresh surface leveled. The leveled surface should be free of voids. If some exist, they should be filled with soils and smoothed.
(2) Put the new probe on the soil surface and then embed the rods of the probe into the soil sample completely. Make sure that there is no air gap between the soil surface and the bottom of the Delrin section.
(3) Connect the probe to the TDR device with the coaxial cable provided. Be sure that the BNC connectors are clean and free of dust or debris before making the connections.
(4) Take TDR measurements. The dielectric constant was calculated by Eq 9. Then water content and dry density can be obtained by a one-step method using the calibration parameters mentioned above.
(5) After TDR measurements, soil samples in situ measured by TDR were excavated to transport to the laboratory.

FIG. 8 Relative error of apparent dielectric constant K_{asc} by the surface reflection coefficients method compared to dielectric constant K_a by the travel time method for group A and B.

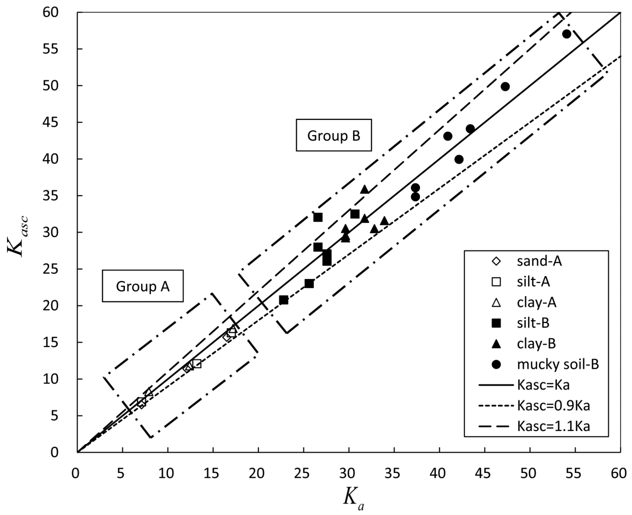
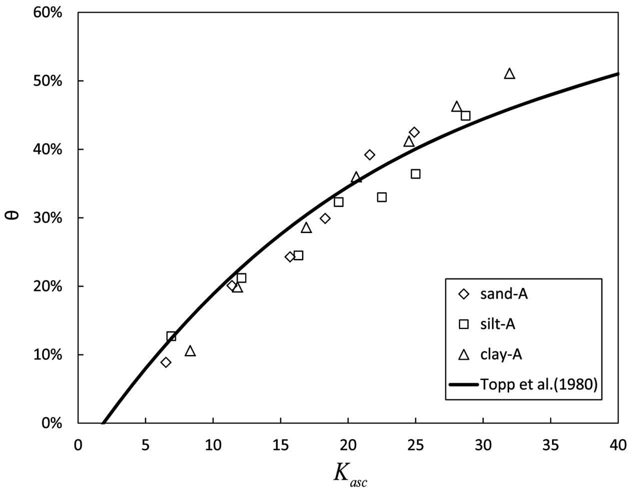


FIG. 9 Relationship between θ and K_{asc}.



Then water content and dry density could be obtained using the oven-dry method and cutting ring method, respectively.

Results and Discussion

A summary of the experimental results of group A are listed in Table 1. In soils with high conductivity, dielectric constants cannot be measured by a conventional travel time method. Therefore, the results of the dielectric constant of group A with high conductivity are not included in Table 1. Group A in **Fig. 8** summarizes the comparison between the apparent dielectric constant K_{asc} estimated by the surface reflection coefficients method and K_a calculated by the travel time method. The results of the dielectric constant with high conductivity are not included in Fig. 8. The existing results indicate that K_{asc} measured by the surface reflection coefficients method matches well with K_a by the travel time method within the relative error range of 10 % in lowly conductive soils. Figure 9 shows the volumetric water content determined by gravimetric water content and dry density versus the apparent dielectric constant K_{asc} measured by the surface reflection coefficients method. The results indicate that the experimental data correspond well with the curve proposed by Topp et al. (1980), and K_{asc} is independent of the soil type.

The results of calibration parameters a, b, c, d, f, and g of group B are listed in Table 2. Group B in Fig. 8 compares K_{asc} calculated by Eq 9 versus the apparent dielectric constant K_a obtained by Eq 1. The data lie within 10 % relative error of the 1:1 line. The results show that the measurement of the dielectric constant using this new probe provides satisfactory accuracy. Because some soil samples in situ have high electrical conductivities, it is indicated that this new probe has a great performance in measuring dielectric constants in soils with high electrical conductivities. Figures 10 and 11 compare water content and dry density measured by this new probe to these soil parameters estimated by traditional methods, respectively. Figure 10 indicates that the relative error of water content measured by the surface reflection coefficients method (w_S) compared to the oven-dry method (w_O) for group B is within 10 %. And it is shown in Fig. 11 that the relative error of dry density measured by the surface reflection coefficients method

TABLE 2 The results of calibration parameters.

Soil Type	a	b	c	d	f	g
Silt (ML)	1.047	8.7568	−0.0076	0.4543	−0.092	0.0501
Clay (CL)	1.305	7.6724	0.0633	0.3363	0.0053	0.0448
Mucky soil (CH)	1.3517	8.4473	0.0358	0.6892	−0.0995	0.0805

FIG. 10 Relative error of water content measured by the surface reflection coefficients method (w_S) compared to the oven-dry method (w_O) for group B.

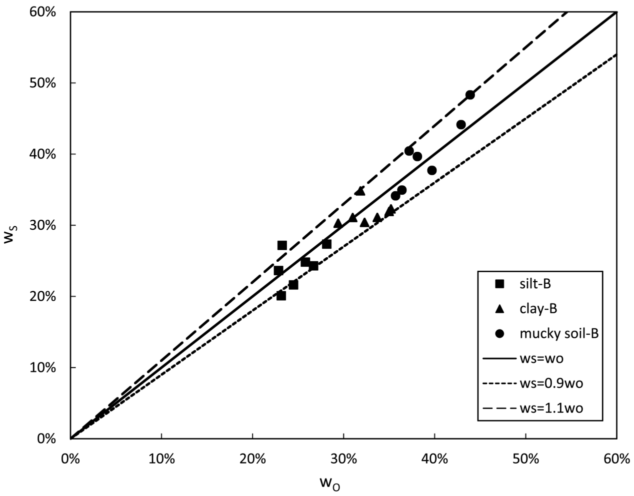
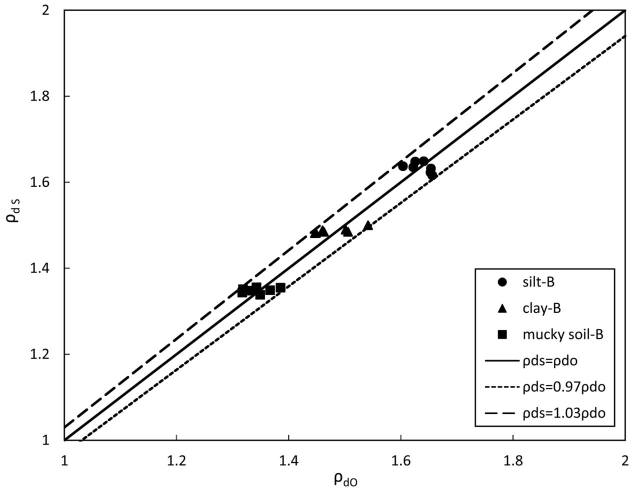


FIG. 11 Relative error of dry density measured by the surface reflection coefficients method (ρ_{dS}) compared to the oven-dry method (ρ_{dO}) for group B.



(ρ_{dS}) compared to the oven-dry method (ρ_{dO}) for group B is less than 3 %. In conclusion, this new probe has greatly extended TDR technology to field tests of soils with high electrical conductivities. The tested soils were medium loose to loose. It was easy to penetrate the probe into the soils by hand. However, for dense soils, for example, lime stabilized compacted soil, it is impossible to penetrate the probe into the soil by hand. And penetrating the probe by using a hammer may damage the probe. Hence, this newly designed probe can only be used in medium dense to loose soils.

Conclusions

A new probe is designed in this paper for field use to overcome the difficulties of existing probes using the surface reflection coefficients method. With this new probe, the surface reflection coefficients method of TDR technology could be extended to materials with high electrical conductivities such as contaminated soils in situ. The performance of the new probe is verified with experimental data on sand, silt, and clay. Finally, this new probe is used to measure the water content and dry density of soils including silt, clay, and mucky soil in situ. Major conclusions include:

1. A series of experiments on aqueous solutions mixed with different amounts of calcium chloride ($CaCl_2$) show that electrical conductivity has a certain effect on the small step of waveform in surface reflection coefficients method. The relationship between the change of the step value and electrical conductivity is presented. Then the equation of the surface reflection coefficients method is modified considering the influence of electrical conductivity.
2. Experiments were conducted on different soil samples including sand, silt, and clay to verify the accuracy of the probe. The dielectric constant was measured both by the travel time method and the surface reflection coefficients method. The results show that the dielectric constant measured by the surface reflection coefficients method matches well with that determined by the travel time method. The relative error is less than 10 %. The relationship between θ and K_{asc} correspond well with the curve proposed by Topp et al. (1980) and K_{asc} is independent of soil type.
3. Field tests were conducted to verify the accuracy of measurements of water content and dry density using this new probe. In the process of foundation excavation, a series of experiments were conducted on different types of soils including silt, clay, and mucky soil. The results show that this new probe has a great performance in measuring dielectric constants in soils with high electrical conductivities. The dielectric constant measured by the surface reflection coefficients method corresponds with that determined by the travel time method. The relative error is less than 10 %. The results of water content and dry density by the surface reflection coefficients method were compared to the conventional method. And it is indicated that the measurements of water content and dry density have a satisfactory accuracy. Compared to the oven-dry method, the relative errors of water content and dry density determined using this new probe are less than 10 % and 3 %, respectively.

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