Designation: D 6565 – 00 (Reapproved 2005)

Standard Test Method for Determination of Water (Moisture) Content of Soil by the Time-Domain Reflectometry (TDR) Method[1]

This standard is issued under the fixed designation D 6565; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of water content (or moisture content) in soil by the use of the electromagnetic technique called Time-Domain Reflectometry (TDR).

1.2 This test method was written to detail the procedure for conventional TDR measurements of soil. Other TDR applications exist for the purpose of quantifying water content in soil and are not covered here, such as flat probe technologies and wetting front advance methods.

1.3 Commercial TDR applications exist which automate the TDR methodology and are not detailed in this test method. It is likely that overlap exists in the automated commercial systems versus this applied method, and the user is encouraged to adhere to this test method when applicable.

1.4 This test method is one of a series on vadose zone characterization methods. Other standards have been prepared on vadose zone characterization techniques.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:* [2]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids

D 1452 Practice for Soil Investigations and Sampling by Auger Borings

D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D 4643 Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven Method

D 4700 Guide for Soil Sampling from the Vadose Zone

D 4944 Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester Method

D 5220 Test Method for Water Content of Soil and Rock In-Place by the Neutron Depth Probe Method

3. Terminology

3.1 *Definitions:*

3.1.1 *time domain reflectometry (TDR)*—an electromagnetic method used in the determination of water content of soil.

3.1.2 Definitions of other terminology used in this guide may be found in Terminology D 653.

4. Summary of Test Method

4.1 A specially constructed, multi-wave-guide TDR probe is inserted into the soil. The electronic cable tester (or automated commercial TDR electronics) is used to send a pulsed waveform to the probe. The cable tester then receives a return signal which was influenced by the dielectric constant of the soil, which in turn is a function of water content. An analysis of the waveform trace supplies the necessary information to calculate the water content of the soil.

5. Significance and Use

5.1 The determination of the water-content, or moisture content, of soil is one of the fundamental needs in the soil physics and hydrology disciplines. The need arises from requirements for defining the optimal time for irrigation, the infiltration rate, the soil-moisture flux, contaminant transport rates, and evaluating the potential for leakage from a waste site or a surface or subsurface barrier.

5.2 The TDR application covered in this test method is that used for point measurements of moisture content in soil. The application is either through manual insertion into the soil or by burying a probe in the subsurface to acquire moisture content

[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21.02 on Vadose Zone Monitoring.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

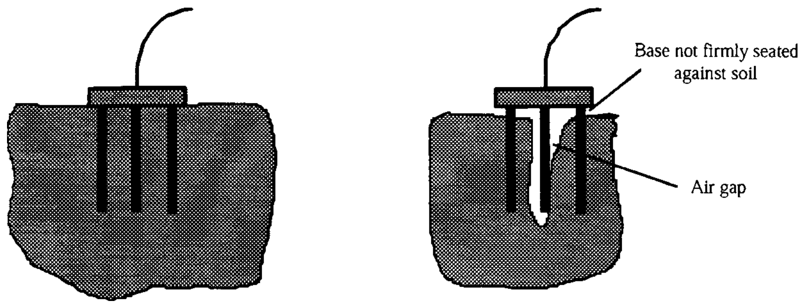

Fig. 1(*a*) Properly installed probe   Fig. 1(*b*) Improperly installed probe

FIG. 1 Properly and Improperly Installed TDR Probes

data at a specific location. In addition, core samples may be tested with TDR at a drill site to acquire real-time soil moisture data.

6. Interferences

6.1 TDR measurements in conductive soils are hampered by the conductivity of the soil and the resulting signal attenuation. Typically, the amplitude of the voltage pulse reflected back to the TDR instrument is diminished in proportion to the soil's electrical conductivity. When the soil's electrical conductivity is high enough, there is insufficient signal strength for the TDR instrument to detect. TDR probes employing a balancing balun transformer are particularly susceptible to this effect. The balun transformer compounds the problems in analyzing the signals from probes with rod lengths of 15 cm or less (**1**).[3]

6.2 Clay soils also attenuate a TDR probe signal. Conductive soils which have a significant amount of clay attenuate the signal the most. A partial solution to signal loss is to reduce the length of the probe (**2**). However, as the probe length shrinks, the precision of the moisture content estimates worsens.

6.3 A solution to the problem is to use a probe rod length of 15 cm and to electrically insulate the probe (**3**). This can be accomplished by spraying the probe rods with a clear resin coating or applying a very thin layer of marine epoxy resin. The marine epoxy resin is a hard, non-conductive, and non-absorbing coating which adheres well to the metallic rods. The rods should be slightly abraded to enhance resin adhesion. The coating should have a minimal effect upon the accuracies observed if applied in an even thickness about the rods. The coatings should be inspected on a regular basis for wear.

6.4 Temperature effects have been observed when using TDR in the field. Temperature effects are particularly troublesome for systems where the user has predefined a probe beginning point within the software and employs long TDR probe cable lengths (~30 m or more). The cable shrinks and contracts as a function of temperature. Naturally the maximum and minimum cable lengths occur during the warmest, and coolest times of the day, respectively. The solution is to avoid defining a beginning point of the cable tester trace within the users software. Also, thermal effects can be minimized by burying the cable or otherwise protecting the cable from exposure. In addition, the dielectric of the soil changes as a function of temperature.

6.5 A static charge on the coaxial cable may cause damage to the TDR cable tester unit. To avoid possible damage to the electronics, always dead-short the TDR probe leads to each other. This will discharge the static charge in the cable prior to connecting the cable assembly to the TDR cable tester unit.

6.6 Voids in the path of, or adjacent to, the probe can cause the soil moisture to appear lower than it actually is. This same effect can be seen when the top of the probe is not seated properly (see Fig. 1(*b*)).

6.7 This test method is not appropriate for measuring the moisture content of frozen soils.

6.8 Metals of natural (for example, ores) or manmade (for example, barrels) origin may affect measurements if they are present in sufficient quantity and are within the volume of soil tested by the device.

6.9 As the moisture content decreases below 5 % by volume, the difference in dielectric between the soil and water diminishes and the ability of the TDR technique to quantify moisture content with any degree of certainty is compromised.

7. Apparatus

7.1 The basic TDR system consists of a Tektronix[4] 1502B cable tester (or comparable unit) and a cable/probe assembly, as shown in Fig. 2. The cable tester generates a fast rise time pulse which propagates along the coaxial transmission line until it reaches an impedance change. At this point, a portion of the signal is reflected back to the cable tester and is displayed as a change in amplitude. If the reflection point is lower in impedance than the cable, then the reflection will be displayed as a drop in amplitude. If it is higher in impedance, then it will be displayed as a rise in amplitude. The cable tester measures the time for a pulse to travel the distance between the beginning and end points of the probe, as displayed on the screen, and converts this time to a distance. Fig. 3 shows a typical TDR trace with the probe connected to the instrument and inserted into a wet soil sample. It should be noted that the impedance of the probe assembly in the wet soil is lower than the cable, hence the amplitude of the return signal is lower. At

[3] The boldface numbers given in parentheses refer to a list of references at the end of the text.

[4] The Tektronix 1502B is the instrument around which the TDR probe technology has been developed. With rare exception, commercial companies selling a TDR probe system employ this instrument in their systems.

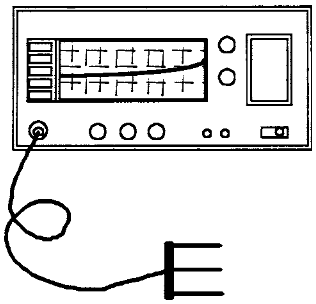

FIG. 2 Basic TDR System

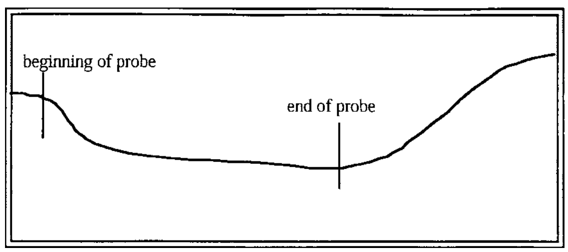

FIG. 3 Typical TDR Trace When the TDR Probe is Inserted Into Moist Soil

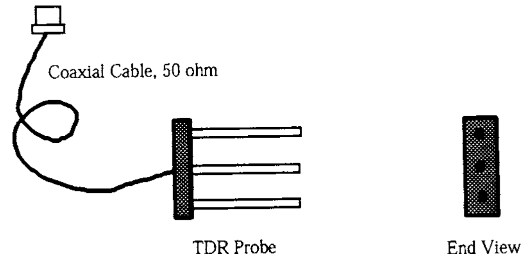

FIG. 4 Typical 3-Rod TDR Probe Configuration

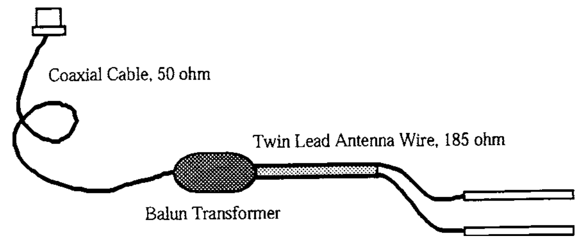

FIG. 5 Typical 2-Rod TDR Probe With Balun Transformer

the end of the probe assembly the impedance again changes (impedance increases) and is reflected in Fig. 3 as a gradual rise in amplitude.

7.2 TDR probes are typically divided into two categories: Two rod probes employing a balancing balun transformer, and multi-rod probes which do not require a balancing balun transformer. Fig. 4 is an example of a multi-rod TDR probe while Fig. 5 is a typical two rod/balun TDR probe. Typically rod lengths, materials, diameters, and rod spacings vary from probe to probe. These parameters are chosen as a function of the soil to be tested, the longevity of the test, and the sensitivities required from the probe.

7.2.1 The two-rod balun probe makes use of a signal balancing balun. A balun (also known as a balancing transformer) allows the user to connect two wires of dissimilar impedances. A typical example of impedance mismatch applicable to TDR probes is the 50 ohm coaxial cable connected to twin lead 185 ohm antenna wire. The balun transformer[5] is inserted at this junction so as to balance the impedance mismatch.

7.2.2 The balun transformer used in two rod probes has typically been a source of signal loss. A new type of balun has been developed (**4**) which alleviates the problems encountered with the typical balun.

7.2.3 Multi-rod, or multi-waveguide, probes employ, at a minimum, three conductive rods arranged in a symmetric pattern. The diameter of the rods, length, rod material, and spacing may vary.

7.2.4 Some commercially available systems offer the user multi-probe configurations, direct digital read out, data storage capabilities, probe lengths up to 120 cm long, time tagging of stored data, and real time data acquisition and control by computer through an RS232 serial interface.

7.3 With the use of a computer, and a series of multiplexers, a large number of TDR probes may be queried in a sequential fashion, and the data stored for later retrieval and analysis.

8. Preparation of Apparatus

8.1 Determining the proper propagation velocity (V_p) to be used in conjunction with the TDR probe is an important item in setting up a TDR probe system. The first step is to accurately measure the length of the cable and probe assembly. The propagation velocity may then be determined by performing the following procedure.

8.1.1 After attaching the TDR probe cable to the TDR cable tester, adjust the distance/division control to the appropriate setting. For example, if the cable/probe assembly is 1 m, adjust the distance/division control to 1 m/div.

8.1.2 Turn the position adjustment until the distance reading is the same as the cable/probe assembly length.

8.1.3 Turn the propagation control (V_p) until the cursor is resting on the first rising portion of the reflected pulse, that is, the end of the probe. Shorting the ends of the probe together will aid in determining the end of the probe as reflected in the TDR trace. The V_p controls of the instrument are now set to the V_p of the cable/probe assembly.

9. Calibration and Standardization

9.1 For best results, the TDR system should be calibrated to the soil to be tested. This can be accomplished by acquiring a sufficient quantity of the soil to be tested, so as to provide a minimum of seven soil samples, mixed to a uniform volumetric water content, as shown in Table 1.

9.2 Use an oven-drying or microwave-drying technique to remove any residual water from the soil samples. Periodic weighing of the sample is required to establish when the soil is dry. Two successive measurements of equal weight should be sufficient.

[5] A typical balun used here is the Type T.P. 103 Balun as sold by the Adams-Russel Co., of Burlington, MA.

TABLE 1 Example of Volumetric Moisture Content of Calibration Sam

5 %	10 %	15 %	20 %	25 %	30 %	35 %

9.3 Using the dry soil, prepare seven soil samples having the volumetric water content as outlined in Table 1. Place the calibration samples into a plastic container. Do not use a metal container for the calibration samples. The calibration container should be of a sufficient size such that the radius of influence of the TDR probe is not affected by the container or surrounding air.

9.4 Insert the probe into the calibration sample and, using the procedure outlined in Section 11, and calculate the volumetric water content. Repeat this procedure until all samples have been sampled at least three times.

9.5 Use an oven-drying or microwave-drying technique to quantify the actual water content of the soil samples used in the TDR calibration (as outlined in Test Methods D 2216 or D 4643).

9.6 If inaccuracies are noted then conduct a regression analysis. Inaccuracies are defined as repeated errors greater than plus or minus 2 % (for example, the calibration sample is mixed to a 15 % volumetric water content and the user continuously arrives at a volumetric water content of 13 % or less, or 17 % or greater). The number of samples and the volumetric water percentages listed in Table 1 have been chosen so as to allow the user to conduct a representative regression analysis. A regression analysis will yield a mathematical relationship between the laboratory sample analyses of water content and the theoretical TDR calculations of water content (from Eq 2). Should it be necessary to work with soils having a significantly large volumetric water content (approximately >35 %), then the user is encouraged to conduct a non-linear regression analysis.

9.7 No commercial calibration standards presently exist by which to calibrate the TDR probe.

10. Procedure

10.1 Set the propagation velocity (v_p) as outlined in Section 8.

10.2 With the probe in air, record the beginning and end points of the probe as indicated by the TDR instrument.

10.3 If small soil samples are to be tested, ensure that the containers used are large enough to allow insertion of the probe without touching either the bottom or sides of the container.

10.4 Insert the probe into the soil sample, taking care to ensure that no air gaps exist between the probe rods or the interface between the soil and probe base. Fig. 1(*a*) depicts a TDR probe properly inserted into a soil sample while Fig. 1(*b*) depicts a TDR probe improperly inserted into a soil sample. Air gaps decrease the accuracies observed. In addition, care should be taken to ensure that the waveguides remain parallel. If the waveguides are not parallel, inaccuracies will result. Record the beginning and end points of the probe while inserted in the soil.

10.5 The beginning point should be the same as noted with the probe in air. If the beginning point is not the same, remove the probe from the calibration sample, and check for damage. If the probe is found to be in proper working order, reinsert the probe into the calibration sample, and again note the beginning and end points.

10.6 If the beginning point is the same as that found in air then continue with the sampling; if not, cease sampling, and check the system for damage or improper instrument settings. Repair or readjust as required.

10.7 Insert the probe into the sample following instructions 10.3-10.6. Determine the apparent trace length, l_a, as shown on the TDR instrument. It is very important to be able to properly determine the correct beginning and end points of the probe when inserted into a soil sample. The end point, as observed on the TDR instrument, will vary with water content. Improperly determining the trace end point will introduce gross errors in the predicted water content. Traditionally, the end points are determined graphically by the user. More recently, various algorithms have been developed to automate the processing of the data to determine the endpoints through mathematical analyses. The application of these automated analysis techniques is beyond the scope of this standard. Using the equations outlined in Section 11, calculate the volumetric water content.

10.8 Leave the probe in the sample and repeat the measurement and the calculation. The soil should be sampled a minimum of three times to ensure repeatability and accuracy. The same sampling rate is applied to soils sampled in the field.

10.9 For systems which have been set-up for long term monitoring, a periodic operational check of the system should be conducted.

11. Calculation

11.1 Time Domain Reflectometry (TDR) is a method which can be used to measure the volumetric water content of soil, θ_v (where: $\theta_v = V_w/V_t$, V_w = volume of water [L^3], and V_t = total volume of soil [L^3]). A unique relationship exists between the volumetric water content of soil (θ_v) and its dielectric constant, K_a, where: $\theta_v = f(K_a)$ (**5**).

11.1.1 The dielectric constant, K_a, is related to the apparent length (l_a) of the probe as shown in Eq 1:

$$K_a = [l_a/(l_p * v_p)]^2 \quad (1)$$

where:

l_p = actual probe rod length [L],
l_a = apparent length of the probe rod as determined from the TDR trace [L], and
v_p = propagation velocity of the signal [L/T].

11.1.2 l_a is determined by subtracting the beginning point of the probe, l_{begin}, from the end point of the probe, l_{end}, while the probe is inserted into the soil sample. Once the apparent length of the probe, l_a, is calculated, this information is used to determine the dielectric constant (K_a) of the soil (Eq 1). Topp (**5**) determined that the dielectric constant of soil is related to the volumetric moisture content by the empirical relationship:

$$\theta_v = -0.053 + (0.0292)K_a - (5.5\times10^{-4})K_a^2 + (4.3\times10^{-6})K_a^3 \quad (2)$$

11.1.3 Other equations have been used to determine moisture content from TDR data, but the Topp equation is the most widely used. In reality, the relationship between actual and predicted moisture content has some uncertainty due to differences in the dielectric of the media. Therefore a regression analysis is typically performed to develop a calibration relationship for better accuracy between observed versus TDR results.

12. Report

12.1 Report the following information:

12.1.1 The volumetric water content to the first decimal (tenths of a percent) when the average of replicate values permits,

12.1.2 The repeatability of the measurements. Accuracies should not vary by more than ±2 % volumetric water content,

12.1.3 The mean, standard deviation, and the standard error,

12.1.4 The calibration equation used and the method used to determine the equations coefficients,

12.1.5 The date, time, and location where the sampling occurred, and

12.1.6 The probe configuration, that is, two-rod with balun, three rod, rod length, and so forth.

13. Precision and Bias

13.1 *Bias*:

13.1.1 The resolution of the TDR measurement depends on the resolution of the TDR instrument, the properties of the soil (electrical properties and dielectric constant), cable length (long cables attenuate the amplitude of the return signal and contribute to noise (for example, antenna effects)), probe configuration, technique used to analyze the TDR data, and operator skills and experience.

13.1.2 A calibration procedure, as outlined in Section 9, is recommended for optimum performance of a TDR system. A regression analysis of laboratory moisture content values versus theoretical TDR calculated moisture content (as defined by Eq 2) should yield a relationship that will estimate moisture contents within ±1 % by volume.

13.2 *Precision*:

13.2.1 Precision of this test method is established by statistical analysis of repeated measurements of a TDR system. Holding all experimental conditions constant, thirty (30) TDR measurements of moisture content are made on a soil sample within a range of interest for moisture. The mean and standard deviation are calculated from these data. Experience has shown that experiments holding all variables constant have resulted in measurement errors of ± 2 % for θ_v. If the data are calibrated to actual soil analyses through regression, then ±1 % precision may be expected (**7**). If variations larger than ± 2 % are encountered for multiple runs using standard calibration techniques, results should be considered suspect, and the tests should be repeated.

13.3 *Multilaboratory Precision*—There is no multilaboratory precision information at this time.

14. Keywords

14.1 Balun transformer; multiplexers; propagation velocity; soil samples; TDR probes; time domain reflectometry (TDR); volumetric water (moisture) content

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