INTERNATIONAL

**Designation: D8153 − 22**

# Standard Test Method for Determination of Soil Water Contents Using a Dielectric Permittivity Probe[1]

This standard is issued under the fixed designation D8153; 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 describes the procedures for measuring the water mass per unit volume of soil and soil-aggregate by use of an in situ permittivity probe. Measurements are taken at a depth beneath the surface of the soil determined by the design of the probe.

1.1.1 For limitations see Section 6 on Interferences.

1.2 The permittivity probe is inserted into a hole drilled or punched into the soil being measured. As its name indicates, the probe measures the dielectric permittivity of the soil into which it is placed. Two electrodes, connected to an oscillating circuit, are mounted a predetermined distance apart. These electrodes act as the plates of a capacitor, with the soil between the plates forming the capacitor dielectric.

1.2.1 The probe circuit creates an oscillating electric field in the soil. Changes in the dielectric permittivity of the soil are indicated by changes in the circuit's operating frequency. Since water has a much higher dielectric constant (80) than the surrounding soil (typically around 4), the water content can be related by a mathematical function to the change in dielectric permittivity, and, consequently, the changes in the circuit's operating frequency.

1.2.2 The construction, deployment, and operating principle of the device described in this test method differ from other methods that measure the dielectric constant, bulk electrical conductivity, complex impedance, or electromagnetic impedance (see Test Methods D6780/D6780M, D7698, and D7830/D7830M) of the soil and relate the results to water mass per unit volume and/or water content.

1.2.3 The water content of the soil measured by the permittivity probe is the volumetric water content, expressed as the ratio of the volume of water to the total volume occupied by the soil. This quantity is often converted, and displayed, by the probe in units of mass of water per volume of soil, or water mass per unit volume. This conversion is performed by multiplying the water content (in volume of water per volume of soil) by the density of water.

1.3 Water content most prevalent in engineering and construction activities is known as the gravimetric water content, ω, and is the ratio of the mass of the water in pore spaces to the total mass of solids, expressed as a percentage. To determine this quantity, the bulk density of the soil under measurement must also be determined.

1.4 *Units*—The values stated in SI units are to be regarded as the standard. Reporting the test results in units other than SI shall not be regarded as nonconformance with this standard.

1.5 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.5.1 For purposes of comparing, a measured or calculated value(s) with specified limits, the measured or calculated value(s) shall be rounded to the nearest decimal or significant digits in the specified limits.

1.5.2 The procedures used to specify how data are collected/recorded and calculated in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that should generally be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design.

1.6 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*



[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.08 on Special and Construction Control Tests.

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## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

C231/C231M Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D1556/D1556M Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method

D2167 Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D2487 Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)

D2488 Practice for Description and Identification of Soils (Visual-Manual Procedures)

D2937 Test Method for Density of Soil in Place by the Drive-Cylinder Method

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D4718/D4718M Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles

D6026 Practice for Using Significant Digits and Data Records in Geotechnical Data

D6780/D6780M Test Methods for Water Content and Density of Soil In situ by Time Domain Reflectometry (TDR)

D6938 Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)

D7698 Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method

D7830/D7830M Test Method for In-Place Density (Unit Weight) and Water Content of Soil Using an Electromagnetic Soil Density Gauge

D8167/D8167M Test Method for In-Place Bulk Density of Soil and Soil-Aggregate by a Low-Activity Nuclear Method (Shallow Depth)

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

## 3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms used in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *permittivity probe, n*—an in situ electronic probe that utilizes the measurement of the dielectric permittivity of the surrounding soil to determine the water mass per unit volume of the soil.

3.2.2 *capacitance standard, n*—a reference material or object prepared of soil, soil and rock, or engineered materials that has a stated dielectric permittivity value and an associated measurement uncertainty.

NOTE 1—The term "bulk density" is used throughout this standard. This term has different definitions in ASTM D653, depending on the context of its use. For this standard, however, "bulk density" refers to, as defined in ASTM D653, "the total mass of partially saturated or saturated soil or rock per unit total volume."

## 4. Summary of Test Method

4.1 The surface of an in situ test site where the water content is to be determined is scraped to a smooth, coplanar surface.

4.2 An access hole, with a nominal diameter of 19 mm, is punched, drilled, or augured into the soil. The hole shall extend a minimum of 25 mm below the end of the probe.

4.3 The probe is inserted into the access hole in such a manner as to minimize any disturbance to the integrity of the hole.

4.4 A measurement of the soil with the permittivity probe is acquired. The measurement consists of a series of readings of the oscillator frequency of the circuit associated with the dielectric permittivity. The readings are averaged to obtain a final result.

4.5 The resulting circuit reading, along with the calibration equation that relates this reading with the water mass per unit volume of the soil, are used to compute the water mass per unit volume of the soil.

4.6 If the data are available, then this calculated water mass per unit volume, in conjunction with the independently determined bulk density of the soil, may be used to determine the (gravimetric) water content of the soil. Bulk density may be determined by test methods such as the ones described in , Test Methods D1556/D1556M, D2167, D2937, D6938, and D8167/D8167M, as examples.

## 5. Significance and Use

5.1 The soil permittivity probe is used for the following purposes:

5.1.1 The test method described is useful as a rapid, nondestructive technique for bulk measurements of the water mass per unit volume of soil and soil-aggregate which may, in conjunction with an independent bulk density determination, be used in the determination of dry density.

5.1.2 The test method is used for quality control and acceptance testing of compacted soil and soil-aggregate mixtures as used in construction and also for research and development. The nondestructive nature allows repetitive measurements at a single test location and statistical analysis of the results.

5.1.3 *Volumetric Water Content*—The fundamental assumptions inherent in the test method are that the dielectric constants value measured by the system in a given test site composed of soil or soil-aggregate are directly correlated to the volumetric water content of the soil or soil-aggregate, and that the material is homogeneous. (See 6, "Interferences.")

NOTE 2—The quality of the result produced by this standard is

[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.

dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

## 6. Interferences

6.1 The elemental and/or molecular composition of the material being tested can affect the measurement, and adjustments may be necessary (see Annex A1.8). Different soils with solids composed of different elements or molecular structure may cause correspondingly different dielectric constant responses with this instrument, thereby possibly yielding different water mass per unit volume measurements with soils of the same water mass per unit volume.

6.2 The water mass per unit volume calculated by this test method is not necessarily the average water content within the volume of the sample involved in the measurement. The measured value is biased by the water mass per unit volume of the material closest to the dielectric spacer in the probe assembly (see 7.1.2). The volume of soil and soil-aggregate represented in the measurement is indeterminate and will vary with the water content and elemental and/or molecular composition of the material. In general, the greater the water mass per unit volume of the material, the smaller the volume involved in the measurement. Approximately 50 % of the typical measurement results from the water content of the 50 to 75 mm diameter centered about the dielectric spacer.

6.3 Oversize particles or large voids in close proximity to the dielectric spacer in the probe assembly (see 7.1.2) may cause higher or lower water mass per unit volume measurements. Where lack of uniformity in the soil due to layering, aggregate or voids is suspected, the test site shall be excavated and visually examined to determine if the test material is representative of the in situ material in general and if an oversize correction is required in accordance with Practice D4718/D4718M.

## 7. Apparatus

7.1 *Soil Permittivity Probe*—While exact details of construction of the apparatus may vary, the system is approximately 140 mm long and 20 mm in diameter (see Fig. 1), and shall consist of:

7.1.1 *Bottom Conductor*—A tapered, conducting cylindrical assembly that attaches below the dielectric spacer.

7.1.2 *Dielectric Spacer*—A non-conducting material, likewise cylindrical and tapered, that attaches between the bottom conductor and the top conductor

7.1.3 *Top Conductor*—A tapered, conducting cylindrical assembly that attaches above the dielectric spacer and directly below the surface plate.

7.2 *Surface Plate*—A disc that, when the soil permittivity probe is engaged with the soil for a measurement, lies directly on the surface of the soil.

7.3 *Positioning Handles*—Two collinear handles that attach above, and parallel to, the surface plate. These handles are used to push the soil permittivity probe into the access hole where the in situ measurement is being taken, and then again to pull the soil permittivity probe back out of the hole once the measurement is complete.



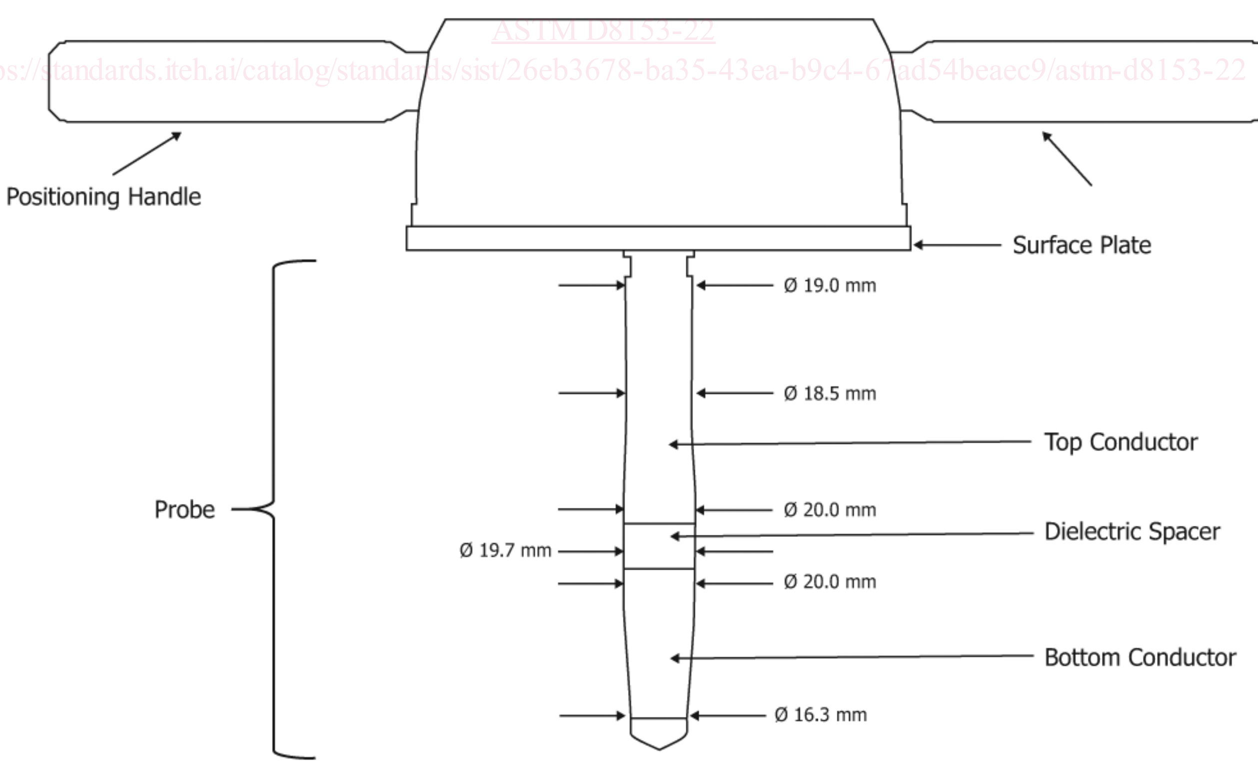


**FIG. 1 Soil Permittivity Probe, Drawn to Scale**

7.4 *Control Unit*—A computer, nuclear density gauge, wireless communications device, or similar electronic devices that contains the operating software for the permittivity probe; typical operation is performed wirelessly, but can be operated through an RS232 cable connection.

7.5 *Site Preparation Device*—A plate, straightedge, or other suitable leveling tool that may be used for planing the test site to the required smoothness.

7.6 *Drive Pin*—A pin with a nominal diameter of 19 mm used to prepare a hole in the test site for inserting the probe.

7.7 *Drive Pin Guide*—A fixture that keeps the drive pin perpendicular to the test site. Generally part of the site preparation device.

7.8 *Hammer*—Heavy enough to drive the pin to the required depth without undue distortion of the hole.

7.9 *Drive Pin Extractor*—A tool that may be used to remove the drive pin in a vertical direction so that the pin will not distort the hole in the extraction process.

7.10 *Slide Hammer, with a Drive Pin Attached*—As an alternative to 7.5 – 7.8, may also be used both to prepare a hole in the material to be tested and to extract the pin without distortion to the hole.

## 8. Calibration

8.1 Probe calibration shall be performed in accordance with the processes described in Annex A1.

## 9. Procedure

9.1 Remove all loose and disturbed material and additional material as necessary to expose the true surface of the material to be tested.

9.2 Prepare an area sufficient in size to accommodate the probe by grading or scraping the area to a smooth condition to obtain maximum contact between the surface plate and material being tested. The optimum condition is total contact between the bottom surface of the surface plate and the surface of the material being tested.

9.3 Make a hole perpendicular to the prepared surface using either a hammer and a drive pin or a slide hammer, using the rod guide to ensure the integrity of the hole. The hole shall extend a minimum of 25 mm below the end of the probe and of an alignment that insertion of the probe will not cause the probe to tilt from the plane of the prepared area.

9.4 Remove the hole-forming device carefully to prevent the distortion of the hole, damage to the surface, or loose material from falling into the hole.

9.4.1 When preparing an access hole in granular soils, care shall be taken in the preparation of the access hole; measurements have the potential to be affected by changes to the density of surrounding material during the hole formation.

9.5 Carefully lower the soil permittivity probe into access hole until the surface plate makes full contact with the soil surface. Be careful to avoid excessive twisting motion while pushing downward with the handles to avoid any shear damage to the probe and better ensure maximum contact between the probe and the hole surface.

9.6 Take a measurement with the soil permittivity probe, using the device to which it is connected electronically to collect and interpret the results. The measurement reading typically become stable within five seconds after installation, with continuous updating (at an approximate rate of one measurement per second) by the device.

9.7 Once the desired measurements are collected at this test site, carefully raise the soil permittivity probe out of the access hole. Again, be careful to avoid excessive twisting motion while pulling up with the handles to avoid any shear damage to the probe, and to better ensure maximum contact between the probe and the interior surface of the hole in the event that the access hole must be used again for successive readings with other instruments.

## 10. Calculation or Interpretation of Results

10.1 As mentioned previously, the soil permittivity probe response is dependent upon the volumetric water content of the soil. The device to which the soil permittivity probe is connected electronically will compute the water mass per unit volume, denoted by $M_w$.

10.2 The aforementioned value of $M_w$ is calculated by the calibration equation for the specific soil or soil-aggregate under test, where $M_w$ is the independent variable of the equation, and the oscillator frequency output of the probe circuit is the dependent variable.

10.3 Once $M_w$ is calculated by the device, it is displayed by the device. The water mass per unit volume value is the mass of water contained in a given volume of soil or soil-aggregate. The water mass per unit volume value, denoted by $M_w$, is calculated as

$$Mw = \theta \rho_w \quad (1)$$

where $\rho_w$ is the density of water at 4.0 ºC (999.8395 kg/m$^3$) and θ is the volumetric water content of the soil.

10.4 Calculated $M_w$ values are displayed to a sensitivity (the nearest value) of 1 kg/m$^3$.

10.5 If the bulk density of the soil or soil-aggregate just measured by the soil permittivity probe is known (for example, the device to which the soil permittivity probe is connected is a device capable of measuring soil or soil-aggregate bulk density), then the dry density of this material may be calculated as:

$$\rho_d = \rho_t - Mw \quad (2)$$

where $\rho_t$ is the bulk density of the material and ρd is the dry density of the material.

10.6 Likewise, if the bulk density of the soil or soil-aggregate just measured by the soil permittivity probe is known, then the water content of the material may be calculated as:

$$\omega = 100 \cdot \frac{Mw}{\rho_d} \quad (3)$$

where ω is the water content of the soil (expressed as a percent).

10.7 Record the water mass per unit volume value to the nearest 1 kg/m$^3$.

## 11. Report: Test Data Sheet(s)/Form(s)

11.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.5.

11.2 Record at a minimum the following general information (data):

11.2.1 Test number or test identification.

11.2.2 Test date/time

11.2.3 Location of test (for example, Station number or GPS or Coordinates or other identifiable information).

11.2.4 Visual description of material tested.

11.2.5 Lift number or elevation or depth.

11.2.6 Name of the operator(s).

11.2.7 Make, model and serial number of the soil permittivity probe.

11.2.8 Water mass per unit volume value in kg/m$^3$.

11.3 The sensitivity of the measurement values listed in reporting and records are described in 10.4.

## 12. Precision and Bias

12.1 The precision of this test method is based on an interlaboratory study ILS 1339, "Standard Test Method for In-Place Bulk Density of Soil and Soil-Aggregate by a Low Activity Nuclear Method (Shallow Depth) and In-Place Water Mass Per Unit Volume of Soil and Soil-Aggregate by Permittivity Method (Shallow Depth)," conducted in 2017. Ten laboratories tested three materials with three replicate readings on each material. Every "test result" represents an individual determination. Practice E691 was followed for the design and analysis of the data.[3]

12.1.1 *Repeatability (r)*—The difference between repetitive results obtained by the same operator in a given laboratory applying the same test method with the same apparatus under constant operating conditions on identical test material within short intervals of time would in the long run, in the normal and correct operation of the test method, exceed the following values only in one case in 20.

12.1.1.1 Repeatability can be interpreted as maximum difference between two results, obtained under repeatability conditions, that is accepted as plausible due to random causes under normal and correct operation of the test method.

12.1.1.2 Repeatability limits are listed in Table 1.

12.1.2 *Reproducibility (R)*—The difference between two single and independent results obtained by different operators applying the same test method in different laboratories using different apparatus on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the following values only in one case in 20.

12.1.2.1 Reproducibility can be interpreted as maximum difference between two results, obtained under reproducibility conditions, that is accepted as plausible due to random causes under normal and correct operation of the test method.

12.1.2.2 Reproducibility limits are listed in Table 1.

12.1.3 The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E177.

12.1.4 Any judgment in accordance with statements 12.1.1 and 12.1.2 would have an approximate 95 % probability of being correct.

12.2 *Bias*—At the time of the study, there was no accepted reference material suitable for determining the bias for this test method, therefore no statement on bias is being made.

12.3 The precision statement was determined through statistical examination of three replicate results, from ten laboratories, on three materials. These three materials were the following, as listed in Table 1, and described in accordance with Practices D2487 and D2488:

Material 1: SC – Coarse graded clayey sand with fines, 1 % gravel, 2 % coarse sand, 28 % medium sand, 44 % fine sand, 25 % fines, liquid limit = 32, plastic index = 13

Material 2: SC – Coarse graded clayey sand with fines, 2 % gravel, 6 % coarse sand, 24 % medium sand, 27 % fine sand, 41 % fines, liquid limit = 42, plastic index = 20

Material 3: Poorly graded gravel with silt, 52 % gravel, 13 % coarse sand, 15 % medium sand,13 % fine sand, 7 % fines.

12.4 To judge the equivalency of two test results, it is recommended to choose the soil type closest in characteristics to the test soil.

## 13. Measurement Uncertainty

13.1 Information on the measurement uncertainty for this test method, and guidance on developing estimated uncertainties, are described in detail in Appendix X2.

[3] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:D18-2001. Contact ASTM Customer Service at service@astm.org.



**TABLE 1 Results of Statistical Analysis (Water Mass Per Unit Volume)**

| Material | Average kg/m$^3$ | Repeatability Standard Deviation kg/m$^{3A}$ | Reproducibility Standard Deviation kg/m$^{3A}$ | Repeatability Limit kg/m$^{3B}$ | Reproducibility Limit kg/m$^{3B}$ |
|---|---|---|---|---|---|
| | $\bar{x}$ | $S_r$ | $S_R$ | r | R |
| 1 | 138 | 5 | 8 | 13 | 24 |
| 2 | 289 | 10 | 11 | 28 | 31 |
| 3 | 81 | 6 | 9 | 18 | 25 |

[A] The number of significant digits and decimal places presented are representative of the input data. In accordance with Practice D6026, the standard deviation and acceptable range of results cannot have more decimal places than the input data.

[B] Acceptable range of two results is referred to as the d2s limit. It is calculated as 1.960$\sqrt{2}$●1s, as defined by Practice E177. The difference between two properly conducted tests should not exceed this limit. The number of significant digits and decimal places presented are equal to that prescribed by this standard or Practice D6026. In addition, the presented value can have the same number of decimal places as the standard deviation, even if that result has more significant digits than the standard deviation.

13.2 Appendix X2 provides examples of measurement uncertainty calculations based on results obtained by the manufacturer while carrying out the test method. These tests were conducted on the three materials described in the precision and bias study for this test method, and for all-purpose sand that may be obtained in most hardware stores.

## 14. Keywords

14.1 dielectric constant; dielectric permittivity; permittivity probe; soil water content; volumetric water content; water mass per unit volume

# ANNEX

**(Mandatory Information)**

## A1. CALIBRATION, VERIFICATION, AND ADJUSTMENT

A1.1 Permittivity probes shall have calibration equations formulated initially and after any repairs that can affect the existing calibration. The initial calibration, and any subsequent calibrations, shall consist of curves, tables, or equivalent coefficients that correlate the independent variable, soil water mass per unit volume, to the dependent variable, probe oscillator frequency output.

A1.2 Because different soils can have different dielectric constant properties, it is possible for different soils with the same water mass per unit volume value to have different probe responses. Consequently, a probe may require a variety of different soil-specific calibration equations for field use if it is used in a variety of different soil types.

A1.3 Calibrations for a specific soil shall cover the entire water mass per unit volume range that one would realistically encounter in a field application.

A1.4 Initial probe calibrations are generally conducted using mechanically and electrically stable, engineered, non-soil capacitance standards

A1.5 Calibration of the permittivity probe using non-soil capacitance standards: the initial calibration of the probe after manufacture or extensive repair shall be performed on capacitance standards, which are non-soil fixtures that can: (*1*) accommodate the probe in a consistent, repeatable manner and (*2*) present the probe with a consistent, repeatable dielectric permittivity value. The repeatability of oscillator frequency output in each capacitance standard shall be established prior to its use as a calibration standard.

A1.6 The standards attach to the permittivity probe with two clips, with one clip attached directly above the dielectric spacer to the top conductor, and the other clip attached directly below the dielectric spacer to the bottom conductor. See Fig. A1.1.

A1.6.1 Each capacitance standard shall have a water mass per unit value equivalence assigned to it prior to its use as a calibration standard. The uncertainty of this water mass per unit equivalence value shall be established prior to its use as a calibration standard.

A1.6.2 Assignment of water mass per unit volume equivalence to a capacitance standard is done in two basic steps:

A1.6.2.1 A reference probe, which is a typical permittivity probe that is reserved for such purposes, undergoes a soil-specific calibration process on a given soil, as described in A1.7.

A1.6.2.2 The reference probe is then inserted in or attached to the capacitance standard in the appropriate measurement configuration, and a measurement is acquired. The water mass per unit volume measured by the reference probe is then assigned to the capacitance standard for that particular soil type, as well as an uncertainty for this assigned value.

A1.6.2.3 A given capacitance standard will have only one assigned water mass per unit volume equivalence for a given soil type. However, if the standard is used for different calibrations of different soil types, it may have a unique assigned water mass per unit volume equivalence for each of these different calibrations.

A1.6.3 For the initial calibration of the permittivity probe, the probe is inserted in or attached to each capacitance standard in the appropriate measurement configuration. Twenty seconds of oscillator frequency readings are taken with the probe, averaged, and recorded.

A1.6.4 Once the oscillator frequency response data have been collected with the probe for each capacitance standard, calibration functions (curves) are computed. A unique calibration function is computed for each soil type for which the capacitance standards have been assigned water mass per unit volume equivalence.

NOTE A1.1—The initial calibration of the permittivity probe generally focuses upon a broad range of soil types, each with a separate and unique calibration. Three soil types, including one gravel, one sand, and one clay have been proven to be successful at properly characterizing the probe response in typical field use.

A1.6.5 The calibration curve for a particular soil type is denoted as follows:

$$Mw = f(D) \tag{A1.1}$$

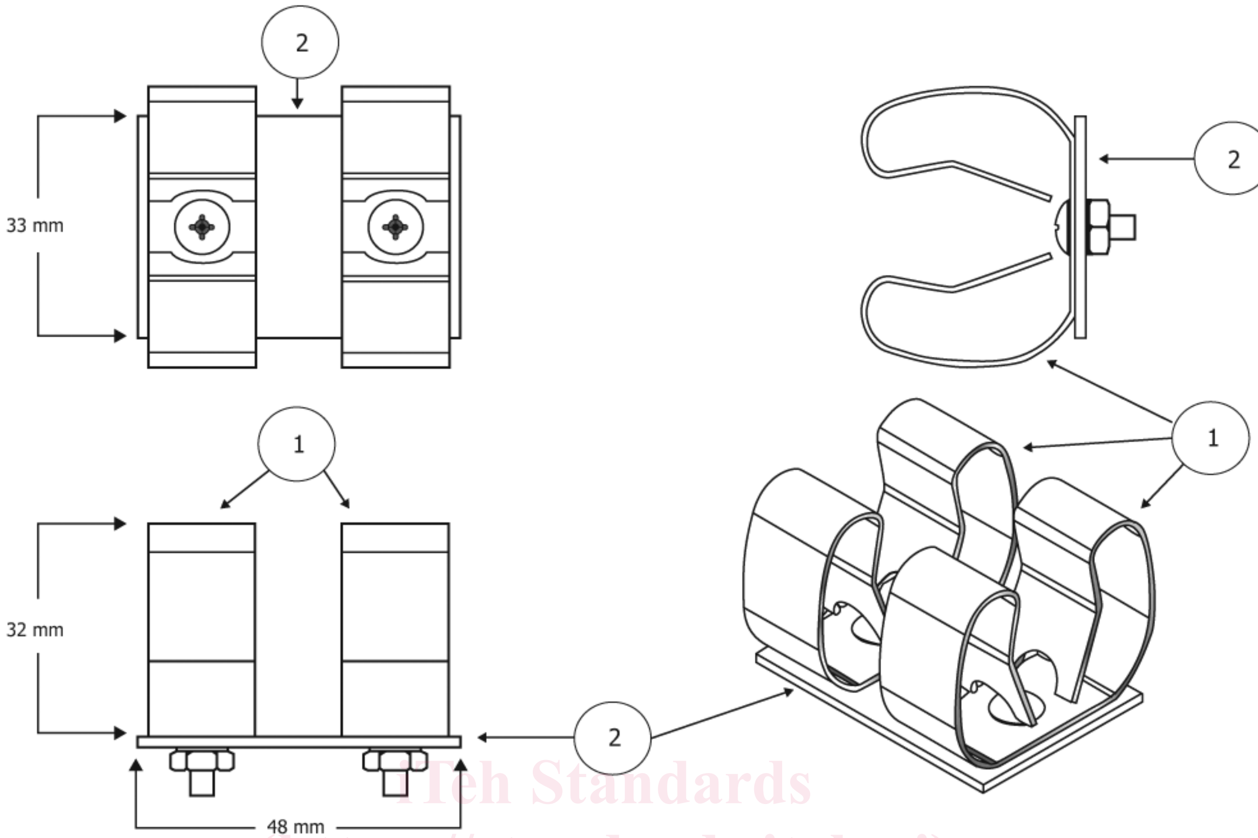


FIG. A1.1 Capacitance Standard, Drawn to Scale: (1) indicates the metal clips, and (2) indicates the PCB board. Best practice is to slide the clip onto the probe rather that pressing it onto the probe to avoid damage to the board.



where:

$Mw$ = water mass per unit volume, kg/m$^3$,
$D$ = oscillator frequency output,
$f(D)$ = the calibration function relating oscillator frequency output to water mass per unit volume. This function is typically linear over the range of practically observed water contents for a particular soil.

A1.6.6 Once a calibration equation has been established for the probe in this manner, the equation must be verified.

A1.6.7 Probe verification is achieved when the probe water mass per unit volume response is found to be within 16 kg/m$^3$ on the capacitance standards on which the probe was calibrated, for each calibration function included in the calibration process.

A1.6.8 This calibration process may be done by the probe manufacturer, the user, or an independent laboratory.

A1.6.9 For each calibration performed on capacitance standards, the estimated measurement uncertainty of the probe shall be computed, based on probe measurement repeatability on the standards and the uncertainty in the water mass per unit volume equivalence value of these standards.

A1.6.10 Probe calibration results shall be formally recorded and documented in the form of a calibration report, where the following shall be recorded:

A1.6.10.1 Unique identification of the probe and the standards used in its calibration.

A1.6.10.2 Water mass per unit volume equivalence of all standards for all soil type calibrations encompassed in the calibration activity.

A1.6.10.3 Probe oscillator frequency output in each standard.

A1.6.10.4 Date and location of the calibration, and identification of the person performing the calibration.

A1.6.10.5 Estimated measurement uncertainties of the probe for each soil type calibration encompassed in the calibration activity.

A1.6.10.6 Uncertainties of the standards.

A1.6.10.7 Probe calibration equations.

A1.6.10.8 Verification results.

A1.6.11 Reestablish or verify the assigned water mass per unit volume equivalence values of the capacitance standards at periods that shall be recommended by the manufacturer.

A1.7 *Calibration Equation Computation of the Permittivity Probe Using Laboratory-prepared Soil Specimens*—Rather than using capacitive standards as described in A1.5 to generate the calibration equation for the probe, one can use multiple soil specimens of known and varying water contents packed into sturdy, non-metallic cylindrical containers. This container shall, at a minimum, have a height of 305 mm and a diameter of 305 mm.

A1.7.1 Prepare a container of compacted material with a water content determined by the oven dry method (Test