Designation: D6031/D6031M – 24

Standard Test Method for Logging In Situ Moisture Content and Density of Soil and Rock by the Nuclear Method in Horizontal, Slanted, and Vertical Access Tubes[1]

This standard is issued under the fixed designation D6031/D6031M; 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 collection and comparison of logs of thermalized-neutron counts and back-scattered gamma counts along horizontal or vertical air-filled access tubes.

1.2 For limitations, see Section 6, "Interferences."

1.3 The in situ water content in mass per unit volume and the density in mass per unit volume of soil and rock at positions or in intervals along the length of an access tube are calculated by comparing the thermal neutron count rate and gamma count rates respectively to previously established calibration data.

1.4 *Units*—The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system are not necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined. Within the text of this standard, SI units appear first followed by the inch-pound (or other non-SI) units in brackets

1.4.1 Reporting the test results in units other than SI shall not be regarded as nonconformance with the standard.

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

1.5.1 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 be 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.* For specific hazards, see Section 8.

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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D1452/D1452M Practice for Soil Exploration and Sampling by Auger Borings

D1586/D1586M Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils

D1587/D1587M Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes (Withdrawn 2024)[3]

D2113 Practice for Rock Core Drilling and Sampling of Rock for Site Exploration (Withdrawn 2023)[3]

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

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

D3550/D3550M Practice for Thick Wall, Ring-Lined, Split Barrel, Drive Sampling of Soils

[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 on Groundwater and Vadose Zone Investigations.

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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.

[3] The last approved version of this historical standard is referenced on www.astm.org.

***A Summary of Changes section appears at the end of this standard**

D4428/D4428M Test Methods for Crosshole Seismic Testing (Withdrawn 2023)[3]
D4564 Test Method for Density and Unit Weight of Soil in Place by the Sleeve Method (Withdrawn 2013)[3]
D5195 Test Method for Density of Soil and Rock In-Place at Depths Below Surface by Nuclear Methods
D5220/D5220M Test Method for Water Mass per Unit Volume of Soil and Rock In-Place by the Neutron Depth Probe Method
D6026 Practice for Using Significant Digits and Data Records in Geotechnical Data

3. Terminology

3.1 *Definitions*—For definitions of common technical terms in this standard, refer to Terminology D653.

4. Summary of the Test Method

4.1 The test method is as follows:

4.1.1 A horizontal, slanted, or vertical hole is bored or driven into the site where the test is to be performed. The depth of the hole shall be at least 300 mm [1 ft] lower than the bottom of the probe when it is in its deepest measurement position.

4.1.2 An access tube is installed in the hole, with any soil or rock falling back into the hole removed.

4.1.3 The probe containing the source(s) and detector(s) are positioned at the desired measurement depth, and a measurement is taken.

5. Significance and Use

5.1 This test method is useful as a repeatable, nondestructive technique to monitor in-place density and moisture of soil and rock along lengthy sections of horizontal, slanted, and vertical access holes or tubes. With proper calibration in accordance with Annex A1, this test method can be used to quantify changes in density and moisture content of soil and rock.

5.2 This test method is used in vadose zone monitoring, for performance assessment of engineered barriers at waste facilities, and for research related to monitoring the movement of liquids (water solutions and hydrocarbons) through soil and rock. The nondestructive nature of the test allows repetitive measurements at a site and statistical analysis of results.

5.3 The fundamental assumptions inherent in the density measurement portion of this test method are that Compton scattering and photoelectric absorption are the dominant interactions of the gamma rays with the material under test.

5.4 The probe response, in counts, can be converted to wet density by comparing the detected rate of gamma radiation with previously established calibration data (see Annex A1).

5.5 The probe count response may also be utilized directly for unitless, relative comparison with other probe readings.

5.5.1 For materials of densities higher than that of about the density of water, higher count rates within the same soil type relate to lower densities and, conversely, lower count rates within the same soil type relate to higher densities.

5.5.2 For materials of densities lower than the density of water, higher count rates within the same soil type relate to higher densities and, conversely, lower count rates within the same soil type relate to lower densities.

5.5.3 Because of the functional inflection of probe response for densities near the density of water, exercise great care when drawing conclusions from probe response in this density range.

5.6 The fundamental assumption inherent in the moisture measurement portion of this test is that the hydrogen contained in the water molecules within the soil and rock is the dominant neutron thermalizing media, so increased water content of the soil and rock results in higher count rates of the moisture content system of the instrument.

6. Interferences

6.1 The sample heterogeneity and elemental composition of the material under test may affect the measurement of water content, density, or both. The apparatus should be calibrated to the material under test at a similar density of dry soil or rock and in the similar type and orientation of access tube, or adjustments must be made in accordance with Annex A2.

6.2 Hydrogen, in forms other than water, as defined by Test Method D2216, will cause measurements in excess of the true moisture content. Some elements such as boron, chlorine, and minute quantities of cadmium, if present in the material under test, will cause measurements lower than the true moisture content. Some elements with atomic numbers greater than 20 such as iron (Fe) or other heavy metals may cause measurements higher than the true density value.

6.3 The measurement of moisture and density using this test method exhibits spatial bias in that it is more sensitive to the material closest to the access tube. The density and moisture measurements are necessarily an average of the total sample involved.

6.4 The sample volume for a moisture measurement is approximately 0.11 m^3 [3.8 ft^3] at a water mass per unit volume of 200 kg/m^3 [12.5 lbm/ft^3]. The actual sample volume for moisture is indeterminate and varies with the apparatus and the moisture content of the material. In general the greater the moisture content of the material, the smaller the measurement volume.

6.5 A density measurement has a sample volume of approximately 0.003 m^3 [0.8 ft^3]. The actual sample volume for density is indeterminate and varies with the apparatus and the density of the material. In general, the greater the density of the material, the smaller the measurement volume.

6.6 Air gaps between the probe and the access tube or voids around the access tube may cause the indicated moisture content and density to be less than the calibrated values.

6.7 Condensed moisture inside the access tube may cause the indicated moisture content to be greater than the true moisture content of material outside the access tube.

7. Apparatus

7.1 While exact details of construction of the apparatus may vary, the system shall consist of:

7.1.1 *Fast Neutron Source*—A sealed mixture of a radioactive material such as americium or radium and a target material such as beryllium, or other fast neutron sources such as californium that do not require a target.

7.1.2 *Slow Neutron Detector*—Any type of slow neutron detector, such as boron trifluoride or helium-3 proportional counters.

7.1.3 *High-Energy Gamma-Radiation Source*—A sealed source of radioactive material, such as cesium-137, cobalt-60, or radium-226.

7.1.4 *Gamma Detector*—Any type of gamma detector, such as a Geiger-Mueller tube.

7.1.5 *Suitable Readout Device.*

7.1.6 *Cylindrical Probe*—The apparatus shall be equipped with a cylindrical probe, containing the neutron and gamma sources and the detectors, connected by a cable or cables of sufficient design and length, that are capable of raising and lowering the probe in vertical applications and pulling it in horizontal applications, to the desired measurement location.

7.1.7 *Reference Standard*—A device containing dense, hydrogenous material for checking equipment operation and to establish conditions for a reproducible reference count rate. It also may serve as a radiation shield.

7.2 Accessories shall include:

7.2.1 *Access Tubing*—The access tubing (casing) is required for all access holes in nonlithified materials (soils and poorly consolidated rock) that cannot maintain constant borehole diameter with repeated measurements. If access tubing is required it must be of a material, such as aluminum, steel, or plastic, having an interior diameter large enough to permit probe access without binding, and an exterior diameter as small as possible to provide close proximity of the material under test. The same type of tubing must be used in the field as is used in calibration.

7.2.2 *Hand Auger or Power Drilling/Trenching Equipment*—Equipment that can be used to establish the access hole or position the access tube when required (see 10.1.1). Any equipment that provides a suitable clean open hole for installation of access tubing and insertion of the probe that ensures the measurements are performed on undisturbed soil and rock while maintaining a constant diameter per width shall be acceptable. The type of equipment and methods of advancing the access hole shall be reported.

7.2.3 *Winching Equipment or Other Motive Devices*—Equipment that can be used to move the probe through the access tubing. The type of such equipment is dependent upon the orientation of the access tubing and the distance over which the probe must be moved.

8. Hazards

8.1 This equipment utilizes radioactive materials that may be hazardous to the health of the users unless proper precautions are taken. Users of this equipment must become completely familiar with all possible safety hazards and with all applicable regulations concerning the handling and use of radioactive materials.

8.2 Effective user instructions together with routine safety procedures are a recommended part of the operation of this apparatus.

8.3 When using winching or other motive equipment, the user shall take additional care to learn its proper use in conjunction with measurement apparatus. Known safety hazards such as cutting and pinching exist when using such equipment.

8.4 This test method does not cover all safety precautions. It is the responsibility of the users to familiarize themselves with all safety precautions.

9. Calibration, Standardization, and Reference Check

9.1 Calibrate the instrument in accordance with Annex A1.

9.2 Adjust the calibration in accordance with Annex A2 if adjustments are necessary.

9.3 Perform and evaluate standardization and reference check on a daily basis, prior to taking field measurements, in accordance with Annex A4.

10. Procedure

10.1 *Installation of Access Tubing (Casing):*

10.1.1 Drill the access hole or excavate a trench at the desired location and install the access tube in a manner to maximize contact with test material and minimize voids. The access tubes shall fit snugly into the access hole or trench. Unstable conditions in fill material around the access tube may result in redistribution of solids over time, piping, or other phenomena that will degrade precision. Voids caused during drilling, tube installation, or backfilling, or a combination thereof, may cause erroneously low results. Excessive compaction of clay-rich backfill material will limit the effectiveness of moisture monitoring for leak detection. Select backfill that approximates the composition, water content, and bulk density of test material as nearly as possible.

10.1.2 Grouting of annular spaces, if required, shall be of minimum functional thickness, and grout mixtures shall not contain excessive water. Grouts thicker than 5 cm [2 in.] create high background counts that will obscure moisture content changes in fine-textured soils and severely limit meaningful density measurements in all soil types. Do not use grout unless it is required to seal off flow pathways along the access tube, such as in some vertical borings and where trenches cross engineered barriers. Grouting can be accomplished using procedures described in Test Methods D4428/D4428M.

10.1.3 Record and note the position of the groundwater table, perched water tables, and changes in soil texture as drilling or trenching progresses.

10.1.4 If groundwater is encountered or saturated conditions are expected to develop, seal the tube at seams and open ends to prevent water seepage into the tube. This will prevent erroneous measurements and possible damage to the probe.

10.1.5 The access tube shall project above the ground and be capped to prevent foreign material from entering. The access tube shall not project out of the test material far enough to be damaged by equipment traffic.

10.2 Pass a dummy probe through the access tube to verify proper clearance before deploying the radioactive sources.

10.3 Standardize the apparatus (see Annex A4).

10.4 Proceed with the test run in a continuous logging mode or in a noncontinuous logging mode as follows:

10.4.1 Set up the winching equipment or other motive devices (see 7.2.3) to begin a logging run by stationing the probe at one end of the access tube to be logged.

10.4.2 Select a timing period for collecting measurement counts based on desired precision (see Annex A3), anticipated measurement response, or site-specific logistical criteria.

10.4.3 For testing in continuous logging mode, advance the probe continuously through the access tube while recording data that relate gamma ray counts and thermal neutron counts to position intervals or time (for constant logging speed), or both.

10.4.4 For testing in noncontinuous logging mode, advance the probe through the access tube to the desired position and stop, record counts while probe is stationary, advance the probe to the next desired position, and repeat. Record data relating gamma counts and thermal neutron counts to discrete positions along the access tube.

11. Calculation

11.1 Calculations related to reporting density as calibrated units are provided in Test Method D5195. For moisture content, these same calculations are provided in Test Method D5220/D5220M.

11.2 Data can be used in a comparative mode, as in graphs or charts. For example, measurements from repeated logging events can be compared directly at each position (or interval) and analyzed to detect statistically significant changes from background.

11.2.1 For data reported as uncalibrated counts that have not been prescaled (see A3.1.2.2), the accepted estimator of the standard deviation of a population of nuclear count measurements is equal to the square root of the mean.[4] Standard deviation estimated from more than one background measurement at any given position (or over any specific interval) can be used to define tolerance levels. The tolerance level defines a threshold neutron count above which there is a defined probability that the count is higher than background.

[4] Kramer, J. H., Everett, L. G., and Cullen, S. J., 1992. "Vadose Zone Monitoring with Neutron Moisture Probe," *Ground Water Monitoring Review*, Vol 12, No. 2, 1992, pp. 177–187.

12. Report: Test Data Sheet(s)/Form(s)

12.1 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 and Practice D6026.

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

12.2.1 Make, model, and serial number of the apparatus.

12.2.2 Name of operator/technician.

12.2.3 Date of instrument calibration.

12.2.4 Method of calibration, such as field, laboratory, factory, etc.

12.2.5 Calibration adjustments.

12.2.6 Date of test.

12.2.7 Standard(s) count for day of the test.

12.2.8 Any adjustment data for the day of the test.

12.2.9 Test site identification including tube location(s) and tube number(s).

12.2.10 Tube type and tube installation method.

12.2.11 Geological log of the borehole.

12.2.12 Distance (depth), measurement count data, and count ratios or calculated density and moisture content.

12.2.13 (Optional) graphical display of the magnitude of count measurements along the access tube transect.

13. Precision and Bias

13.1 *Precision*—It is not possible to specify the precision of the procedure in Test Method D6031/D6031M for logging in situ moisture content and density of soil and rock by the nuclear method in horizontal, slanted, and vertical access tubes because it is not feasible and too costly at this time to have ten or more agencies participate in an in situ testing program at a given site.

13.1.1 Subcommittee D18.21 is seeking any data from the users of this test method that might be used to make a limited statement on precision.

13.2 *Bias*—No information can be presented on the bias of the procedure in Test Method D6031/D6031M for measuring density of soil and rock in-place at depths below the surface by the nuclear method because it is not feasible and too costly at this time to have ten or more agencies participate in an in situ testing program at a given site.

14. Keywords

14.1 access tube; in-place density and moisture; in situ density and moisture; nuclear methods; winching equipment

ANNEXES

(Mandatory Information)

A1. CALIBRATION

A1.1 *Calibration Curves*—Calibration curves, tables, or equations shall be established or verified once each year or as recommended by the manufacturer, by determining the nuclear count rate of at least two samples of different known moisture content and at least three samples of different known density. This data may be presented in the form of a graph, table, equation coefficients, or stored in the apparatus to allow converting the count rate data to material moisture content or density. The method and test procedures used in establishing these count rate data must be the same as those used for obtaining the count rate data for in-place material.

A1.2 *Density*—Calibration standards may be established using one of the following methods, or as recommended by the manufacturer. The standards must be of sufficient size to not change the count rate if enlarged in any dimension. Access tubing used in the standards must be the same type and size as that to be used for in-place measurements.

A1.2.1 Prepare containers of soil and rock of a range of different densities. Place the material in lifts of thickness that depends upon the compaction method being used. Each lift is to receive equal compactive effort. Calculate the density of each container of material based on the measured volume and mass (weight) of the material.

A1.2.2 Prepare containers of cured concrete using different aggregate to sand ratio mixes to obtain a range of densities. Place the concrete in the containers in a way that will ensure a uniform mixture and uniform densities.

A1.2.3 Prepare containers of non-soil materials. Calculate the soil and rock equivalent density of each container of material based on the measured volume and mass (weight) of the material.

A1.2.4 Take sufficient measurements in each prepared container to establish a correlation between the apparatus measurements and the densities of the material in the containers.

A1.3 *Field Calibration for Density*—The apparatus may be calibrated in the field by using the following method when a verification of laboratory calibration accuracy to field materials is required, or in instances where neither of the previous calibration standards are available, or a more accurate calibration is required.

A1.3.1 During placement of access tubing, obtain undisturbed samples of the material around the tubing from points along it that are representative of the material to be tested. Take undisturbed samples from the soil or rock by any suitable drilling and sampling method appropriate for the material (see Practices D1452/D1452M, D1587/D1587M, and D2113, double-tube or triple-tube core samplers, piston samplers, or double-tube hollow stem samplers), and determine the average sample density by trimming excess material and measuring the mass and volume of the samples. Samples shall be taken over the length of the access tube in which the probe will be used. At a minimum, obtain undisturbed samples at 2-m [6.6-ft] intervals and at all locations where the material around the access tube changes composition or texture.

A1.3.2 As soon as possible after the access tubing has been installed, take measurements in accordance with Section 10 using the appropriate type of winching equipment detailed in Section 7. The winching speed for continuous logging mode shall be determined by the user, but generally it will fall within the range from 0.6 to 3.0 m/min [2.0 to 10.0 ft/min]. Based upon laboratory calibrations, calculate the gauge density measurement for each reading taken. Take the test measurement counts so that they will include or be adjacent to the location of the undisturbed samples. Compare the sample densities to the gauge measurement(s) closest to it (with respect to length along the tubing), and make any needed adjustments to the laboratory calibrations (see Annex A2). Follow the manufacturer's recommendations for any such adjustments. The sample density and measurement count ratios may be presented in the form of a graph, table, equation coefficients, or stored in the gauge to allow converting future instrument count ratios to material densities.

A1.3.3 Report all sample data including changes in strata and all anomalous data obtained, such as voids. The initial count profile and adjusted density data shall be reported with later readings to review changes in density with subsequent readings.

A1.4 *Moisture Content*—Calibration standards may be established using one of the following methods or as recommended by the manufacturer. The standards must be verified to be large enough to not change the observed count rate if made larger in any dimension. Access tubing used in the standards must be the same type and size as that to be used for in-place measurements.

A1.4.1 Prepare homogenous standards of hydrogenous materials having moisture contents determined by comparison (using a nuclear instrument) to saturated silica sand standards with known moisture contents. As an alternative, determine the equivalent moisture content by calculation if the hydrogen, carbon, and oxygen content is known or can be calculated from the specific gravity and chemical composition. A zero-moisture content standard can be prepared by using an non-hydrogenous material, such as a magnesium alloy, as the standard.

A1.4.2 Prepare containers of soil and rock compacted to uniform densities with a range of moisture contents. Determine the moisture content of the materials by oven drying (see Test Method D2216). If desired, calculate water mass per unit volume θ_v using Test Methods D2937 or D4564 and Eq A1.1. Whenever possible, use soil and rock obtained from the test site for this calibration.

$$\theta_v = \theta_g \times \rho_d \tag{A1.1}$$

where:

θ_v = water mass per unit volume, g/cm^3,
θ_g = water content, g water/g soil, and
ρ_d = in-place dry density of soil, g/cm^3.

A1.4.3 Take sufficient measurements in each prepared container to establish a correlation between the apparatus measurements and the moisture contents of the material in the containers.

A1.5 *Field Calibration for Moisture Content*—The instrument may be calibrated in the field using the following method when a verification of laboratory calibration accuracy to field materials is required, or in instances where neither of the previous calibration standards are available or a more accurate calibration is required.

A1.5.1 During placement of access tubing obtain undisturbed samples of the material from around the tubing. Take volumetric or gravimetric samples from the soil or rock by any suitable drilling and sampling method appropriate for the material (see Test Method D1586/D1586M and Practices D1452/D1452M, D1587/D1587M, D2113, and D3550/D3550M) and determine the percent water content by oven drying (see Test Method D2216). Note the sampling intervals for the samples. Samples shall be taken over the length of the access tube that the probe will be taking measurements. At a minimum obtain samples at 2 m [6.6 ft] intervals and at all locations where the material around the access tube changes composition.

A1.5.2 As soon as possible after the access tubing has been installed, take measurements in accordance with Section 10 using the appropriate type of winching equipment detailed in Section 7. The winching speed for continuous logging mode shall be determined by the user. Generally, it will fall within the range from 0.6 to 3.0 m/min [2.0 to 10.0 ft/min]. In addition to these initial measurements, measurements also shall be taken when periodic samples are taken. Take the test measurement counts so that they will include or be adjacent to the location of the gravimetric or volumetric samples. Compare the sample moisture contents to the gauge measurement(s) closest to it (with respect to length along the tubing), and make any needed adjustments to the laboratory calibrations (see Annex A2). Follow the manufacturer's recommendations for any such adjustments. The sample moisture content and measurement count ratios may be presented in the form of a graph, table, equation coefficients, or stored in the gauge to allow converting future instrument count ratios to material moisture contents.

A1.5.3 Report all sample data including changes in strata and all anomalous data obtained, such as voids. The initial count profile and adjusted moisture content data shall be reported with later readings to review changes in moisture content with subsequent readings.

A2. CALIBRATION ADJUSTMENTS

A2.1 Check the calibration response prior to performing tests on materials that are distinctly different from the material types used in establishing the apparatus calibration. The calibration response also shall be checked on newly acquired or repaired apparatus.

NOTE A2.1—Some apparatus utilizing a microprocessor may have provision to input a correction factor that is established by determining the correlation between the apparatus measurement and gravimetric measurements.

A2.2 Take sufficient measurements and compare them to other accepted methods, such as volumetric sampling (see Test Methods D2937 or D4564), to establish a correlation between the apparatus calibration and the other method.

A2.2.1 Adjust the existing calibration to correct for the difference or establish a new calibration in accordance with Annex A1.

A3. PRECISION OF APPARATUS

A3.1 *Instrument Precision for Density* is defined as the as the change in measured density that occurs corresponding to a one standard deviation change in the count due to the random decay of the radioactive source. The density of the material and time period of the count shall be stated.

A3.1.1 The precision of the apparatus on a sample with a density of approximately 2000 kg/m^3 [125 lbm/ft^3] shall be better than 8 kg/m^3 [0.5 lbm/ft^3] at the manufacturer's stated period of time for the measurement. Other timing periods may be available that may be used where higher or lower precisions are desired for statistical purposes. The precision may be determined by the procedure defined in A3.1.2 or A3.1.3.

A3.1.2 The precision of the apparatus is determined from the slope of the calibration response and the statistical deviation of the count (detected gamma radiation) for the period of measurement as follows: