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Standard Test Method for One-Dimensional Consolidation Properties of Soils Using Controlled-Strain Loading[1]

This standard is issued under the fixed designation D 4186; 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.

ϵ^1 NOTE—Sections 1.3 and 13, and a Summary of Changes were added editorially in January 1999.

1. Scope *

1.1 This test method covers the determination of the rate and magnitude of consolidation of soil when it is restrained laterally and drained axially and subjected to controlled-strain loading.

NOTE 1—The determination of the rate and magnitude of consolidation of soil when it is subjected to incremental loading is covered by Test Method D 2435.

1.2 The values stated in SI units are to be regarded as the standard. The values stated in inch-pound units are approximate.

1.3 This test method is currently undergoing extensive review.

1.4 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems 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:*

D 422 Test Method for Particle-Size Analysis of Soils[2]
D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]
D 854 Test Method for Specific Gravity of Soils[2]
D 1587 Practice for Thin-Walled Tube Sampling of Soils[2]
D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures[2]
D 2435 Test Method for One-Dimensional Consolidation Properties of Soils[2]
D 3550 Practice for Ring-Lined Barrel Sampling of Soils[2]
D 4220 Practices for Perserving and Transporting Soil Samples[2]
D 4318 Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils[2]

3. Terminology

3.1 *Definitions*—The definitions of terms used in this method shall be in accordance with Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *back pressure*—the pore–water pressure at the drainage boundary.

3.2.2 *excess pore-water pressure,* u_b—the pore-water pressure developed at the impervious end of the specimen (usually the base of the specimen) in excess of the back pressure.

3.2.3 *applied vertical stress,* σ_v—the axial stress applied at the drainage boundary in excess of the back pressure.

3.2.4 *pore pressure ratio*—the excess pore water pressure divided by the applied vertical stress.

4. Significance and Use

4.1 Information concerning rate and magnitude of consolidation settlement of soil is essential in the design of earth and earth-supported structures. The results of this method may be used to analyze or estimate one-dimensional consolidation settlements and rates.

4.2 *Strain Rate*:

4.2.1 It is recognized that consolidation test results are strain-rate dependent. Strain rates recommended in this standard are within the range usually encountered in Test Method D 2435.

4.2.2 Field strain rates vary greatly with time, depth below the loaded area, and radial distance from the loaded area. Because field rates cannot be accurately determined or predicted, it is not feasible to relate the laboratory-test strain rate to the field strain rate. However, it may be feasible to relate field pore pressure ratios ($u_b \sigma_v$) to laboratory pore pressure ratios. Further research is needed in this area.

4.2.3 The constant-rate-of-strain consolidation test does not address the problem of strain-rate effects but does provide a means for studying strain rate effects.

4.3 This method is not applicable to soils of high permeability, such as sands and other coarse-grained soils, or to partially saturated soils.

[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.05 on Structural Properties of Soils.

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

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

4.4 This method makes the following assumptions:

4.4.1 The ratio of soil permeability to soil compressibility is constant,

4.4.2 Flow of soil pore water occurs only in the vertical direction,

4.4.3 Darcy's law for flow through porous media applies,

4.4.4 The soil is saturated,

4.4.5 The soil is homogeneous,

4.4.6 The compressibility of the soil grains and water is negligible,

4.4.7 The log stress versus strain relationship is linear during a short-time interval of loading, and

4.4.8 The distribution of excess pore-water pressures across the specimen is parabolic.

5. Apparatus

5.1 *Axial Loading Device*—The axial compression device may be a screw jack driven by an electric motor through a geared transmission, a platform weighing scale equipped with a screw-jack activated yoke, a hydraulic or pneumatic loading device, or any other compression device with sufficient capacity and control to axially compress the specimen at the constant rate of strain prescribed in 9.6. If the axial loading device is outside the consolidometer, see 5.8.

5.2 *Axial Load-Measuring Device*—The axial load-measuring device may be a load ring, strain-gage load cell, hydraulic load cell, or any other load-measuring device capable of the accuracy prescribed in this paragraph and may be a part of the axial loading device. The axial load-measuring device shall be capable of measuring the axial load to an accuracy of 0.25 % of the maximum load applied to the specimen.

NOTE 2—For a constant rate of deformation to be transmitted from the axial loading device through the load-measuring device, it is important that the load-measuring device be relatively stiff. Some hydraulic load cells or proving rings may not provide sufficient stiffness.

5.3 *Pore-Water Pressure-Measuring Device*—The pore-water pressure-measuring device shall be a differential pressure transducer. Separate pressure transducers for measuring pore-water pressure at the base of the specimen and back pressures may be used if both have the required accuracy and both are monitored during the test. The device shall be constructed and located such that the pore-water pressure at the base of the specimen can be measured with negligible drainage of pore water from the base of the specimen on one side of the transducer. The other side of the transducer measures the back pressure applied to the specimen. Negligible drainage of pore water from the base of the specimen can be attained if the coefficient of volume change of the pore pressure-measuring device and de-aired, water-filled cavities connecting the device to the base of the specimen is less than 10^{-5} in.^{3}/psi (10^{-8} m^3/Pa). The pore pressure-measuring device shall be capable of measuring the pore-water pressure at the base of the specimen to an accuracy of 0.25 % of the maximum anticipated pore pressure.

5.4 *Back Pressure-Maintaining Device*, capable of applying and controlling the back pressure to within $\pm$ 2.0 %. This device may consist of a reservoir, it may have reservoirs connected to the top and bottom of the specimen and partially filled with de-aired water; the upper part of the reservoir shall be connected to a compressed gas supply, the gas pressure being controlled by a pressure regulator and measured by a pressure gage. (See Note 3.) However, a hydraulic system pressurized by a deadweight acting on a piston or any other pressure-maintaining device capable of applying and controlling the back pressure to the tolerance prescribed in this paragraph may be used. A low volume-change valve shall be provided in the back-pressure measuring device as near as possible to the base of the specimen. This valve, when open, shall permit the application of back pressure to the base of the specimen; when closed, shall prevent the drainage of water from the specimen base and pore-water pressure-measuring device to the reservoir of the back pressure-maintaining device.

NOTE 3—All gas-water interfaces should be small in area relative to the area of the specimen and should be in reservoirs connected to the consolidometer by a length of small diameter tubing.

5.5 *Deformation Indicator*—The deformation indicator shall be a dial indicator or displacement transducer having a sensitivity of 0.002 mm (0.0001 in.) and a range of at least 50 % of the specimen height, or other measuring device meeting these requirements for sensitivity and range.

5.6 *Timer*, indicating the elapsed testing time to the nearest 1 s for establishing the rates of strain application prescribed in 9.6.

5.7 *Balances*, devices for determining the mass of the soil specimens as well as portions of the apparatus. All measurements of mass should be accurate to 0.1 %.

5.8 *Consolidometer*, to hold the specimen in a ring that is fixed to a rigid base, with porous stones on each face of the specimen. Any potentially submerged parts of the consolidometer shall be made of a material that is noncorrosive in relation to the soil or other parts of the consolidometer. The bottom of the ring shall form a leakproof seal with the rigid base capable of withstanding internal pressures of 1400 kPa (200 psi). The consolidometer shall be constructed such that placement of the specimen into the ring and consolidometer will not entrap air at the base of the specimen. The axial loading device and back pressure-maintaining device may be an integral part of the consolidometer. If the design of the consolidometer is such that back pressures affect axial load readings (due to pressure pushing the piston from the consolidometer), the change in readings with changes in back pressure shall be determined by calibration. The consolidometer shall conform to the following requirements:

5.8.1 *Minimum Specimen Diameter* shall be 50 mm (2.0 in.) and shall be at least 6 mm (0.25 in.) less than the diameter of the sample tube if using undisturbed samples, except as indicated in 7.2.

5.8.2 *Minimum Specimen Thickness* shall be 20 mm (0.75 in.) but shall be not less than 10 times the maximum grain diameter as determined in accordance with Method D 422.

5.8.3 *Minimum-Specimen-Diameter-to-Thickness Ratio*- shall be 2.5.

5.8.4 *Thickness of the Ring* shall be such that, under assumed hydrostatic stress conditions in the specimen, the change in diameter of the ring will not exceed 0.03 % under the greatest load applied.

5.8.5 *Ring* shall be made of a material that is noncorrosive in relation to the soil and pore fluid being tested. The inner surface shall be highly polished or shall be coated with a low-friction material.

5.9 *Porous Disk*:

5.9.1 The porous stones shall be of silicon carbide, aluminum oxide, metal, or other suitable material that is not attacked by the soil or soil moisture and shall be of medium grade. For soft fine-grain soils, a fine-grade porous stone shall be used. The stone shall be fine enough that the soil will not extrude into the pores, but have sufficient permeability so as not to impede the flow of water from the specimen. (Exact criteria have not been established.)

5.9.2 The diameter of the top stone shall be 0.2 to 0.5 mm (0.01 to 0.02 in.) less than that of the ring.

5.9.3 The stone shall be thick enough to prevent breaking. The top stone shall be loaded through a corrosion-resistant plate of sufficient rigidity to prevent breakage of the stone.

5.10 *Moist Room*—In climates where moisture loss during preparation exceeds 0.1 %, the specimen shall be prepared in a moist room.

5.11 *Trimmer or Cylindrical Cutter*, for trimming the specimen down to the inside diameter of the consolidometer ring with a minimum of disturbance.

5.12 *Specimen-Measuring Device*, capable of measuring specimen height and diameter to the nearest 0.02 mm (0.001 in.).

5.13 *Drying Oven*, that can be maintained at 230 ± 9°F (110 ± 5°C).

5.14 *Miscellaneous Equipment*—Specimen trimming and carving tools, including spatulas, knives, and wire saws, moisture content cans, and data sheets as required.

6. Sampling

6.1 Sampling and field investigation shall be conducted in accordance with Practice D 1587. Specimens cut from block samples may also be used.

6.2 If suitable specimens can be obtained using Practice D 3550, then they may be used.

6.3 Transport and handling of samples shall be conducted in accordance with Practice D 4220.

7. Specimens

7.1 Prepare the specimen so moisture loss is less than 0.1 %; if necessary, prepare the specimen in a moist room. Trim the specimen to the inside diameter of the consolidometer ring. Fill with remolded soil any minor indentations in the specimen that would leave voids between the specimen and the ring. Place the specimen in the ring and trim it flush with the plane surface of the ring. The surface must be smooth. A specimen ring with the cutting edge attached provides the most accurate fit in most soils.

7.2 Organic soils, such as peat, and those soils that are easily damaged, may be transferred directly from the sampling tube to the ring where the ring and tube sizes have been selected for this purpose, provided that the cutting edge of the ring has the same diameter as the sample.

7.3 Determine the mass and height of the specimen. Record the specimen mass, height, and diameter.

NOTE 4—Precautions should be taken to minimize disturbance of the soil or changes in moisture and density during specimen preparation; vibration, distortion, and compression must be avoided.

7.4 Use the material trimmed adjacent to the specimen (see 7.1) to determine the natural moisture content (based on dry mass) in accordance with Method D 2216 and the specific gravity in accordance with Test Method D 854. Determine initial wet weight of the specimen and its volume from the mass, diameter, and height of the specimen ring. A more accurate determination of the specimen dry weight and moisture is found by drying the specimen at the end of the test (see 9.11). The value determined from the trimmings is approximate but permits determining the void ratio before the test is complete. The specific gravity can be estimated where an accurate void ratio is not needed.

7.5 The liquid and plastic limits as determined by Test Method D 4318, are useful in identifying the soil and in correlating the results of tests on different soils. These tests may also be performed on the trimmings.

8. Preparation of Apparatus

8.1 De-air the water in the back pressure-maintaining device and pore-water pressure-measuring system (see 5.3 and 5.4).

8.2 Saturate the porous stones with de-aired water.

8.3 Place the bottom porous stone in the consolidometer so as not to entrap any air in the pore water pressure-measuring system.

NOTE 5—Guidelines for system saturation may be found in one or more of the references listed at the end of this method.

9. Procedure

9.1 Assemble the specimen, ring, porous stones, and loading plate in the consolidometer. Avoid entrapping any air between the bottom porous stone and the specimen.

9.2 Place the consolidometer in the axial loading device, adjust the deformation indicator for the initial or zero reading, and apply a seating pressure of 5 kPa (100 lbf/ft^2). The axial loading device may be set to maintain constant seating pressure or maintain a constant specimen height. If a constant specimen height is desired, the seating pressure required to maintain constant specimen height must be recorded. (For very soft soils, a seating pressure of 2.5 kPa (50 lbf/ft^2), or less, is desirable.)

9.3 Check to ensure that the system formed by the water reservoirs of the back pressure-maintaining device and the consolidometer is completely de-aired. Open the valve connecting the consolidometer base to a de-aired water source and fill the reservoir to the appropriate level. Apply the appropriate value of back pressure simultaneously to the top and bottom of the specimen for the appropriate length of time to ensure complete saturation of the specimen, or to ensure as near complete saturation of the specimen as practical. The back pressure shall be applied slowly to specimens having low initial degrees of saturation to minimize deformation of the specimen and prestressing.

9.4 If necessary (see 5.8), adjust the axial load-measuring device to compensate for the load produced by the back pressure, or record the axial load produced on the axial load-measuring device by the back pressure (no volume change), and subtract this value from all load readings.

9.5 If the axial loading device is set to maintain constant seating pressure, record the amount of consolidation or swell that occurs prior to controlled-strain loading. If the axial loading device is set to maintain constant specimen height, record the decrease or increase in axial load that occurs prior to controlled-strain loading.

9.6 *Strain Rate Selection*—It is desirable to select a strain rate that will cause the absolute value of the excess pore-water pressure to be between 3 and 30 % (See Note 6) of the applied vertical stress at any time during the test.

NOTE 6—To achieve this, it is good practice to target a maximum value of 20 % and in no case may the maximum valve exceed 30 %. Guidelines for strain rate selection may be found in one or more of the references listed at the end of this method. The excess pore-water pressure may be limited to values less than 30 % for purposes of getting results consistent with incremental loading tests (Test Method D 2435).

9.7 *Axial Loading*—Close the valve connecting the specimen base to the back pressure-maintaining device and begin to apply the axial load so as to produce axial strain at the constant rate selected in 9.6. Record axial load, excess pore-water pressure, deformation, and elapsed time values at approximately 1-min intervals for the first 10 min, 5-min intervals for the next 1 h, and 15-min intervals thereafter. Take sufficient readings to define the stress-strain curve; hence more frequent readings may be required when significant changes in test parameters occur. Continuous recording or plotting, or both, may be used to obtain necessary data. Continue the loading until the desired stress or strain is obtained. When axial loading is complete, allow the excess pore-water pressure to dissipate at constant axial load or constant deformation and monitor axial load, deformation, and excess pore pressure.

9.8 *Secondary Compression* may be evaluated at any time during the test. To obtain secondary compression data, interrupt the controlled-strain axial loading at any pre-selected axial load and maintain the axial-load constant. Continue to record axial load, excess pore-water pressure, deformation, and elapsed time as suggested in 9.7. In addition, record deformation and elapsed time at time intervals of 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, and 30 min and 1, 2, 4, 8, etc. h, measured from the time of interruption of controlled-strain loading. Readings shall continue at least until the slope of the characteristic linear secondary portion of the deformation versus log of time plot is apparent. If further axial loading is required, resume the controlled-strain axial loading at the previous constant strain rate and record axial load, excess pore water pressure, deformation, and elapsed time at the 1, 5, and 15-min intervals described in 9.7. The procedure in this paragraph may be repeated at subsequent higher stress levels, when necessary.

NOTE 7—Interruption of the controlled-strain test to obtain secondary compression data under constant load may affect the void ratio-effective stress relationship. Further research is needed to define these effects.

9.9 *Rebound*—When rebound or unloading characteristics are desired, unload the specimen at a constant strain rate so that a positive total vertical stress is maintained. (See Note 8.) The excess pore water pressure will become negative. Back pressures must be sufficiently high or strain rates sufficiently low to maintain the pressure at the base of the specimen greater than atmospheric pressure. If the coefficient of consolidation for the rebound portion is desired, back pressures must be sufficiently high or strain rates sufficiently low to maintain a greater pressure at the base of the specimen than the back pressure required for saturation. Record axial load, excess pore-water pressure, deformation, and elapsed time at the 1, 5, and 15-min intervals described in 9.7. When rebound is complete, allow the excess pore water pressure to dissipate at constant axial load or constant deformation.

NOTE 8—Some have found that unloading strain rates on the order of one-tenth the loading strain rates are sufficient to maintain positive total vertical stress on the specimen and keep reasonable values of pore water pressures at the base.

9.10 An alternative loading, unloading, or reloading schedule may be employed that reproduces the construction stress changes, or obtains better definition of some part of the stress-strain (or stress-void ratio) curve, or aids in interpreting the field behavior of the soil. This shall be indicated clearly on the test results.

9.11 At the completion of the test, remove the entire specimen from the consolidometer, weigh, oven-dry, and reweigh to obtain the weight of solids.

10. Calculation

10.1 Calculate the initial void ratio, water content, unit weight, and degree of saturation, based on the dry weight of the total specimen. Specimen volume is computed from values measured in 7.3. Compute volume of solids by dividing the dry weight of specimen by the specific gravity of the solids. The volume of voids is assumed to be the difference between the specimen volume and the volume of the solids.

10.2 Calculate void ratio, e (or alternatively, axial strain, ϵ), total vertical stress, σ_v, and average effective vertical stress, σ'_v for each set of values recorded in 9.7-9.9.

10.2.1 Calculate the void ratio as follows:

$$e = e_0 - \Delta H/H_s \tag{1}$$

where:
e_0 = initial void ratio,
ΔH = deformation,
H_s = height of solids; volume of solids divided by the cross-sectional area of the specimen.

10.2.2 Calculate the axial strain as follows:

$$\epsilon = \Delta H/H_0 \tag{2}$$

where:
H_0 = initial height of the specimen as measured in 7.3.

10.2.3 Calculate the applied axial stress as follows:

$$\sigma_v = P/A \tag{3}$$

where:
P = applied axial load (see Note 9), and
A = cross-sectional area of the specimen.

10.2.4 Calculate the average effective vertical stress (see 4.4.8) as follows:

NOTE 9—If applied axial load is measured outside the cell, the load must be corrected to account for the force caused by the back pressure acting on the piston.

$$\sigma'_v = (\sigma_v^3 - 2\sigma_v^2 u_b + \sigma_v u_b^2)^{1/3} \tag{4}$$

where:

u_b = excess pore-water pressure measured at the base of the specimen.

10.3 When the excess pore-water pressure measured at the base of the specimen exceeds 3 kPa (0.5 psi), calculate the coefficient of consolidation, C_v, for the interval between two sets of readings (see 4.4.7), recorded in 9.7-9.9, as follows:

$$c_v = -\frac{H^2 \log\left[\frac{\sigma_{v2}}{\sigma_{v1}}\right]}{2\Delta t \log\left[1 - \frac{u_b}{\sigma_v}\right]} \tag{5}$$

where:

σ_{v1} = applied axial stress at time t_1
σ_{v2} = applied axial stress at time t_2
H = average specimen height between t_1 and t_2
Δt = elapsed time between t_1 and $t_2 = t_2 - t_1$
u_b = average excess pore pressure between t_2 and t_1, and
σ_v = average total applied axial stress between t_2 and t_1.

If strain rates are changed at any time during the test, the values of C_v calculated at those times may be inaccurate.

NOTE 10—The above averages are obtained from one-half the sum of the two values.

10.3.1 It is best to compute C_v between consecutive readings and assign the value of C_v to the average value of σ'_v between the two readings.

10.3.2 If the values of effective vertical stress do not change significantly between consecutive readings, the time interval may be increased.

11. Report

11.1 The report shall include the following information:

11.1.1 Identification and description of sample, including whether soil is undisturbed, remolded, compacted, or otherwise prepared,

11.1.2 Initial moisture content,

11.1.3 Initial wet unit weight,

11.1.4 Initial percent saturation,

11.1.5 If void ratio calculations are made, value of specific gravity of solids in the calculations,

11.1.6 Condition of test (value of back pressure, swell or consolidation during backpressure or seating pressure necessary to maintain constant height, strain rate(s) during loading and unloading),

11.1.7 Plot of void ratio versus log of average effective vertical stress or axial strain versus log of average effective vertical stress,

11.1.8 Plot of coefficient of consolidation versus log of average effective vertical stress,

11.1.9 Plot of pore pressure versus log of average effective vertical stress.

11.1.10 Plot of pore pressure ratio versus log of average effective vertical stress.

11.1.11 For tests in which secondary compression data were obtained, a plot of deformation versus log of time shall be provided, and

11.1.12 Departures from the procedure outlined, including special loading sequences.

12. Precision

12.1 Undisturbed soil samples from homogeneous soil deposits at the same location often exhibit significantly different consolidation properties. No method exists to evaluate the precision of a group of consolidation tests on undisturbed samples, due to sample variability.

12.2 A suitable test material and method of sample preparation have not been developed for the determination of laboratory variances, due to the difficulty in producing identical cohesive soil samples. No estimates of precision for this test method are available.

13. Keywords

13.1 compressibility; compressibility coefficient; CRS; consolidation coefficient; consolidation test; consolidometer; preconsolidation stress; settlement

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SUMMARY OF CHANGES

This section identifies the location of changes to this test method since the last edition.

(*1*) Section 1.3 has been added.

(*2*) Section 13, Keywords, has been added.