Standard Method of Test for

One-Dimensional Consolidation Properties of Soils

AASHTO Designation: T 216-07
ASTM Designation: D 2435-04

1. SCOPE

1.1. This test method covers procedures for determining the magnitude and rate of consolidation of soil when it is restrained laterally and drained axially while subjected to incrementally applied controlled-stress loading. Two alternative procedures are provided as follows:

1.1.1. *Test Method A*—This test method is performed with constant load increment duration of 24 hours, or multiples thereof. Time-deformation readings are required on a minimum of two-load increments.

1.1.2. *Test Method B*—Time-deformation readings are required on all load increments. Successive load increments are applied after 100 percent primary consolidation is reached, or at constant time increments as described in Test Method A.

Note 1—The determination of the rate and magnitude of consolidation of soil when it is subjected to controlled-strain loading is covered by ASTM D 4186.

1.2. This test method is most commonly performed on undisturbed samples of fine grained soils naturally sedimented in water, however, the basic test procedure is applicable as well, to specimens of compacted soils and undisturbed samples of soils formed by other processes such as weathering or chemical alteration. Evaluation techniques specified in this test method are generally applicable to soils naturally sedimented in water. Tests performed on other soils such as compacted and residual (weathered or chemically altered) soils may require special evaluation techniques.

1.3. It shall be the responsibility of the agency requesting this test to specify the magnitude and sequence of each load increment, including the location of a rebound cycle, if required, and, for Test Method A, the load increments for which time-deformation readings are desired.

Note 2—Time-deformation readings are required to determine the time for completion of primary consolidation and for evaluating the coefficient of consolidation, c_v. Since c_v varies with stress level and load increment (loading or unloading), the load increments with timed readings must be selected with specific reference to the individual project. Alternatively, the requesting agency may specify Test Method B wherein the time-deformation readings are taken on all load increments.

1.4. The values stated in SI units are to be regarded as the standard. The values stated in inch-pound units are approximate and given for guidance only. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.4.1. In the engineering profession, it is customary practice to use, interchangeably, units representing both mass and force, unless dynamic calculations ($F = Ma$) are involved. This implicitly combines two separate systems of units, that is, the absolute system and the gravimetric system. It is scientifically undesirable to combine two separate systems within a single standard. This test method has been written using SI units; however, inch-pound conversions are given in the gravimetric system, where the pound (lbf) represents a unit of force (weight). The use of balances or scales recording pounds of mass (lbm), or the recording of density in lb/ft^3 should not be regarded as nonconformance with this test method.

1.5. *This standard does not purport to address the safety concerns 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. *AASHTO Standards*:

- T 88, Particle Size Analysis of Soils
- T 89, Determining the Liquid Limit of Soils
- T 90, Determining the Plastic Limit and Plasticity Index of Soils
- T 100, Specific Gravity of Soils
- T 207, Thin-Walled Tube Sampling of Soils
- T 265, Laboratory Determination of Moisture Content of Soils

2.2. *ASTM Standards*:

- D 653, Terminology Relating to Soil and Rock
- D 2435, Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading
- D 2487, Classification of Soils for Engineering Purposes
- D 2488, Practice for Description and Identification of Soils (Visual-Manual Procedure)
- D 3550, Practice for Ring-Lined Barrel Sampling of Soils
- D 4186, Test Method for One-Dimensional Consolidation Properties of Soils Using Controlled-Strain Loading
- D 4220, Practice for Preserving and Transporting Soil Samples
- D 4452, Methods for X-Ray Radiography of Soil Samples
- D 4546, Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils
- D 6026, Standard Practice for Using Significant Digits in Geotechnical Data

3. TERMINOLOGY

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

4. SUMMARY OF TEST METHOD

4.1. In this test method a soil specimen is restrained laterally and loaded axially with total stress increments. Each stress increment is maintained until excess pore water pressures are completely dissipated. During the consolidation process, measurements are made of change in the specimen height and these data are used to determine the relationship between the effective stress and void ratio or strain, and the rate at which consolidation can occur by evaluating the coefficient of consolidation.

5. SIGNIFICANCE AND USE

5.1. The data from the consolidation test are used to estimate the magnitude and rate of both differential and total settlement of a structure or earthfill. Estimates of this type are of key importance in the design of engineered structures and the evaluation of their performance.

5.2. The test results can be greatly affected by sample disturbance. Careful selection and preparation of test specimens is required to minimize disturbance.

5.3. Consolidation test results are dependent upon the magnitude of the load increments. Traditionally, the load is doubled for each increment resulting in a load-increment ratio of one. For undisturbed samples, this load procedure has provided data from which estimates of the preconsolidation pressure also referred to as the maximum past pressure, using established evaluation techniques, compare directly with field measurement. Other load schedules may be used to model particular field conditions or meet special requirements. For example, it may be desirable to inundate and load the specimen in accordance with the wetting or loading pattern expected in the field in order to best simulate the response. Smaller than standard load increment ratios may be desirable for soils that are highly sensitive or whose response is highly dependent on strain rate. The test method specified to estimate the preconsolidation pressure provides a simple technique to verify that one set of time readings are taken after the preconsolidation pressure. Several other evaluation techniques exist and may yield different estimates of the preconsolidation pressure. Therefore, the requesting agency may specify an alternate technique to estimate the preconsolidation pressure.

5.4. Consolidation test results are dependent upon the duration of each load increment. Traditionally, the load duration is the same for each increment and equal to 24 hours. For some soils, the rate of consolidation is such that complete consolidation (dissipation of excess pore pressure) will require more than 24 hours. The apparatus in general use does not have provisions for formal verification of pore pressure dissipation. It is necessary to use an interpretation technique which indirectly determines that consolidation is complete. This test method specifies two techniques, however, the requesting agency may specify an alternative technique and still be in conformance with this test method.

5.5. The apparatus in general use for this test method does not have provisions for verification of saturation. Most undisturbed samples taken from below the water table will be saturated. However, the time rate of deformation is very sensitive to degree of saturation and caution must be exercised regarding estimates for duration of settlements when partially saturated conditions prevail. The extent to which partial saturation influences the test results may be a part of the test evaluation and may include application of theoretical models other than conventional consolidation theory. Alternatively, the test may be performed using an apparatus equipped to saturate the specimen.

5.6. This test method uses conventional consolidation theory based on Terzaghi's consolidation equation to compute the coefficient of consolidation, c_v. The analysis is based upon the following assumptions:

5.6.1. The soil is saturated and has homogeneous properties;

5.6.2. The flow of pore water is in the vertical direction;

5.6.3. The compressibility of soil particles and pore water is negligible compared to the compressibility of the soil skeleton;

5.6.4. The stress-strain relationship is linear over the load increment;

5.6.5. The ratio of soil permeability to soil compressibility is constant over the load increment; and

5.6.6. Darcy's law for flow through porous media applies.

6. APPARATUS

6.1. *Load Device*—A suitable device for applying vertical loads or total stresses to the specimen. The device should be capable of maintaining specified loads for long periods of time with an accuracy of ±0.5 percent of the applied load and should permit quick application of a given load increment without significant impact.

Note 3—Load application generally should be completed in a time corresponding to 0.01 t_{100} or less. For soils where primary consolidation is completed in three minutes load application should be less than two seconds.

6.2. *Consolidometer*—A device to hold the specimen in a ring that is either fixed to the base or floating (supported by friction on periphery of specimen) with porous disks on each face of the specimen. The inside diameter of the ring shall be determined to a tolerance of 0.075 mm (0.003 in.). The consolidometer shall also provide a means of submerging the specimen, for transmitting the concentric vertical load to the porous disks, and for measuring the change in height of specimen.

6.2.1. *Minimum Specimen Diameter*—The minimum specimen diameter shall be 50 mm (2.00 in.). The diameter of the sample in the tube shall be greater than the diameter of the consolidation test ring. The diameter of the sample must be greater than the test ring to reduce sampling disturbance and prevent lateral displacement.

6.2.2. *Minimum Specimen Height*—The minimum initial specimen height shall be 12 mm (0.5 in.), but shall not be less than 10 times the maximum particle diameter.

Note 4—If large particles are found in the specimen after testing, include in the report this visual observation or the results of a particle-sized analysis in accordance with T 88 (except the minimum sample-sized requirement shall be waived).

6.2.3. *Minimum Specimen Diameter-to-Height Ratio*—The minimum specimen diameter-to-height ratio shall be 2.5.

Note 5—The use of greater diameter-to-height ratios is recommended. To minimize the effects of friction between the sides of the specimen and ring, a diameter-to-height ratio greater than four is preferable.

6.2.4. *Specimen Ring Rigidity*—The rigidity of the ring shall be such that, under hydrostatic stress conditions in the specimen, the change in diameter of the ring will not exceed 0.03 percent of the diameter under the greatest load applied.

6.2.5. *Specimen Ring Material*—The ring shall be made of a material that is noncorrosive in relation to the soil tested. The inner surface shall be highly polished or shall be coated with a low-friction material. Silicone grease or molybdenum disulfide is recommended; polytetrafluoroethylene is recommended for non-sandy soils.

6.3. *Porous Disks*—The porous disks shall be of silicon carbide, aluminum oxide, or similar noncorrosive material. The grade of the disks shall be fine enough to prevent intrusion of soil into the pores. If necessary, a filter paper (Note 6) may be used to prevent intrusion of the soil into the disks; however, the permeability of the disks, and filter paper, if used, must be at least one order of magnitude higher than that of the specimen.

Note 6—Whatman No. 54 filter paper has been found to meet requirements for permeability and durability.

6.3.1. *Diameter*—The diameter of the top disk shall be 0.2 to 0.5 mm (0.01 to 0.02 in.) less than the inside diameter of the ring. If a floating ring is used, the bottom disk shall have the same diameter as the top disk.

Note 7—The use of tapered disks is recommended, with the larger diameter in contact with the soil.

6.3.2. *Thickness*—Thickness of the disks shall be sufficient to prevent breaking. The top disk shall be loaded through a corrosion-resistant plate of sufficient rigidity to prevent breakage of the disk.

6.3.3. *Maintenance*—The disks shall be clean and free from cracks, chips, and nonuniformities. New porous disks should be boiled for at least 10 minutes and left in the water to cool to ambient temperature before use. Immediately after each use, clean the porous disks with a nonabrasive brush and boil to remove clay particles that may reduce their permeability. It is recommended that porous disks be stored in a jar with de-aired water between tests.

6.4. *Specimen Trimming Device*—A trimming turntable or a cylindrical cutting ring may be used for trimming the sample down to the inside diameter of the consolidometer ring with a minimum of disturbance. A cutter having the same inside diameter as the specimen ring shall attach to or be integral with the specimen ring. The cutter shall have a sharp edge, a highly polished surface and be coated with a low-friction material. Alternatively, a turntable or trimming lathe may be used. The cutting tool must be properly aligned to form a specimen of the same diameter as that of the ring.

6.5. *Deformation Indicator*—To measure change in specimen height, with a readability of 0.0025 mm (0.0001 in.).

6.6. *Miscellaneous Equipment*—Including timing device with 1-second readability, distilled or demineralized water, spatulas, knives, and wire saws, used in preparing the specimen.

6.7. *Balances*, in accordance with T 265.

6.8. *Drying Oven*, in accordance with T 265.

6.9. *Water Content Containers*, in accordance with T 265.

6.10. *Environment*—Tests shall be performed in an environment where temperature fluctuations are less than ±4°C (±7°F) and there is no direct exposure to sunlight.

7. CALIBRATION

7.1. The measured vertical deformations must be corrected for apparatus flexibility whenever the calibration correction determined in Section 7.4 exceeds five percent of the measured deformation and in all tests where filter paper disks are used.

7.2. Assemble the consolidometer with a copper or hard steel disk of approximately the same height as the test specimen and at least 1 mm (0.04 in.) smaller in diameter than the ring, but no more than 5 mm smaller in diameter than the ring, in place of the sample. Moisten the porous disks. If filter papers are to be used (Section 6.3), they should be moistened and sufficient time (a minimum of two minutes) allowed for the moisture to be squeezed from them during each increment of the calibration process.

7.3. Load and unload the consolidometer as in the test and measure the deformation for each load applied. When filter papers are used, it is imperative that calibration be performed following the exact loading and unloading schedule to be used. This is due to the inelastic deformation characteristics of filter paper. Recalibration for tests without filter paper need be done only on an annual basis, or after replacement and reassembly of apparatus components.

7.4. At each load applied, plot or tabulate the corrections to be applied to the measured deformation of the test specimen. Note that the metal disk will deform also; however, the correction due to this deformation will be negligible for all but extremely stiff soils. If necessary, the compression of the metal disk can be computed and applied to the corrections.

8. SAMPLING

8.1. AASHTO T 207 and ASTM D 3550 cover procedures and apparatus that may be used to obtain undisturbed samples generally satisfactory for testing (Note 8). Specimens may also be trimmed from large undisturbed block samples fabricated and sealed in the field. Finally, remolded specimens may be prepared from bulk samples to density and moisture conditions stipulated by the agency requesting the test.

Note 8—Not all tube diameters specified may be of sufficient size for testing.

8.2. Undisturbed samples destined for testing in accordance with this test method shall be preserved, handled, and transported in accordance with the practices for Group C and D samples in ASTM D 4220. Bulk samples for remolded specimens should be handled and transported in accordance with the practice for Group B samples.

8.3. *Storage*—Storage of sealed samples should be such that no moisture is lost during storage, that is, no evidence of partial drying of the ends of the samples or shrinkage. Time of storage should be minimized, particularly when the soil or soil moisture is expected to react with the sample tubes.

8.4. The quality of consolidation test results diminishes greatly with sample disturbance. It should be recognized that no sampling procedure can ensure completely undisturbed samples. Therefore, careful examination of the sample is essential in selection of specimens for testing.

Note 9—Examination for sample disturbance, stones, or other inclusions, and selection of specimen location is greatly facilitated by x-ray radiography of the samples. (See ASTM D 4452.)

9. SPECIMEN PREPARATION

9.1. All possible precautions should be taken to minimize disturbance of the soil or changes in moisture and density during specimen preparation. Avoid vibration, distortion, and compression.

9.2. Prepare test specimens in an environment where soil moisture change during preparation is minimized.

Note 10—A high-humidity environment is usually used for this purpose.

9.3. Trim the specimen and insert it into the consolidation ring. When specimens come from undisturbed soil collected using sample tubes, the inside diameter of the tube shall be at least 5 mm (0.25 in.) greater than the inside diameter of the consolidation ring, except as noted in Sections 9.4 and 9.5. It is recommended that either a trimming turntable or cylindrical cutting ring be used to cut the soil to the proper diameter. When using a trimming turntable, make a complete perimeter cut, reducing the specimen diameter to the inside diameter of the consolidation ring. Carefully insert the specimen into the consolidation ring, by the width of the cut, with a minimum of force. Repeat until the specimen protrudes from the bottom of the ring. When using a cylindrical cutting ring, trim the soil to a gentle taper in front of the cutting edge. After the taper is formed, advance the cutter a small distance to form the final diameter. Repeat the process until the specimen protrudes from the ring.

9.4. Fibrous soils, such as peat, and those soils that are easily damaged by trimming, may be transferred directly from the sampling tube to the ring, provided that the ring has the same diameter as the sample tube.

9.5. Specimens obtained using a ring-lined sampler may be used without prior trimming, provided they comply with the requirements of ASTM D 3550 and this test method.

9.6. Trim the specimen flush with the plane ends of the ring. The specimen may be recessed slightly below the top of the ring, to facilitate centering of the top stone, by partial extrusion and trimming of the bottom surface. For soft to medium soils, a wire saw should be used for trimming the top and bottom of the specimen to minimize smearing. A straightedge with a sharp cutting edge may be used for the final trim after the excess soil has first been removed with a wire saw. For stiff soils, a sharpened straightedge alone may be used for trimming the top and bottom. If a small particle is encountered in any surface being trimmed, it should be removed and the resulting void filled with soil from the trimmings.

Note 11—If, at any stage of the test, the specimen swells beyond its initial height, the requirement of lateral restraint of the soil dictates the use of a recessed specimen or the use of a specimen ring equipped with an extension collar of the same inner diameter as the specimen ring. At no time should the specimen extend beyond the specimen ring or extension collar.

9.7. Determine the initial wet mass of the specimen, M_{T_o}, in the consolidation ring by measuring the mass of the ring with specimen and subtracting the tare mass of the ring.

9.8. Determine the initial height, H_o, of the specimen to the nearest 0.025 mm (0.001 in.) by taking the average of at least four evenly spaced measurements over the top and bottom surfaces of the specimen using a dial comparator or other suitable measuring device.

9.9. Compute the initial volume, V_o, of the specimen to the nearest 0.25 cm^3 (0.015 in.^{3}) from the diameter of the ring and the initial specimen height.

9.10. Obtain two or three natural water content determinations of the soil in accordance with T 265 from material trimmed adjacent to the test specimen if sufficient material is available.

9.11. When index properties are specified by the requesting agency, store the remaining trimmings taken from around the specimen and determined to be similar material in a sealed container for determination as described in Section 10.

10. SOIL INDEX PROPERTY DETERMINATIONS

10.1. The determination of index properties is an important adjunct to but not a requirement of the consolidation test. These determinations when specified by the requesting agency should be made on the most representative material possible. When testing uniform materials, all index tests may be performed on adjacent trimmings collected in Section 9.11. When samples are heterogeneous or trimmings are in short supply, index tests should be performed on material from the test specimen as obtained in Section 11.6, plus representative trimmings collected in Section 9.11.

10.2. *Specific Gravity*—The specific gravity shall be determined in accordance with T 100 on material from the sample as specified in Section 10.1. The specific gravity from another sample judged to be similar to that of the test specimen may be used for calculation in Section 12.2.5 whenever an accurate void ratio is not needed.

10.3. *Atterberg Limits*—The liquid limit shall be determined in accordance with T 89. The plastic limit and plasticity index shall be determined in accordance with T 90 using material from the sample as specified in Section 10.1. Determination of the Atterberg limits are necessary for proper material classification but are not a requirement of this test method.

10.4. *Particle-Sized Distribution*—The particle-sized distribution shall be determined in accordance with T 88 (except the minimum sample-sized requirement shall be waived) on a portion of the test specimen as obtained in Section 11.6. A particle-sized analysis may be helpful when visual inspection indicates that the specimen contains a substantial fraction of coarse-grained material but is not a requirement of this test method.

11. PROCEDURE

11.1. Preparation of the porous disks and other apparatus will depend on the specimen being tested. The consolidometer must be assembled in such a manner as to prevent a change in water content of the specimen. Dry porous disks and filters must be used with dry, highly expansive soils and may be used for all other soils. Damp disks may be used for partially saturated soils. Saturated disks may be used when the specimen is saturated and known to have a low affinity for water. Assemble the ring with specimen, porous disks, filter disks (when needed) and consolidometer. If the specimen will not be inundated shortly after application of the seating load (Section 11.2), enclose the consolidometer in a loose-fitting plastic or rubber membrane to prevent change in specimen volume due to evaporation.

Note 12—In order to meet the stated objectives of this test method, the specimen must not be allowed to swell in excess of its initial height prior to being loaded beyond its preconsolidation pressure. Detailed procedures for the determination of one-dimensional swell or settlement potential of cohesive soils is covered by ASTM D 4546.

11.2. Place the consolidometer in the loading device and apply a seating pressure of 5 kPa (100 lbf/ft^2). Immediately after application of the seating load, adjust the deformation indicator and record the initial zero reading, d_o. If necessary, add additional load to keep the specimen from swelling. Conversely, if it is anticipated that a load of 5 kPa (100 lbf/ft^2) will cause significant consolidation of the specimen, reduce the seating pressure to 2 or 3 kPa (about 50 lbf/ft^2) or less.

11.3. If the test is performed on an intact specimen that was either saturated under field conditions or obtained below the water table, inundate shortly after application of the seating load. As inundation and specimen wetting occur, increase the load as required to prevent swelling. Record the load required to prevent swelling and the resulting deformation reading. If specimen inundation is to be delayed to simulate specific conditions, then inundation must occur at a pressure that is sufficiently large to prevent swell. In such cases, apply the required load and inundate the specimen. Take time deformation readings during the inundation period as specified in Section 11.5. In such cases, note in the test report the pressure at inundation and the resulting changes in height.

11.4. The specimen is to be subjected to increments of constant total stress. The duration of each increment shall conform to guidelines specified in Section 11.5. The specific loading schedule will depend on the purpose of the test, but should conform to the following guidelines. If the slope and shape of a virgin compression curve or determination of the preconsolidation pressure is required, the final pressure shall be equal to or greater than four times the preconsolidation pressure. In the case of overconsolidated clays, a better evaluation of recompression parameters may be obtained by imposing an unload-reload cycle after the preconsolidation pressure has been defined. Details regarding location and extent of an unload-reload cycle is the option of the agency requesting the test (Section 1.3), however, unloading shall always span at least two decrements of pressure.

11.4.1. The standard loading schedule shall consist of a load increment ratio (LIR) of one which is obtained by doubling the pressure on the soil to obtain values of approximately 12, 25, 50, 100, 200, etc. kPa (250, 500, 1000, 2000, 4000, etc. lbf/ft^2).

11.4.2. The standard rebound or unloading schedule should be selected by halving the pressure on the soil (that is, use the same increments of Section 11.4.1, but in reverse order). However, if desired, each successive load can be only one-fourth as large as the preceding load, that is, skip a decrement.

11.4.3. 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 deformation (compression) curve, or aids in interpreting the field behavior of the soil.

Note 13—Small increments may be desirable on highly compressible specimens or when it is desirable to determine the preconsolidation pressure with more precision. It should be cautioned, however, that load increment ratios less than 0.7 and load increments very close to the preconsolidation pressure may preclude evaluation for the coefficient of consolidation, c_v, and the end-of-primary consolidation as discussed in Section 12.

11.5. Before each pressure increment is applied, record the height or change in height, d_f, of the specimen. Two alternative procedures are available that specify the time sequence of readings and the required minimum load duration. Longer durations are often required during specific load increments to define the slope of the characteristic straight-line secondary compression portion of the deformation versus log of time graph. For such increments, sufficient readings should be taken near the end of the pressure increment to define this straight-line portion. It is not necessary to increase the duration of other pressure increments during the test.

11.5.1. *Test Method A*—The standard load increment duration shall be 24 hours. For at least two load increments, including at least one load increment after the preconsolidation pressure has been exceeded, record the height or change in height, d, at time intervals of approximately 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, and 30 minutes, and 1, 2, 4, 8, and 24 hours (or 0.09, 0.25, 0.49, 1, 4, 9 minutes, etc., if using Section 12.3.2 to present time-deformation data), measured from the time of each incremental pressure application. Take sufficient readings near the end of the pressure increment period to verify that primary consolidation is completed. For some soils, a period of more than 24 hours may be required to reach the end-of-primary consolidation (as determined in Section 12.3.1.1 or 12.3.2.3). In such cases, load increment durations greater than 24 hours are required. The load increment duration for these tests is usually taken at some multiple of 24 hours and should be the standard duration for all load increments of the test. The decision to use a time interval greater than 24 hours is usually based on experience with particular types of soils. If, however, there is a question as to whether a 24-hour period is adequate, a record of height or change in height with time should be made for the initial load increments in order to verify the adequacy of a 24-hour period. Load increment durations other than 24 hours shall be noted in the report. For pressure increments where time versus deformation data are not required, leave the load on the specimen for the same length of time as when time versus deformation readings are taken.

11.5.2. *Test Method B*—For each increment, record the height or change in height, d, at time intervals of approximately 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, 30 minutes, and 1, 2, 4, 8, and 24 hours (or 0.09, 0.25, 0.49, 1, 4, 9 minutes, etc., if using Section 12.3.2 to present time deformation data), measured from the time of each incremental pressure application. The standard load increment duration shall exceed the time required for completion of primary consolidation as determined by Sections 12.3.1.1, 12.3.2.3 or a criterion set by the requesting agency. For each increment where it is impossible to verify the end of primary consolidation (for example, low LIR or rapid consolidation), the load increment duration shall be constant and exceed the time required for primary consolidation of an increment applied after the preconsolidation pressure and along the virgin compression curve. Where secondary compression must be evaluated, apply pressures for longer periods. The report shall contain the load increment duration for each increment.

Note 14—The suggested time intervals for recording height or change in height are for typical soils and load increments. It is often desirable to change the reading frequency to improve interpretation of the data. More rapid consolidation will require more frequent readings. For most soils, primary consolidation during the first load decrements will be complete in less time (typically one-tenth) than would be required for a load increment along the virgin compression curve, however, at very low stresses the rebound time can be longer.

11.6. To minimize swell during disassembly, rebound the specimen back to the seating load (5 kPa). Once height changes have ceased (usually overnight), dismantle quickly after releasing the final small load on the specimen. Remove the specimen and the ring from the consolidometer and wipe any free water from the ring and specimen. Determine the mass of the specimen in the ring and subtract the tare mass of the ring to obtain the final wet specimen mass, M_{T_f}. The most accurate determination of the specimen dry mass and water content is found by drying the entire specimen at the end of the test. If the soil sample is homogeneous and sufficient trimmings are available for the specified index testing (Section 9.11), then determine the final water content w_f, in accordance with T 265 and dry mass of solids, M_d, using the entire specimen. If the soil is heterogeneous or more material is required for the specified index testing, then determine the final water content, w_{f_p}, in accordance with T 265 using a small wedge shaped section of the specimen. The remaining undried material should be used for the specified index testing.

12. CALCULATION

12.1. Calculations as shown are based on the use of SI units. Other units are permissible, provided the appropriate conversion factors are used to maintain consistency of units throughout the calculations. See Section 1.4.1 for additional comments on the use of inch-pound units.

12.2. *Specimen Properties*:

12.2.1. Obtain the dry mass of the total specimen, K_d, by direct measurement or for the case where part of the specimen is used for index testing, calculate the dry mass as follows:

$$M_d = \frac{M_{T_f}}{1+w_{f_p}} \quad (1)$$

where:

M_{T_f} = moist mass of total specimen after test, g or kg; and

w_{f_p} = water content (decimal form) wedge of specimen taken after test.

12.2.2. Calculate the initial and final water content, in percent, as follows:

initial water content:

$$w_o = \frac{M_{T_o} - M_d}{M_d} \times 100 \tag{2}$$

final water content:

$$w_f = \frac{M_{T_f} - M_d}{M_d} \times 100 \tag{3}$$

where:

M_d = dry mass of specimen, g or kg; and

M_{T_o} = moist mass of specimen before test, g or kg.

12.2.3. Calculate the initial dry density of the specimen as follows:

$$\rho_d = \frac{M_d}{V_o} \tag{4}$$

where:

ρ_d = dry density of specimen, g/cm^3 or kg/m^3; and

V_o = initial volume of specimen, cm^3 or m^3.

12.2.4. Calculate the dry unit weight of the specimen as follows:

$$\gamma_d = 9.81 \times \rho_d / 1000 \tag{5}$$

where:

γ_d = dry unit weight, kN/m^3

ρ_d = dry density, kg/m^3

12.2.5. Compute the volume of solids as follows:

$$V_s = \frac{M_d}{G\rho_w} \tag{6}$$

where:

G = specific gravity of the solids, and

ρ_w = density of water, 1.0 g/cm^3 or Mg/m^3.

12.2.6. Since the cross-sectional area of the specimen is constant throughout the test, it is convenient for subsequent calculations to introduce the term "equivalent height of solids," defined as follows:

$$H_s = \frac{V_s}{A} \tag{7}$$

where:

A = specimen area, cm^2 or mm^2.

12.2.7. Calculate void ratio before and after test as follows:

void ratio before test:

$$e_o = \frac{H_o - H_s}{H_s} \quad (8)$$

void ratio after test:

$$e_f = \frac{H_f - H_s}{H_s} \quad (9)$$

where:

H_o = initial specimen height, cm or mm; and

H_f = final specimen height, cm or mm.

12.2.8. Calculate the degree of saturation, in percent, before and after test as follows:

$$\text{initial degree of saturation: } S_o = \frac{M_{T_o} - M_d}{A\rho_w\left(H_o - H_s\right)} \times 100 \quad (10)$$

$$\text{initial degree of saturation: } S_f = \frac{M_{T_f} - M_d}{A\rho_w\left(H_f - H_s\right)} \times 100 \quad (11)$$

where:

M_{T_o}, M_{T_f}, and M_d = gram

A = cm^2

ρ_w = 1 g/cm^3

H_f and H_s = cm

12.3. *Time-Deformation Properties*—From those increments of load where time-deformation readings are obtained, two alternative procedures (Section 12.3.1 or 12.3.2) are provided to present the data, determine the end-of-primary consolidation and compute the rate of consolidation. Alternatively, the requesting agency may specify a method of its choice and still be in conformance with this test method. The deformation readings may be presented as measured deformation, deformation corrected for apparatus compressibility or converted to strain (Section 12.4).

12.3.1. Referring to Tables 1 and 2 (Figure 1), plot the deformation readings, d, versus the log of time (normally in minutes) for each increment of load.

12.3.1.1. First draw a straight line through the points representing the final readings which exhibit a straight-line trend and constant slope (C). Draw a second straight-line tangent to the steepest part of the deformation-log time curve (D). The intersection represents the deformation, d_{100}, and time, t_{100}, corresponding to 100 percent primary consolidation (E). Compression in excess of the above estimated 100 percent primary consolidation is defined as secondary compression.

12.3.1.2. Find the deformation representing zero percent primary consolidation by selecting any two points that have a time ratio of 1 to 4. The deformation at the larger of the two times should be greater than one-fourth, but less than one-half of the total deformation for the load increment. The deformation corresponding to zero percent primary consolidation is equal to the deformation at the smaller time, less the difference in deformation for the two selected times.

Load Increment (kPa)	d_f Corrected (mm)	$\Sigma\Delta H$ (mm)	Σ $\Sigma\Delta H/H_o$ (%)	H $(H_o - \Delta H)$ (mm)	e $(H - H_s)/H_s$
initial	5.3300	0	0	19.0500	1.231
5	5.3012	0.0288	0.15	19.0212	1.228
10	5.2743	0.0557	0.29	18.0943	1.225
20	5.2167	0.1133	0.59	18.9367	1.218
40	5.1161	0.2139	1.12	18.8361	1.206
80	4.9433	0.3867	2.03	18.6633	1.186
160	4.4740	0.8560	4.49	18.1940	1.131
320	2.9804	2.3496	12.33	16.7004	0.956
640	1.8908	3.4392	18.05	15.6108	0.828
1280	0.9860	4.3440	22.80	14.7060	0.722
320	1.0747	4.2553	22.34	14.7947	0.733
80	1.4000	3.9300	20.63	15.1200	0.771
20	1.8169	3.5131	18.44	15.5369	0.820
5	2.2319	3.0981	16.26	15.9519	0.868

H_o = 19.050 mm
H_s = 8.538 mm

d_{50} Corrected (mm)	$\Sigma\Delta H$ (mm)	Σ_{50} (%)	H_{50} (mm)	e_{50}	t_{50} (sec)	c_v (mm²/sec)
5.0604	0.2696	1.42	18.780	1.200	52	3.34× 10-1
4.7945	0.5355	2.81	18.515	1.169	144	1.17× 10-1
3.7861	1.5439	8.10	17.506	1.050	516	2.93× 10-1
2.4983	2.8317	14.86	16.218	0.900	282	4.59× 10-1
1.5077	3.8223	20.06	15.228	0.784	156	7.32× 10-1

Figure 1—Void Ratio and Strain Information

12.3.1.3. The deformation, d_{50}, corresponding to 50 percent primary consolidation is equal to the average of the deformations corresponding to the 0 and 100 percent deformations. The time, t_{50}, required for 50 percent consolidation may be found graphically from the deformation-log time curve by observing the time that corresponds to 50 percent of the primary consolidation on the curve.

12.3.2. Referring to Figure 1, plot the deformation readings, d, versus the square root of time (normally in minutes) for each increment of load.

12.3.2.1. First draw a straight line through the points representing the initial readings that exhibit a straight-line trend. Extrapolate the line back to $t = 0$ and obtain the deformation ordinate representing zero percent primary consolidation.

12.3.2.2. Draw a second straight line through the zero percent ordinate so that the abscissa of this line is 1.15 times the abscissa of the first straight line through the data. The intersection of this second line with the deformation-square root of time, curve is the deformation, d_{90}, and time t_{90}, corresponding to 90 percent primary consolidation.

12.3.2.3. The deformation at 100 percent consolidation is one-ninth more than the difference in deformation between 0 and 90 percent consolidation. The time of primary consolidation, t_{100}, may be taken at the intersection of the deformation-square root of time curve and this deformation ordinate. The deformation, d_{50}, corresponding to 50 percent consolidation is equal to the deformation at five-ninths of the difference between 0 and 90 percent consolidation.

12.3.3. Compute the coefficient of consolidation for each increment of load using the following equation and values appropriate to the chosen method of interpretation:

$$c_v = \frac{TH^2{}_{D_{50}}}{t} \qquad (12)$$

where:

T = a dimensionless time factor: for method in Section 12.3.1, use 50 percent consolidation with $T = T_{50} = 0.197$; for method in Section 12.3.2, use 90 percent consolidation with $T = T_{90} = 0.848$,

t = time corresponding to the particular degree of consolidation, second or minute: for method in Section 12.3.1, use $t = t_{50}$; for method in Section 12.3.2, use $t = t_{90}$, and

$H_{D_{50}}$ = Length of the drainage path at 50 percent consolidation cm or m: for double-sided drainage, $H_{D_{50}}$ is half the specimen height at the appropriate increment; and for one-sided drainage, $H_{D_{50}}$ is the full-specimen height.

12.4. *Load-Deformation Properties*:

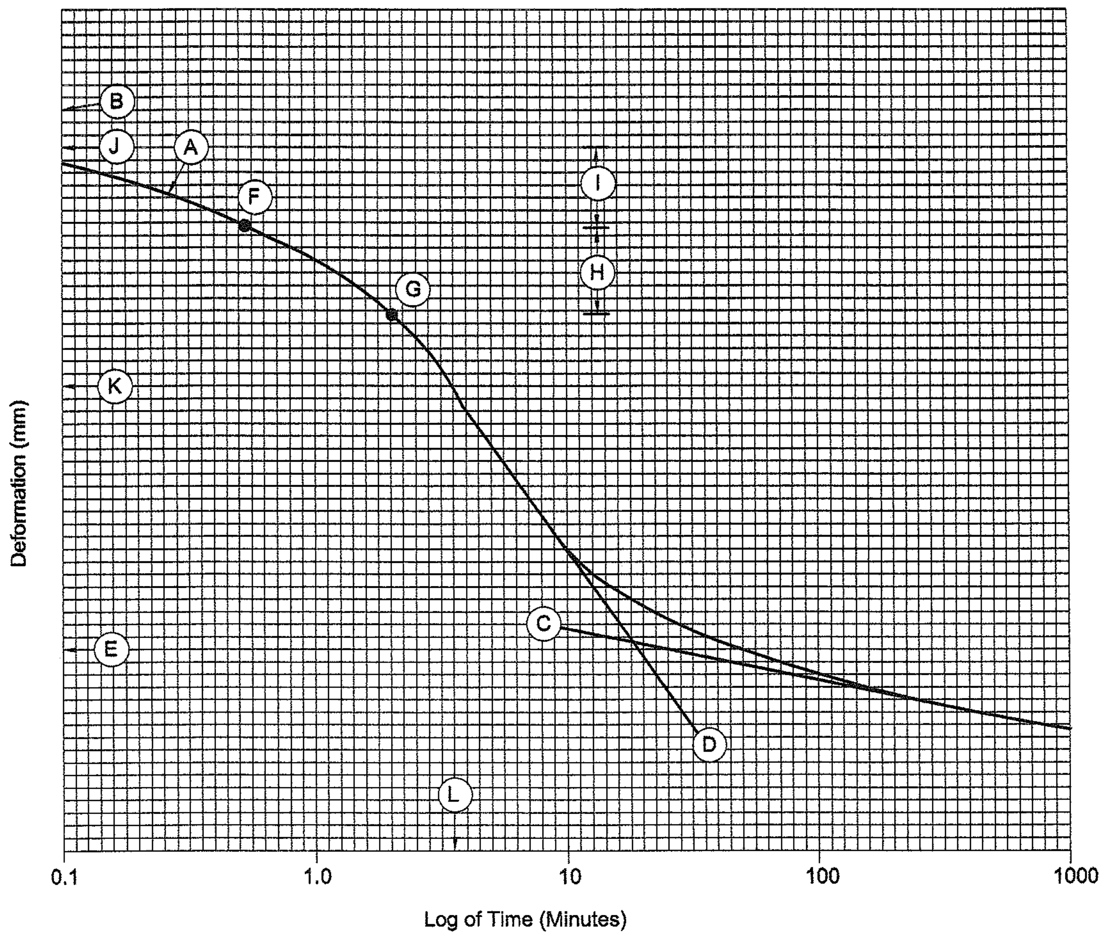
12.4.1. Tabulate the deformation or change in deformation, d_f, readings corresponding to the end of each increment and, if using Test Method B, corresponding to the end-of-primary consolidation, d_{100}.

12.4.2. Calculate the change in height, $\Delta H = d - d_0$, relative to the initial specimen height for each reading. If necessary, correct the deformation for the apparatus flexibility by subtracting the calibration value obtained in Section 9 from each reading.

12.4.3. Represent the deformation results in one of the following formats:

12.4.3.1. Calculate the void ratio as follows:

$$e = e_o - \frac{\Delta H}{H_s} \tag{13}$$



A	Time-deformation curve from data points
B	Deformation at time - 0 minutes
C	Extension of final linear portion of curve
D	Extension of steepest linear portion of curve
E	d_{100} Deformation at intersection of lines C and D
F	t_1 Selected point in time
G	t_2 time at four times t_1 (deformation at time t_2 should be less than 50% and larger than 25% of the total deformation for load increment)
H	Increment of deformation between times t_1 and t_2
I	Increment of deformation equal to F
J	d_0 Calculated initial deformation
K	d_{50} mean of d_0 and d_{100}
L	t_{50} time at d_{50}

Figure 2—Time Deformation Curve from Log-of-Time Method

12.4.3.2. Alternatively, calculate the vertical strain, in percent, as follows:

$$\in=\frac{\Delta H}{H_0}\times 100 \qquad (14)$$

12.4.4. Calculate the vertical stress as follows:

$$\sigma_v=\frac{P}{A}\times 10000 \qquad (15)$$

where:

σ_v = vertical stress, kPa;
P = applied load, kN; and
A = specimen area, cm^2.

12.4.5. Referring to Figure 2, plot the deformation results (void ratio or strain) corresponding to the end of each increment and, if using Test Method B, corresponding to the end-of-primary consolidation versus the logarithm of the pressure.

Note 15—In some cases, it may be preferable to present the load-deformation curve in arithmetic scale.

12.4.6. Referring to Figure 3, determine the value of the preconsolidation pressure using the following procedure:

Note 16—Any other recognized method of estimating preconsolidation pressure may also be used, provided the method is identified in the report. (See references.)

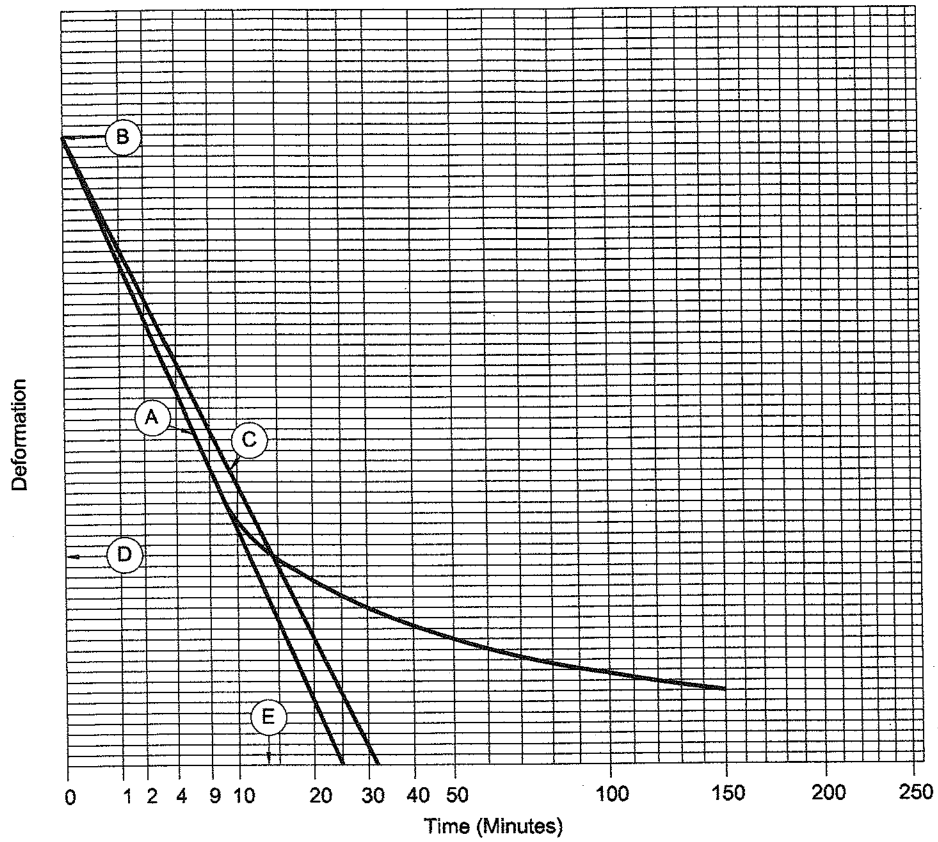
12.4.6.1. Estimate the point of maximum curvature on the consolidation curve (B).

12.4.6.2. Draw the tangent to the consolidation curve at this point (C), and a horizontal line through the point (D), both extended towards increasing values on the abscissa.

12.4.6.3. Draw the line bisecting the angle between these lines (E).

12.4.6.4. Extend the tangent to the steep, linear portion of the consolidation curve (virgin compression branch) (F) upwards to intersection with the bisector line (E). The pressure (G) (abscissa) corresponding to this point of intersection is the estimated preconsolidation pressure.

12.4.7. Complete evaluation often includes consideration of information not generally available to the laboratory performing the test. For this reason further evaluation of the test is not mandatory. Many recognized methods of evaluation are described in the literature. Some of these are discussed in the References listed in Section 16.



A Time deformation curve from data points
B d_0 extension of initial linear portion of curve A to time = 0 minutes
C Construction line with slope - 1.15 times initial linear portion of curve A
D d_{90} Deformation at point where curve A crosses line C
E t_{90} Time at point where curve A crosses line C

Figure 3—Time-Deformation Curve from Square Root of Time Method

13. REPORT

13.1. In addition to project name and location, boring number, sample number, and depth, report the following information:

13.1.1. Description and classification of the soil in accordance with ASTM D 2488 or ASTM D 2487 when Atterberg limit data are available. Specific gravity of solids, Atterberg limits, and the grain-sized distribution shall also be reported when available plus the source of such information if other than measurements obtained on test specimen. Also note occurrence and approximate size of isolated large particles.

13.1.2. *Soil Condition*:

13.1.2.1. Average water content of trimmings,

13.1.2.2. Initial and final water content of specimen,

13.1.2.3. Initial and final dry unit weight of specimen, 13.1.2.4. Initial and final void ratio of specimen,

13.1.2.5. Initial and final degree of saturation of specimen, and

13.1.2.6. Preconsolidation pressure.

13.1.3. *Test Procedure*:

13.1.3.1. Preparation procedure used relative to trimming; state whether the specimen was trimmed using a trimming turntable, trimmed using a cutting shoe, or tested directly in a ring from a ring lined sampler.

13.1.3.2. Condition of test (natural moisture or inundated, pressure at inundation).

13.1.3.3. Method of testing (A or B).

13.1.3.4. Test Method used to compute coefficient of consolidation.

13.1.3.5. Listing of loading increments and decrements, and load increment duration, if differing from 24 hours; end of increment deformation results and, for Test Method B, end-of-primary deformation results and coefficient of consolidation. (See Tables 1 and 2.) All departures from the procedure outlined, including special loading sequences.

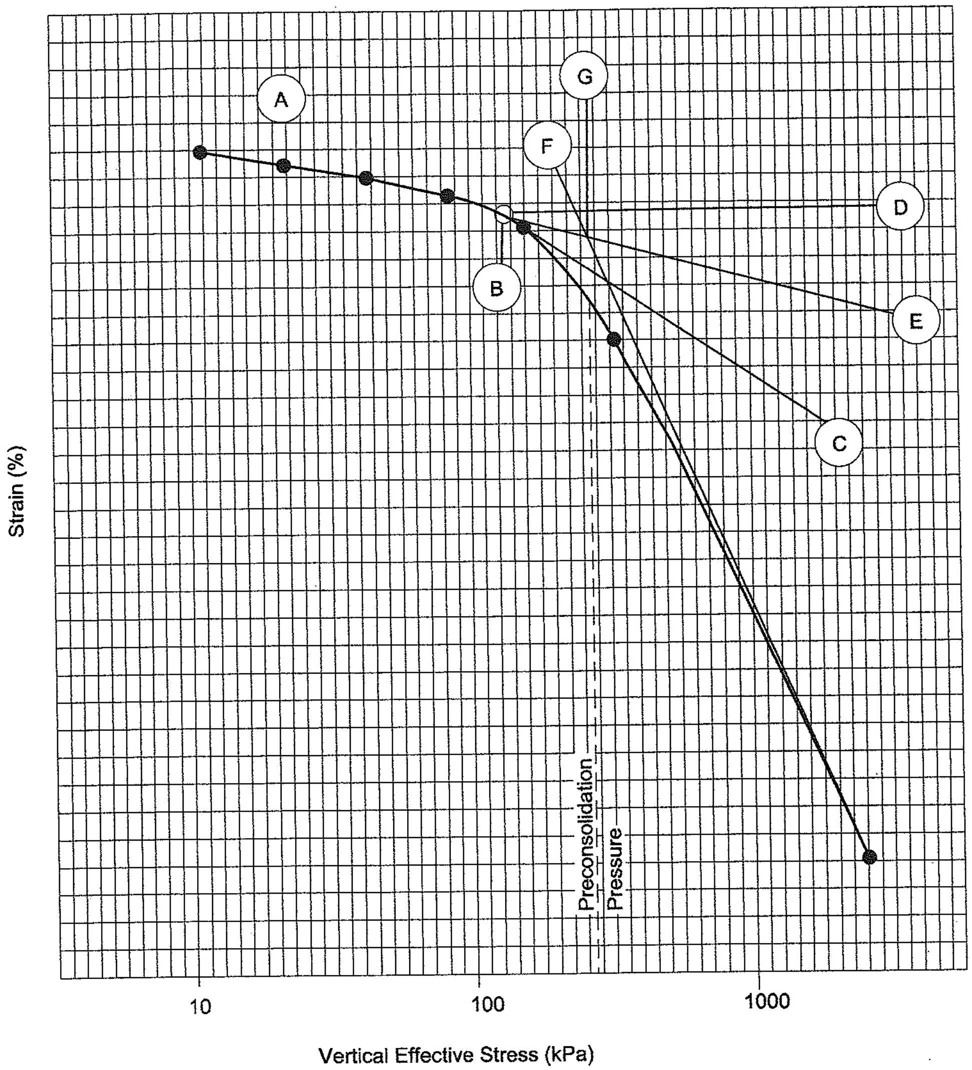
13.1.4. *Graphical Presentations*:

13.1.4.1. Graph of deformation versus log time (Figure 1) or square root of time (Figure 2) for those load increments where time rate readings were taken.

13.1.4.2. Graph of void ratio versus log of pressure curve or percent compression versus log of pressure curve. (See Figure 3.)

13.1.4.3. In cases where time rate of deformation readings have been taken for several load increments, prepare a graph of the log of coefficient of consolidation versus average void ratio or average percent compression for the respective load increments. (See Figure 4.) Alternatively, a graph of coefficient of consolidation or log of coefficient of consolidation versus log of average pressure may be used. If time rate readings were obtained for only two-load increments, simply tabulate the values of cv versus the average pressure for the increment.

Note 17—The average pressure between two-load increments is chosen because it is a convenient coordinate for plotting the result. Unless the rate of pore pressure dissipation is measured, it is not possible to determine the actual effective pressure at the time of 50 percent consolidation. Furthermore, some ambiguity may arise in cases where the test has been carried through one or more intermediate load-rebound cycles.



A Stress-strain curve from data points
B Point of maximum curvature
C Tangent line to curve at point B
D Horizontal line through point B
E Line bisecting angle between lines C and D
F Tangent to linear portion of curve in virgin compression range
G Intersection of lines E and F (vertical effective stress at point G equals the preconsolidation pressure)

Figure 4—Evaluation for Preconsolidation Pressure from Casagrande Method

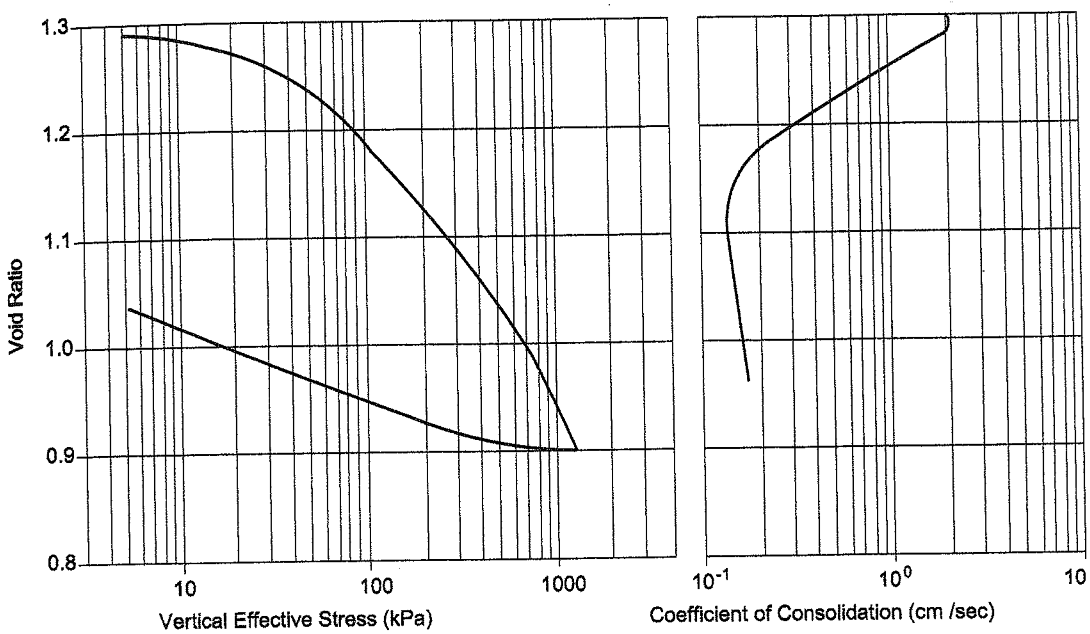


Figure 5—Example of Consolidation Test Summary Plots

14. PRECISION AND BIAS

14.1. *Statement of Precision*—Due to the nature of the soil materials tested by this test method, it is either not feasible or too costly at this time to produce multiple specimens which have uniform physical properties. Any variation observed in the data is just as likely to be due to specimen variation as to operator or laboratory testing variation.

14.2. *Statement of Bias*—There is no acceptable reference value for this test method, therefore, bias cannot be determined.

15. KEYWORDS

15.1. Compressibility; compression curves; consolidation; consolidation coefficient; consolidation test; consolidometer; preconsolidation pressure; primary consolidation; rebound; secondary compression; settlement; swelling.

16. REFERENCES

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