Designation:D 5311–92(Reapproved 1996) Designation: D5311 – 11

Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil[1]

This standard is issued under the fixed designation D5311; 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

1.1This test method covers the determination of the cyclic strength (sometimes called the liquefaction potential) of saturated soils in either undisturbed or reconstituted states by the load-controlled cyclic triaxial technique. *

1.1 This test method covers the determination of the cyclic strength (sometimes called the liquefaction potential) of saturated soils in either intact or reconstituted states by the load-controlled cyclic triaxial technique.

1.2 The cyclic strength of a soil is evaluated relative to a number of factors, including: the development of axial strain, magnitude of applied cyclic stress, number of cycles of stress application, development of excess pore-water pressure, and state of effective stress. A comprehensive review of factors affecting cyclic triaxial test results is contained in the literature (**1**).[2]

1.3 Cyclic triaxial strength tests are conducted under undrained conditions to simulate essentially undrained field conditions during earthquake or other cyclic loading.

1.4 Cyclic triaxial strength tests are destructive. Failure may be defined on the basis of the number of stress cycles required to reach a limiting strain or 100 % pore pressure ratio. See Section 3 for Terminology.

1.5This test method is generally applicable for testing cohesionless free draining soils of relatively high permeability. When testing well-graded materials, silts, or clays, it should be recognized that pore-water pressures monitored at the specimen ends to not in general represent pore-water pressure values throughout the specimen. However, this test method may be followed when testing most soil types if care is taken to ensure that problem soils receive special consideration when tested and when test results are evaluated.

1.6There are certain limitations inherent in using cyclic triaxial tests to simulate the stress and strain conditions of a soil element in the field during an earthquake.

1.6.1Nonuniform stress conditions within the test specimen are imposed by the specimen end platens. This can cause a redistribution of void ratio within the specimen during the test.

1.6.2A 90° change in the direction of the major principal stress occurs during the two halves of the loading cycle on isotropically consolidated specimens.

1.6.3The maximum cyclic shear stress that can be applied to the specimen is controlled by the stress conditions at the end of consolidation and the pore-water pressures generated during testing. For an isotropically consolidated contractive (volume decreasing) specimen tested in cyclic compression, the maximum cyclic shear stress that can be applied to the specimen is equal to one-half of the initial total axial pressure. Since cohesionless soils are not capable of taking tension, cyclic shear stresses greater than this value tend to lift the top platen from the soil specimen. Also, as the pore-water pressure increases during tests performed on isotropically consolidated specimens, the effective confining pressure is reduced, contributing to the tendency of the specimen to neck during the extension portion of the load cycle, invalidating test results beyond that point.

1.6.4While it is advised that the best possible undisturbed specimens be obtained for cyclic strength testing, it is sometimes necessary to reconstitute soil specimens. It has been shown that different methods of reconstituting specimens to the same density may result in significantly different cyclic strengths. Also, undisturbed specimens will almost always be stronger than reconstituted specimens.

1.6.5The interaction between the specimen, membrane, and confining fluid has an influence on cyclic behavior. Membrane compliance effects cannot be readily accounted for in the test procedure or in interpretation of test results. Changes in pore-water pressure can cause changes in membrane penetration in specimens of cohesionless soils. These changes can significantly influence the test results.

1.6.6The mean total confining pressure is asymmetric during the compression and extension stress application when the chamber pressure is constant. This is totally different from the symmetric stress in the simple shear case of the level ground liquefaction.

[1] This test method is under the jurisdiction of ASTM Committee D-18 D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.09 on Dynamic Properties of Soils.

Current edition approved Oct. 15, 1992. Published January 1993.on Cyclic and Dynamic Properties of Soils.

Current edition approved Nov. 1, 2011. Published January 2012. Originally approved in 1992. Last previous edition approved in 2004 as D5311–92(2004)$^{\epsilon1}$. DOI: 10.1520/D5311-11.

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

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

~~1.7The values stated in both inch-pound and SI units are to be regarded separately as the standard. The values given in parentheses are for information only.~~

1.5 This test method is generally applicable for testing cohesionless free draining soils of relatively high permeability. When testing well-graded materials, silts, or clays, pore-water pressures monitored at the specimen ends may not represent pore-water pressure values throughout the specimen. However, this test method may be followed when testing most soil types if care is taken to ensure that problem soils receive special consideration when tested and when test results are evaluated.

1.6 The values stated in either SI units or inch-pound units [presented in brackets] are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.7 All observed and calculated values shall conform to the guide for significant digits and rounding established in Practice D6026. The procedures in Practice D6026 that are used to specify how data are collected, recorded, and calculated are regarded as the industry standard. In addition, they are representative of the significant digits that should generally be retained. The procedures do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the objectives of the user. Increasing or reducing the significant digits of reported data to be commensurate with these considerations is common practice. Consideration of the significant digits to be used in analysis methods for engineering design is beyond the scope of this standard.

1.7.1 The method used to specify how data are collected, calculated, or recorded in this standard is not directly related to the accuracy to which the data can be applied in design or other uses, or both. How one applies the results obtained using this standard is beyond its scope.

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

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D422 Test Method for Particle-Size Analysis of Soils

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D~~854Test Method for Specific Gravity of Soils~~[3] 854 Test Methods for Specific Gravity of Soil Solids by Water Pycnometer

D1587 Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes

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

D2850 ~~Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression~~[3] Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils

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

D4220 Practices for Preserving and Transporting Soil Samples

D4253 Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table

D4254 Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density

[3] 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*~~, Vol 04.08.~~volume information, refer to the standard's Document Summary page on the ASTM website.

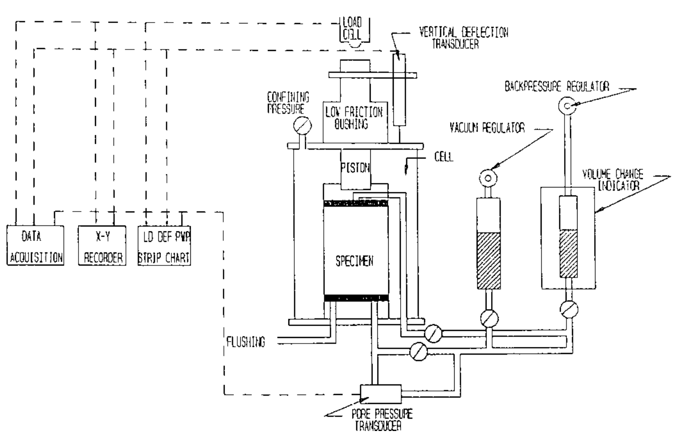

FIG. 1 Schematic Representation of Load-Controlled Cyclic Triaxial Strength Test Equipment

D4318 Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D4767 Test Method for Consolidated-Undrained Triaxial Compression Test on Cohesive Soils[3] Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils
D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions for terms used in this test method (including *liquefaction*) are in accordance with Terminology D 653D 653. Additional descriptions of terms are defined in 3.2 and in 10.2 and Fig. 1) are in accordance with Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *full or 100 % pore pressure ratio*— a condition in which Δu equals $\sigma`_{3c}$.

3.2.2 *peak pore pressure ratio*—the maximum pore pressure ratio measured during a particular loading sequence.

3.2.3 *peak (single amplitude) strain*—the maximum axial strain (from the origin or initial step) in either compression or extension produced during a particular loading sequence.

3.2.4 *peak to peak (double amplitude) strain*— the difference between the maximum axial strain in compression and extension during a given cycle under cyclic loading conditions.

3.2.5 *pore pressure ratio*—the ratio, expressed as a percentage, of the change of excess pore-water pressure, Δu, to the effective minor principal stress, $\sigma`_{3c}$, at the end of primary consolidation.

3.2.6 *cyclic stress ratio*—the ratio of the applied deviator stress to the effective confining pressure (incorporating changes in excess pore water pressure) during cyclic loading.

4. Summary of Test Method

4.1 A cylindrical soil specimen is sealed in a watertight rubber membrane and confined in a triaxial chamber where it is subjected to a confining pressure. An axial load is applied to the top of the specimen by a load rod.

4.2 Specimens are consolidated isotropically (equal axial and radial stress). Tubing connections to the top and bottom specimen platens permit flow of water during saturation, consolidation and measurement of pore-water pressure during cyclic loading.

4.3 Following saturation and consolidation, the specimen is subjected to a sinusoidally varying axial load by means of the load rod connected to the specimen top platen. The cyclic load, specimen axial deformation, and porewater pressure development with time are monitored.

4.4 The test is conducted under undrained conditions to approximate essentially undrained field conditions during earthquake or other dynamic loading. The cyclic loading generally causes an increase in the pore-water pressure in the specimen, resulting in a decrease in the effective stress and an increase in the cyclic axial deformation of the specimen.

4.5 Failure may be defined as when the peak excess pore-water pressure equals the initial effective confining pressure, full or 100 % pore pressure ratio (sometimes called initial liquefaction), or in terms of a limiting cyclic strain or permanent strain.

5. Significance and Use

5.1 Cyclic triaxial strength test results are used for evaluating the ability of a soil to resist the shear stresses induced in a soil mass due to earthquake or other cyclic loading.

5.1.1 Cyclic triaxial strength tests may be performed at different values of effective confining pressure on isotropically consolidated specimens to provide data required for estimating the cyclic stability of a soil.

5.1.2 Cyclic triaxial strength tests may be performed at a single effective confining pressure, usually equal to 14.5 lb/in.100 kN/m^2 (100 $kN/m^{(14.5\ lb/in.^2}$), or alternate pressures as appropriate on isotropically consolidated specimens to compare cyclic strength results for a particular soil type with that of other soils, Ref **(2)**.

5.2 The cyclic triaxial test is a commonly used technique for determining cyclic soil strength.

5.3 Cyclic strength depends upon many factors, including density, confining pressure, applied cyclic shear stress, stress history, grain structure, age of soil deposit, specimen preparation procedure, and the frequency, uniformity, and shape of the cyclic wave form. Thus, close attention must be given to testing details and equipment.

5.4 There are certain limitations inherent in using cyclic triaxial tests to simulate the stress and strain conditions of a soil element in the field during an earthquake.

5.4.1 Nonuniform stress conditions within the test specimen are imposed by the specimen end platens. This can cause a redistribution of void ratio within the specimen during the test.

5.4.2 A 90° change in the direction of the major principal stress occurs during the two halves of the loading cycle on isotropically consolidated specimens.

5.4.3 The maximum cyclic shear stress that can be applied to the specimen is controlled by the stress conditions at the end of consolidation and the pore-water pressures generated during testing. For an isotropically consolidated contractive (volume decreasing) specimen tested in cyclic compression, the maximum cyclic shear stress that can be applied to the specimen is equal to one-half of the initial total axial pressure. Since cohesionless soils are not capable of taking tension, cyclic shear stresses greater than this value tend to lift the top platen from the soil specimen. Also, as the pore-water pressure increases during tests performed on isotropically consolidated specimens, the effective confining pressure is reduced, contributing to the tendency of the specimen to neck during the extension portion of the load cycle, invalidating test results beyond that point.

5.4.4 While it is advised that the best possible intact specimens be obtained for cyclic strength testing, it is sometimes necessary to reconstitute soil specimens. It has been shown that different methods of reconstituting specimens to the same density may result in significantly different cyclic strengths. Also, intact specimens will almost always be stronger than reconstituted specimens.

5.4.5 The interaction between the specimen, membrane, and confining fluid has an influence on cyclic behavior. Membrane compliance effects cannot be readily accounted for in the test procedure or in interpretation of test results. Changes in porewater pressure can cause changes in membrane penetration in specimens of cohesionless soils. These changes can significantly influence the test results.

5.4.6 The mean total confining pressure is asymmetric during the compression and extension stress application when the chamber pressure is constant. This is totally different from the symmetric stress in the simple shear case of the level ground liquefaction.

NOTE 1—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 In many ways, triaxial equipment suitable for cyclic triaxial strength tests is similar to equipment used for the unconsolidated-undrained triaxial compression test (see Test Method ~~D 2850~~D2850) and the consolidated-undrained triaxial compression test (see Test Method ~~D 4767~~D4767). However, there are special features described in the following subsections that are required to perform acceptable cyclic triaxial tests. A schematic representation of a typical load-controlled cyclic triaxial strength test set-up is shown in Fig. 1.

6.2 *Triaxial Compression Cell*—The primary considerations in selecting the cell are tolerances for the piston, top cap, and low friction piston seal.

6.2.1 Two linear ball bushings or similar bearings ~~should~~shall be used to guide the load rod to minimize friction and to maintain alignment.

6.2.2 The load rod diameter ~~should~~shall be large enough to minimize lateral bending. A minimum load rod diameter of ⅙ the specimen diameter has been used successfully in many laboratories.

6.2.3 The load rod seal is a critical element in triaxial cell design for cyclic soils testing. The seal must exert negligible friction on the load rod. The maximum acceptable piston friction tolerable without applying load corrections is commonly considered to be ± 2 % of the maximum single amplitude cyclic load applied in the test. The use of an air bushing as proposed in Ref **(3)** will meet or exceed these requirements.

6.2.4 Top and bottom platen alignment is critical if premature specimen failure caused by the application of a nonuniform state of stress to the specimen is to be avoided. Internal tie-rod triaxial cells that allow for adjustment of alignment before placement of the chamber have been found to work well at a number of laboratories. These cells allow the placement of the cell wall after the specimen is in place between the loading platens. Acceptable limits of platen eccentricity and parellelism are shown in Fig. 2.

6.2.5 Since in cyclic triaxial tests extension as well as compression loads may be exerted on the specimen, the load rod shall be connected to the top platen by straight threads backed by a shoulder on the piston that tightens up against the platen.

6.2.6 There shall be provision for specimen drainage at both the top and bottom platens.

6.2.7 *Porous Discs*—The specimen shall be separated from the specimen cap and base by rigid porous discs of a diameter equal to that of the specimen. The coefficient of permeability of the discs shall be approximately equal to that of fine sand (3.9×10^{-5} in./s [1×10^{-4} cm/s]). The discs shall be regularly checked to determine whether they have become clogged.

6.3 Dynamic loading equipment used for load-controlled cyclic triaxial tests shall be capable of applying a uniform sinusoidal load at a frequency range of 0.1 to 2.0 Hz. The frequency of 1.0 Hz is preferred. The loading device shall be able to maintain uniform cyclic loadings to at least 20 % peak-to-peak strains. Unsymmetrical compression-extension load peaks, nonuniformity of pulse duration,“ ringing,” or load fall-off at large strains shall not exceed tolerance illustrated in Fig. 3. The equipment shall also be able to apply the cyclic load about an initial static load on the loading rod. Evaluate uniformity of the load trace into the failure state to ensure that load uniformity criteria presented in previous sections are achieved. Show this in an appropriate way by calculating the percent load drift (~~P_{error}~~Error$_{\Delta P}$) between the maximum load (ΔP_{max}) based on the initial loading cycle and the measured load in the *n*~~th cycle as follows:~~th cycle (ΔP_n) as follows:

$$\Delta P_{max} = (\Delta P_c + \Delta P_e)_{max} \quad (1)$$

D5311-11_1

~~P_{error} should be < 5% at axial strains of ± 5%.~~ D5311-11_1

ΔPn

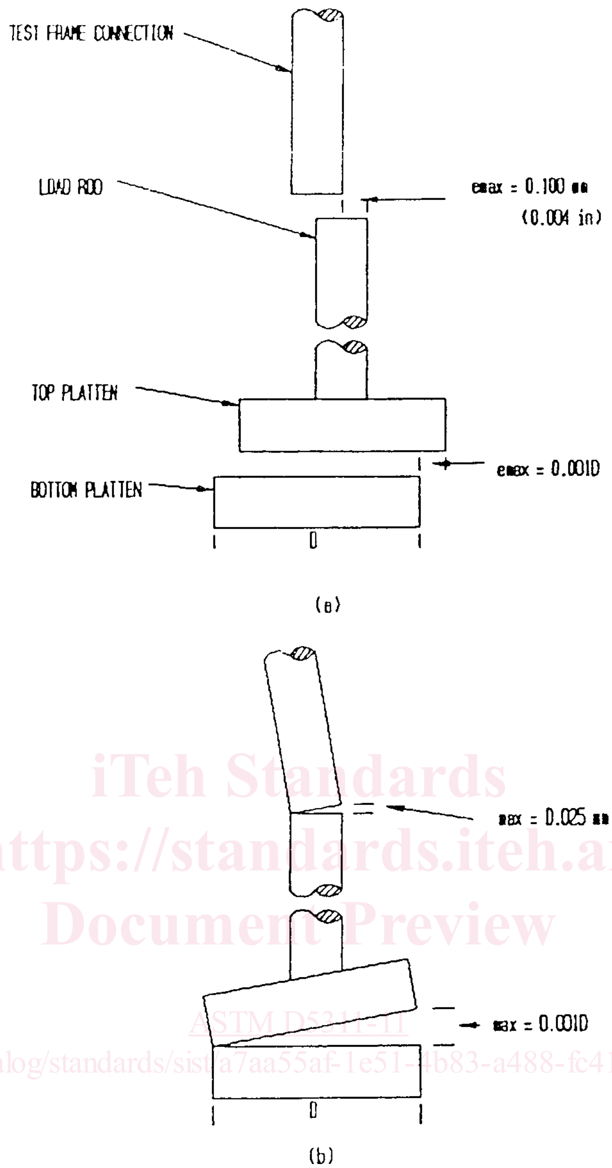

FIG. 2 Limits on Acceptable ~~1—~~ Platen and Load Rod Alignment (a) Eccentricity and (b) ~~p~~ Parallelism~~.~~

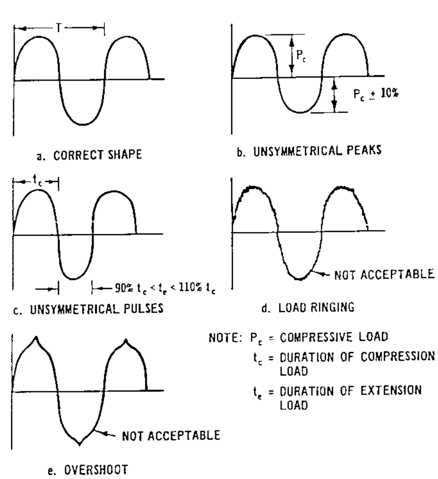

FIG. 3 Examples of Acceptable and Unacceptable Sinusoidal Loading Wave Forms for Cyclic Triaxial Strength Tests

where:

ΔP_{max} = ~~maximum load,~~ maximum change in peak applied loads,
ΔP_c = change in peak applied load in compression,
ΔP_e = change in peak applied load in extension, ~~and~~
~~P_{error}~~ΔP_n = ~~percent load drift.~~load on the nth cycle, and
$Error_{\Delta P}$ = percent load drift, which shall be less than 5 % at axial strains of ± 5 %.

NOTE ~~1—For~~ 2—For less than 20 cycles for samples with high fines content, a non-uniform pore pressure distribution may result.

6.4 *Recording Equipment*—Load, displacement, and pore water pressure transducers are required to monitor specimen behavior during cyclic loading; provisions for monitoring the chamber pressure during loading are optional (see Table 1).

6.4.1 *Axial Load Measurement*—The desired maximum cyclic load-measuring device may be ~~a load ring,~~ an electronic load ~~cell, hydraulic load cell,~~ cell or any other load-measuring device capable of measuring the axial load to an accuracy of within ± 1 % of the axial load. Generally, the load cell capacity ~~should~~shall be no greater than five times the total maximum load applied to the test specimen to ensure that the necessary measurement accuracy is achieved. The minimum performance characteristics of the load cell are presented in Table 1.

6.4.2 *Axial Deformation Measurement*— Displacement measuring devices such as linear variable differential transformer (LVDT), potentiometer-type deformation transducers, and eddy current sensors may be used if they have an accuracy of ± 0.02 % of the initial specimen height (see Table 1). Accurate deformation measurements require that the transducer be properly mounted to avoid excessive mechanical system compression between the load frame, the triaxial cell, the load cell, and the loading piston.

6.4.3 *Pore-Water Pressure Transducer*— The specimen pore-water pressure shall be measured to within ± ~~0.25 psi (2 kPa).~~2 kPa (0.25 psi). During cyclic loading the pore-water pressure shall be measured in such a manner that as little water as possible is allowed to go into or out of the specimen. To achieve this requirement for cyclic loading, a very stiff electronic pressure transducer must be used. The measuring device shall have a compliance of all the assembled parts of the pore-water pressure measurement system relative to the total volume of the specimen satisfying the following requirement:

D5311-11_2

where:

ΔV = change in volume of the pore-water measurement system due to a pore pressure change, ~~in.~~m^3 ~~(m~~(in.^{3}),
V = the total volume of the specimen, ~~in.~~m^3 ~~(m~~(in.^{3}), and
Δu = the change in pore pressure, ~~psi (kPa).~~kPa (psi).

The pore-water pressures shall be measured using the drainage line(s) leading to either (or both) the specimen cap or base.

6.4.4 *Recorders*—Specimen behavior is evaluated from continuous time records of applied load, axial deformation, and change in pore-water pressure. Fast recording system response is essential if specimen performance is to be monitored accurately when failure conditions are approached. Required response characteristics are given in Table 1. Resolution of each variable ~~should~~shall be better than 2 % of the maximum value being measured.

6.4.5 *Volume Change Measurement Device*— The volume of water entering or leaving the specimen shall be measured with an

TABLE 1 Data Acquisition

Minimum Response Characteristics for Cyclic Triaxial Strength Tests

1. *Analog Recorders:*
Recording speeds: 0.5 to 50 cm/s (0.2 to 20 in./s) system accuracy (including linearity and hysteresis): 0.5 %^{A} frequency response: 100 Hz
2. *Digital Recorders:*
Minimum sampling rate: 40 data points per cycle
3. *Measurement Transducers:*

	Load Cell	Displacement Transducer (LVDT)^B	Pore Pressure
Minimum sensitivity, mV/V	2	0.2 mV/0.025 mm/V (0.2 mV/0.001 in./V) (AC LVDT) 5 mV/0.025 mm/V (5 mV/0.001 in./V) (DC LVDT)	2
Nonlinearity, % full scale	±	± 0.25	± 0.5
Hysteresis, % full scale	±0.25	0.0	± 0.5
Repeatability, % full scale	±0.10	± 0.01	± 0.5
Thermal effects on zero shift or sensitivity %of full scale/°C (°F)	± 0.005 (± 0.025)	...	± 0.02 (± 0.01)
Maximum deflection at full rated value in mm (in.)	0.125 (0.005)	...	...
Volume change characteristics, cm^3/kPa (cu in./psi)	...	...	<2.4 × 10^{-4} (<1.0 × 10^{-4})

^{A} System frequency response, sensitivity, and linearity are functions of the electronic system interfacing, the performance of the signal conditioning system used, and other factors. It is therefore a necessity to check and calibrate the above parameters as a total system and not on a component basis.

^{B} LVDT's, unlike strain gages, cannot be supplied with meaningful calibration data. System sensitivity is a function of excitation frequency, cable loading, amplifier phase characteristics, and other factors. It is necessary to calibrate each LVDT-cable-instrument system after installation, using a known input standard.