INTERNATIONAL

Designation: ~~D5778 – 12~~ D5778 – 20

Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils[1]

This standard is issued under the fixed designation D5778; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method covers the procedure for determining the ~~point~~ resistance ~~during penetration~~ of a ~~conical-shaped penetrometer~~ friction cone or a piezocone as it is advanced into subsurface soils at a steady rate.

~~1.2 This test method is also used to determine the frictional resistance of a cylindrical sleeve located behind the conical point as it is advanced through subsurface soils at a steady rate.~~

1.2 This test method applies to ~~friction-cone penetrometers of the electric and electronic type.~~ electronic friction cones and does not include hydraulic, pneumatic, or free-fall cones, although many of the procedural requirements herein could apply to those cones. Also, offshore/marine Cone Penetration Testing (CPT) systems may have procedural differences because of the difficulties of testing in those environments (for example, tidal variations, salt water and waves). Field tests using mechanical-type ~~penetrometers~~cones are covered elsewhere by Test Method D3441.

1.3 This test method can be used to determine ~~porewater~~ pore water pressures developed during the ~~penetration, thus termed piezocone. Porewater~~ penetration when using a properly saturated piezocone. Pore water pressure dissipation, after a push, can also be monitored for correlation to time rate of consolidation and permeability.

1.4 Additional sensors, such as inclinometer, seismic ~~geophones~~ (Test Methods D7400), resistivity, electrical conductivity, dielectric, and temperature sensors, may be included in the ~~penetrometer~~cone to provide ~~useful~~additional information. The use of an inclinometer is ~~highly~~ recommended since it will provide information on potentially damaging situations during the sounding process.

1.5 ~~Cone penetration test~~ CPT data can be used to interpret subsurface stratigraphy, and through use of site specific correlations, they can provide data on engineering properties of soils intended for use in design and construction of earthworks and foundations for structures.

1.6 *Units*—The values stated in SI units are to be regarded as standard. ~~Within Section 13 on Calculations, SI units are considered the standard. Other commonly used units such as the inch-pound system are shown in brackets. The various data reported should be displayed in mutually compatible units as agreed to by the client or user. Cone tip projected area is commonly referred to in square centimetres for convenience. The values stated in each system are not equivalents; therefore, each system shall be used independently of the other.~~ No other units of measurement are included in this standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method

~~NOTE 1—This test method does not include hydraulic or pneumatic penetrometers. However, many of the procedural requirements herein could apply to those penetrometers. Also, offshore/marine CPT systems may have procedural differences because of the difficulties of testing in those environments (for example, tidal variations, salt water, waves). Mechanical CPT systems are covered under Test Method D3441.~~

1.7 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026, unless superseded by this test method.

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

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.02 on Sampling and Related Field Testing for Soil Evaluations.

Current edition approved ~~Jan. 1, 2012~~June 1, 2020. Published ~~February 2012~~July 2020. Originally approved in 1995. Last previous edition approved in ~~2007~~2012 as D5778 ~~–07.~~ –12. DOI: ~~10.1520/D5778-12.~~10.1520/D5778-20.

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

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

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D3441 Test Method for Mechanical Cone Penetration Testing of 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

D6026 Practice for Using Significant Digits in Geotechnical Data

D7400 Test Methods for Downhole Seismic Testing

~~E4 Practices for Force Verification of Testing Machines~~

3. Terminology

~~3.1 *Definitions:*~~

~~3.1.1 Definitions are in accordance with Terminology Convention (D653).~~

3.1 *Definitions:*

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *apparent load ~~transfer—~~transfer, n—*~~apparent~~ resistance measured on either the ~~cone~~tip or friction sleeve of ~~an electronic~~a friction cone ~~penetrometer~~ while that element is in a no-load condition but the other element is loaded. ~~Apparent load transfer is the sum of cross talk, subtraction error, and mechanical load transfer.~~

3.2.2 *~~baseline—~~baseline, n—*a set of zero load ~~readings, expressed in terms of apparent resistance,~~ readings that are used as reference values during performance of testing and calibration.

3.2.3 *cone ~~tip—~~tip, n—*the conical point of a cone ~~penetrometer~~ on which the end bearing ~~component of penetration~~ resistance is developed. ~~The cone has a 60° apex angle, a diameter of 35.7 mm, and a corresponding projected (horizontal plane) surface area or cone base area of 10 cm^2. Also, enlarged cones of 43.7 mm diameter (base area = 15 cm^2) are utilized.~~

3.2.4 *cone penetration ~~test—~~test, n—*~~a series of penetration readings performed at one location over the entire vertical depth when using a cone penetrometer.~~ pushing of a cone at the end of a series of cylindrical push rods into the ground at a constant rate of penetration. Also referred to as a cone sounding.

3.2.5 *cone, ~~penetrometer—~~n—*~~a penetrometer in which the leading end of the penetrometer tip is a conical point designed for penetrating soil and for measuring the end-bearing component of penetration resistance.~~ assembly containing the cone tip, friction sleeve, any other sensors and measuring systems as well as the connection to the push rods.

3.2.6 *cone tip resistance, q_c~~—~~, n—*the measured end-bearing component of ~~penetration resistance. The resistance to penetration developed on the cone is~~cone resistance, equal to the vertical force applied to the cone tip divided by the cone base area.

3.2.7 *corrected total cone tip resistance, q_t~~—~~, n—*cone tip resistance corrected for water pressure acting behind the cone tip (see ~~13.2.1~~13.1.1). ~~Correction for water pressure requires measuring water pressures with a piezocone element positioned behind the tip at location u_2 (See section 3.2.26). The correction results in estimated total tip resistance, q_t.~~

3.2.7.1 *Discussion—*

Correction for water pressure requires measuring water pressures with a piezocone element positioned behind the cone tip at location u_2 (See section 3.2.20).

~~3.2.8 *cross talk*—an apparent load transfer between the cone and the friction sleeve caused by interference between the separate signal channels.~~

3.2.8 *electronic cone, ~~penetrometer—~~n—*a ~~friction~~ cone ~~penetrometer that uses force transducers, such as strain gauge load cells, built into a non-telescoping penetrometer tip for measuring, within the penetrometer tip, the components of penetration resistance.~~that uses transducers to obtain the measurements.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.9 *electronic piezocone*, ~~*penetrometer*—~~*n—*an electronic cone ~~penetrometer equipped with a low volume fluid chamber, porous element, and pressure transducer for determination of porewater pressure at the porous element soil interface measured simultaneously with end bearing and frictional components of penetration~~ that can measure the pore water pressure simultaneously with the cone tip resistance and the friction sleeve resistance.

~~3.2.11 *end bearing resistance*—same as cone resistance or tip resistance, q_c.~~

3.2.10 *equilibrium pore water pressure, u_0*~~—~~*, n—*at rest water pressure at depth of interest. Also referred to as piezometric pressure.

3.2.11 *excess pore water pressure,* ~~*Δu*—~~*Δu, n—*~~the difference between porewater pressure measured as the penetration occurs~~ (pore water pressure in excess of the equilibrium pore water pressure caused by the penetration of the~~u), and estimated equilibrium porewater pressure (u~~ cone into the ground.~~$_0$), or: Δu = (u – u_0). Excess porewater pressure can either be positive or negative for shoulder position filters.~~

3.2.11.1 *Discussion—*

Excess pore water pressure can either be positive or negative for filters with a piezocone element positioned behind the cone tip at location u_2 (see 3.2.20).

~~3.2.14 *friction cone penetrometer*—a cone penetrometer with the capability of measuring the friction component of penetration resistance.~~

3.2.12 *friction ratio, R_f*~~—~~*, n—*the ratio of the friction sleeve resistance, f_s, to the cone tip resistance, q_c, with the latter measured at ~~where the~~ the depth for the middle of the friction ~~sleeve and cone point are at the same depth,~~ sleeve, expressed as a percentage.

NOTE 1—Some methods to interpret CPT data use friction ratio defined as the ratio of sleeve friction, f_s, to cone tip resistance corrected for pore pressure effects q_t, (**1**). It is not within the scope of this standard to recommend which methods of interpretation are to be used.

3.2.13 *friction* ~~*reducer*—~~*reducer, n—*~~a narrow local protuberance on the outside of the push rod surface, placed at a certain distance above the penetrometer tip, that is provided to reduce the total side friction on the push rods and allow for greater penetration depths for a given push capacity.~~ local and symmetrical enlargement of the diameter of a push rod to obtain a reduction of the friction along the push rods.

3.2.14 *friction* ~~*sleeve*—~~*sleeve, n—*an isolated cylindrical ~~sleeve~~ section ~~on~~of a ~~penetrometer tip~~ cone upon which the friction component of penetration resistance develops. ~~The friction sleeve has a surface area of 150 cm^2 for 10-cm^2 cone tips or 225 cm^2 for 15-cm^2 tips.~~

3.2.15 *friction sleeve resistance, f_s*~~—~~*, n—*the friction component of ~~penetration~~cone resistance developed on a friction sleeve, equal to the shear force applied to the friction sleeve divided by ~~its surface area.~~the friction sleeve surface area. Also referred to as local side friction or sleeve friction.

3.2.16 ~~*FSO*—~~*full-scale output, n—*~~abbreviation for full-scale output. The~~ the output of an electronic ~~force~~ transducer when loaded to 100 % rated capacity.

3.2.17 ~~*local side*~~*measuring system,* ~~*friction*—~~*n—*~~same as friction sleeve resistance, f~~all sensors and auxiliary parts used~~$_s$ (see 3.2.18).~~to transfer and/or store the electrical signals generated during the cone penetration test.

3.2.17.1 *Discussion—*

The measuring system normally includes components for measuring force (cone resistance, sleeve friction), pressure (pore pressure), inclination, clock time and penetration length.

~~3.2.21 *penetration resistance measuring system*—a measuring system that provides the means for transmitting information from the penetrometer tip and displaying the data at the surface where it can be seen or recorded.~~

3.2.18 ~~*penetrometer*—~~*penetration depth, n—*~~an apparatus consisting of a series of cylindrical push rods with a terminal body (end section), called the penetrometer tip, and measuring devices for determination of the components of penetration resistance.~~ vertical depth of the base of the cone, relative to a fixed point.

3.2.19 ~~*penetrometer tip*—~~*penetration length, n—*~~the terminal body (end section) of the penetrometer which contains the active elements that sense the components of penetration resistance. The penetrometer tip may include additional electronic instrumentation for signal conditioning and amplification.~~ sum of the lengths of the push rods and the cone.

~~3.2.24 *piezocone*—same as *electronic piezocone penetrometer* (see 3.2.10).~~

~~3.2.25 *piezocone porewater pressure, u*—fluid pressure measured using the piezocone penetration test.~~

3.2.20 *piezocone porewater pressure measurement location: u_1, u_2, u_3—, n—*fluid pressure measured by the piezocone penetrometer at specific locations on the penetrometer as follows (**2**, **3**, **4**)[3]: u_1—porous filter location on the midface or tip of the cone, u_2—porous filter location at the shoulder position behind the in the cylindrical extension of the cone tip (standard location) and, u_3—porous filter location behind the friction sleeve.

3.2.21 *porewater pressure—pore water pressure, n—*total porewaterpore water pressure magnitude measured during penetration penetration.(same as 3.2.25 above).

3.2.22 *porewater pressure ratio parameter, pore water pressure ratio, B_q—, n—*the ratio of excess porewater pressure at the standard measurement location pore water pressure, Δu_2, measured with a piezocone element positioned behind the cone tip at location u_2 (see 3.2.20) to corrected total cone tip resistance q_t, minus the total vertical overburden stress, σ_{vo}. (see Eq 10).

3.2.23 *push rods—rods, n—*the thick-walled tubes or rods used to advance the penetrometer tip.cone.

3.2.30 *sleeve friction, sleeve, and friction resistance*—same as friction sleeve resistance.

3.2.31 *subtraction error*—an apparent load transfer from the cone to the friction sleeve of a subtraction type electronic cone penetrometer caused by minor voltage differences in response to load between the two strain element cells.

3.3 *Abbreviations:*

3.3.1 *CPT*—abbreviation for the cone penetration test.

3.3.2 *PCPT FSO—(2, 3) or CPTu (4)*—abbreviation for piezocone penetration test (note: symbol "u" added for porewater pressure measurements).full scale output.

3.3.3 *CPTù—MO—*abbreviation for the piezocone penetration test with dissipation phases of porewater pressures (ù).measured output.

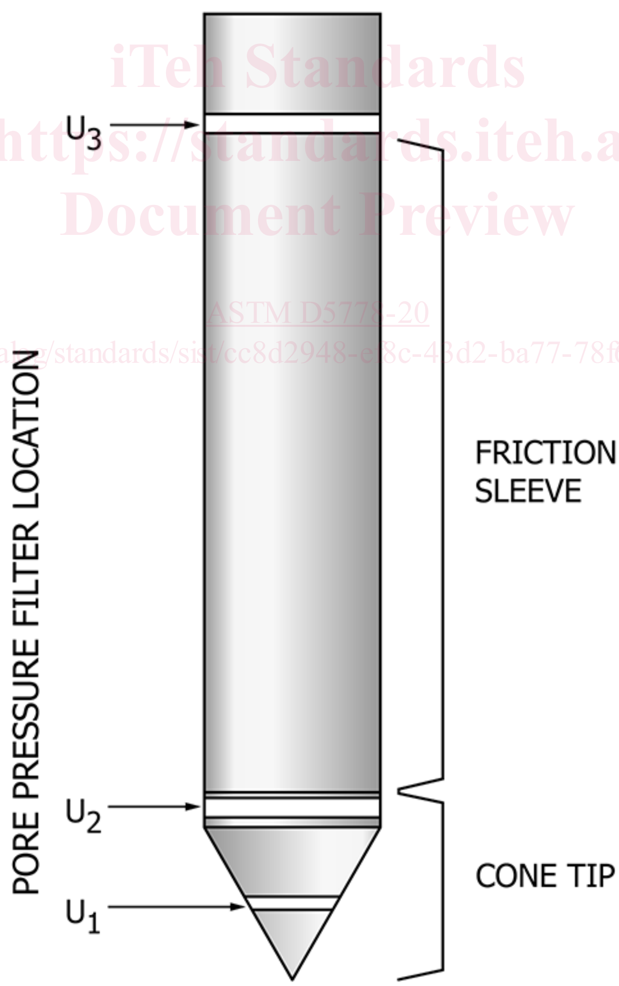

FIG. 1 Piezocone Pore Water Pressure Measurement Locations (courtesy ConeTec Data Services)

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

~~3.3.4 *SCPTu*—abbreviation for seismic piezocone test Test Methods D7400 (includes one or more geophones to allow downhole geophysical wave velocity measurements).~~

~~3.3.5 *RCPTu*—abbreviation for resistivity piezocone (includes electrical conductivity or resistivity module).~~

4. Summary of Test Method

4.1 A ~~penetrometer tip with a conical point having a 60° apex angle and a cone base area of 10 or 15 cm~~cone ^{2}is advanced through the soil at a constant rate of 20 mm/s. The force on the ~~conical point (cone)~~ cone tip required to penetrate the soil is measured ~~by electrical methods, at a minimum of every 50 mm of penetration. Improved resolution may often be obtained at 20- or 10-mm interval readings. Stress is calculated by dividing the measured force (total cone force) by~~using an electric transducer. The cone tip resistance ~~*the*~~q_c ~~cone base area to obtain cone resistance,~~is calculated by dividing the vertical force ~~q~~applied~~$_c$.~~ to the cone tip by the cone base area.

4.2 A friction sleeve is present on the ~~penetrometer~~cone immediately behind the cone tip, and the force exerted on the friction sleeve is measured ~~by electrical methods at a minimum of every~~using an electric transducer. The friction sleeve resistance, ~~*50*~~f_s ~~mm of penetration. Stress is calculated by dividing the measured axial force~~is calculated by dividing the shear force applied to the friction sleeve by the surface area of the friction ~~sleeve to determine sleeve resistance,~~ sleeve. ~~f_s.~~

4.3 Most modern ~~penetrometers~~cones are capable of registering pore water pressure induced during advancement of the ~~penetrometer tip~~ cone using an ~~electronic~~electric pressure transducer. These ~~penetrometers~~cones are ~~called "piezocones." The piezocone is advanced at a rate of 20 mm/s, and readings are taken at a minimum of every 50 mm of penetration.~~ formally called "electronic piezocones," but given their prevalence they are often simply referred to as "cones." The dissipation of either positive or negative excess ~~porewater~~ pore water pressure can be monitored by stopping penetration, unloading the push ~~rod,~~rods, and recording ~~porewater~~ pore water pressure as a function of time. When ~~porewater~~ pore water pressure becomes constant it is measuring the equilibrium value (designated u_0) ~~or piezometric level~~ at that depth.

4.4 The forces and, if applicable, pressure readings are taken at penetration length intervals of no more than 50 mm. Improved resolution may often be obtained at 20- or 10-mm interval readings.

5. Significance and Use

5.1 Tests performed using this test method provide a detailed record of cone ~~resistance~~ tip resistance, which is useful for evaluation of site stratigraphy, engineering properties, homogeneity and depth to firm layers, voids or cavities, and other discontinuities. The use of a friction sleeve and ~~porewater~~ pore water pressure element can provide an estimate of soil classification, and correlations with engineering properties of soils. When properly performed at suitable sites, the test provides a rapid means for determining subsurface conditions.

5.2 This test method provides data used for estimating engineering properties of soil intended to help with the design and construction of earthworks, the foundations for structures, and the behavior of soils under static and dynamic loads.

5.3 This method tests the soil ~~in-situ~~ in situ and soil samples are not ~~obtained.~~ obtained during the test. The interpretation of the results from this test method provides estimates of the types of soil penetrated. Engineers may obtain soil samples from parallel borings for correlation purposes but prior information or experience may preclude the need for borings.

NOTE 2—The quality of the results produced by this standard is dependent on the competence of the personal performing the test, 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 and Practice D3740 provides a means of evaluating some of those factors.

6. Interferences

6.1 Refusal, deflection, or damage to the ~~penetrometer~~cone may occur in coarse grained soil deposits with maximum particle sizes that approach or exceed the diameter of the cone.

6.2 Partially lithified and lithified deposits may cause refusal, deflection, or damage to the ~~penetrometer.~~cone.

6.3 ~~Standard push~~ Push rods can be damaged or broken under extreme loadings. The amount of force that push rods are able to sustain is a function of the unrestrained length of the rods and the weak links in the ~~push rod-penetrometer tip string~~ string, such as push rod joints and push ~~rod-penetrometer tip~~ rod-cone connections. The force at which rods may break is a function of the equipment configuration and ground conditions during penetration. Excessive rod deflection is the most common cause for rod breakage.

7. Apparatus

7.1 *Cone*—The cone shall meet requirements as given below and in 10.1. In a conventional cone, the forces at the cone tip and friction sleeve are measured by two load cells within the cone. (Fig. 2)

7.1.1 In the subtraction-type cone (Fig. 2a) the cell nearest the cone tip measures the compressive force on the cone tip, while the second cell measures the sum of the compressive forces on both the cone tip and friction sleeve. The compressive force from

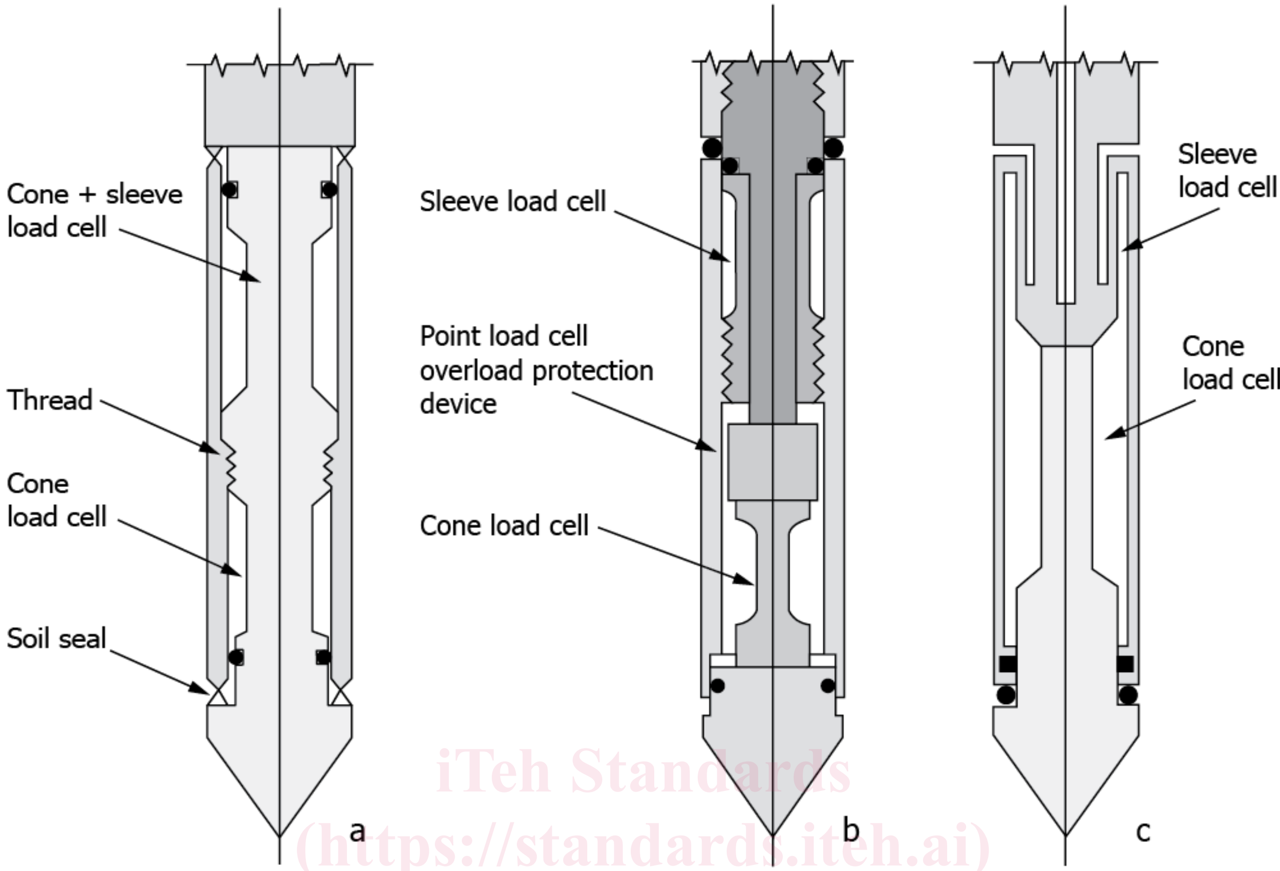

FIG. ~~1~~2 ~~Common~~ Configurations for Electric Friction-Cone Penetrometers (1) Showing: (a) ~~Compression-type Tip and Sleeve Load Cells, (b) Tension-type Sleeve Design, and (c) Subtraction-type Penetrometer~~Subtraction type, (b) Compression type, and (c) Tension type (courtesy ConeTec Data Services)

the friction sleeve portion is then computed by subtraction. This cone design is common in the industry because of its rugged design, even though the calculated friction sleeve force may not be as accurate since it is very small compared to the cone tip force.

7.1.2 In the compression-type cone (Fig. 2b) there are separate load cells for the cone tip and the friction sleeve. This design results in a higher degree of accuracy in friction sleeve measurement, but may be more susceptible to damage under extreme loading conditions.

7.1.3 Designs are also available where both the cone tip and sleeve load cells are separate, but where the load cell for the friction sleeve operates in tension (Fig. 2c).

7.1.4 Typical general purpose electronic cones are manufactured to full scale outputs (FSO) equivalent to net loads of 100 to 200 kN. Often, weak soils are the most critical in an investigation program, and to gain better resolution, the FSO can be lowered. However, this may place electrical components at risk if overloaded in stronger soils, in which case pre-boring may be required to avoid damage. The selection of cone type and resolution should consider such factors as practicality, availability, calibration requirements, cost, risk of damage, and preboring requirements.

7.2 *Cone Tip*—Nominal dimensions, with manufacturing and operating tolerances, for the cone are shown on Fig. 3.

NOTE 3—In some applications it may be desirable to scale the cone diameter down to a smaller projected area. Cones with 5 cm^2 projected area find use in the field applications and even smaller sizes (1 cm^2) are used in the laboratory for research purposes. These cones should be designed with dimensions adjusted proportionally to the square root of the diameter ratio. In thinly layered soils, the diameter affects how accurately the layers may be sensed. Smaller diameter cones may sense thinner layers more accurately than larger cones.

7.2.1 The cone tip is made of high strength steel of a type and hardness suitable to resist wear due to abrasion by soil. Cone tips that have worn to the operating tolerance shown in Fig. 3 shall be replaced.

7.3 *Friction Sleeve*—The outside diameter of the manufactured friction sleeve and the operating diameter are equal to the diameter of the base of the cone with a tolerance of +0.35 mm and −0.0 mm, but not more than 36.1 mm for a 10-cm^2 cone and 44.2 mm for a 15-cm^2 cone. The friction sleeve is made from high strength steel of a type and hardness to resist wear due to abrasion by soil. Chrome-plated steel is not recommended due to differing frictional behavior. The surface area of the friction sleeve is 150 cm^2 ± 2 % for a 10-cm^2 cone and 225 cm^2 ± 2 % for a 15-cm^2 cone. If it has been demonstrated that comparable results are obtained, the surface area of the friction sleeve for a 15-cm^2 cone can be adjusted to a minimum of 200 cm^2 ± 2 %.

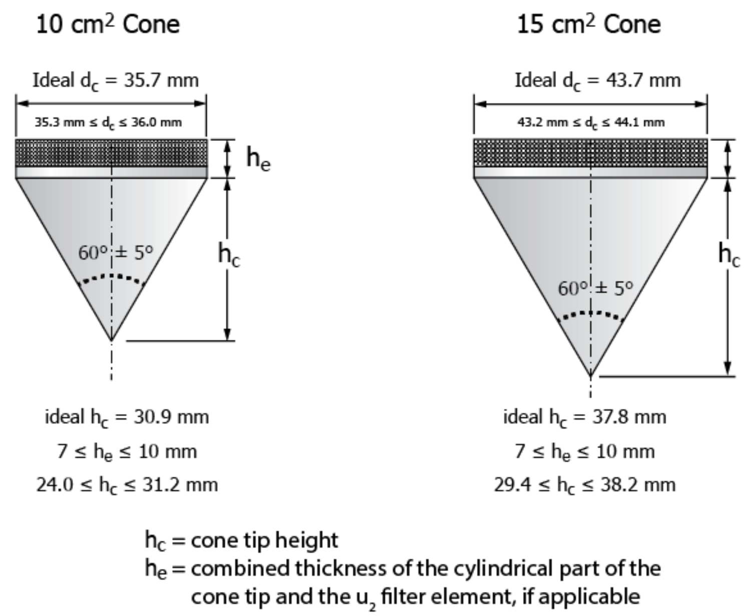

FIG. ~~2~~3 Manufacturing and Operating Tolerances of ~~Cones~~ Cone Tips (5) (courtesy ConeTec Data Services)

NOTE 4—If the cone base area is altered to other values, as provided for in Note 2, the surface area of the friction sleeve should be adjusted proportionally to the cone base area ratio.

7.3.1 The top diameter of the sleeve must not be smaller than the bottom diameter or significantly lower sleeve resistance will occur. The top and bottom of the sleeve should be periodically checked for wear with a suitable tool. Normally, the top of the sleeve will wear faster than the bottom. Friction sleeves that have worn to the operating tolerance shall be replaced.

7.3.2 Friction sleeves must be designed with equal end areas, which are exposed to water pressures (**1**, **5**, **6**, **7**, **8**). This will remove the tendency for unbalanced end forces to act on the sleeve. Sleeve design must be checked in accordance with A1.6 to ensure proper response.

7.4 *Gap*—The gap (annular space) between the cylindrical extension of the cone tip base and the other elements of the cone shall be kept to the minimum necessary for operation of the sensing devices and shall be designed and constructed in such a way to prevent the entry of soil particles. These gap requirements also apply to the gaps at either end of the friction sleeve and to other elements of the cone.

7.4.1 The gap between the cylindrical extension of the cone tip and other elements of the cone must not be larger than 5 mm.

7.4.2 If a seal is placed in the gap, it should be properly designed and manufactured to prevent entry of soil particles. It must have a deformability at least two orders of magnitude greater than the material comprising the load transferring components of the sensing devices in order to prevent load transfer from the cone tip to the sleeve.

7.5 *Diameter Requirements*—The cone shall have the same diameter as the cone tip (that is, equal to the diameter of the base of the cone with a tolerance of +35 mm and –0.0 mm, but not more than 36.1 mm for a 10-cm^2 cone and 44.2 mm for a 15-cm^2 cone) for the complete length of the cone (**5**, **9**, **10**).

7.5.1 For some cone designs, it may be desirable to increase the diameter of the cone body to house additional sensors or reduce friction along push rods. These diameter changes are acceptable if they do not have significant influence on tip and sleeve data, and therefore these diameter changes shall be at least 400 mm from the cylindrical extension of the cone tip base for a 10-cm^2 cone and 500 mm for a 15-cm^2 cone. If the cone diameter is not constant, information on diameters of the complete cone shall be reported.

NOTE 5—The effects caused by cone diameter changes on tip and sleeve resistance are dependent on the magnitude of diameter increase, location, and soil conditions. If there is question regarding a specific design with diameter increases, comparison studies can be made to a cone with constant diameter. Most practitioners feel that diameter increases equivalent to addition of a friction reducer with area increases of 15 to 20 % should be restricted to a location at least eight to ten cone diameters behind the friction sleeve.

7.6 *Cone Axis*—The axis of the cone tip, the friction sleeve, and the remainder of the cone must be coincident.

7.7 *Force Sensing Devices*—The typical force sensing device is a strain gauge load cell that contains temperature compensated bonded strain gauges. The configuration and location of strain gauges should be such that measurements are not influenced by possible eccentricity of loading.

7.7.1 The transducers shall have an accuracy of at least ±100 kPa or 5 % of the reading (whichever is larger), except if the transducer is dedicated to measuring the friction sleeve resistance, in which case the precision shall be at least 15 kPa or 15 % of the reading (whichever is larger).

7.8 ~~*Friction Cone Penetrometer—*~~*Electronic Piezocone—*~~The penetrometer tip should meet requirements as given below and in~~A piezocone can contain porous filter element(s), pressure transducer(s), and fluid ~~10.1. In a conventional friction-type cone penetrometer, the forces at the cone tip and friction sleeve are measured~~filled ports connecting the elements to the transducer to measure pore water pressure. Fig. 4 ~~by two load cells within the penetrometer. Either independent load~~shows some common design types used in practice for 10-cm^2 ~~cells or~~and 15-cm^2 ~~subtraction-type penetrometers are acceptable for use (~~piezocones (with ideal dimensions). ~~Fig. 1).~~

7.8.1 ~~In the subtraction-type penetrometer, the cone and sleeve both produce~~The pore water pressure measurement location of the porous element shall be either in the cone tip (Type 1 or ~~*compressive*~~u_1 ~~forces on the load cells. The load cells~~), immediately behind the cone tip (Type 2 or ~~*are*~~u_2 ~~joined together in such a manner that the cell~~) or immediately behind the friction sleeve (Type 3 or ~~*nearest*~~u_3 ~~the cone (the "C" cell in~~). Some piezocones used for research purposes ~~Fig. 1b~~may~~) measures the compressive force on~~ have multiple measurement locations. The Type 2 piezocone is preferred to allow correction of tip resistances. Moreover, this type is less subject to damage and abrasion, and shows fewer compressibility effects (**1, 8**).~~the cone while the second cell (the "C + S" cell~~ However, Type 2 cones may be subject to cavitation at shallow depths in dense soils because the zone behind the height of cylindrical extension is a zone of dilation in ~~Fig. 1~~drained soils. Similar response can occur in stiff fissured clays and crusts ~~b~~(**1**).~~) measures~~ Pore water pressure measurements obtained at the ~~*sum*~~u_1 ~~of the compressive forces on both the cone and friction sleeve. The compressive force from the friction sleeve portion is computed then by subtraction. This cone design is common in industry because of its rugged design. This design forms the basis for minimum performance~~location are more effective for dissipation readings, compressibility determinations and layer detection, particularly in fissured soils and materials prone to cause cavitation of Type 2 piezocones, but are more subject to wear and damage ~~**requirements**~~(**4, 11**~~**for**~~).~~electronic penetrometers.~~

~~7.1.1.1 Alternative designs have separate and non-dependent load cells separate for tip and sleeve. For instance, in Fig. 1*a*, the cone penetrometer tip produces a compression force on the cone load cell (the "C" cell in Fig. 1*a*) while the friction sleeve produces a tensile force on the independent friction sleeve load cell (the "S" cell). Designs are also available where both the tip~~

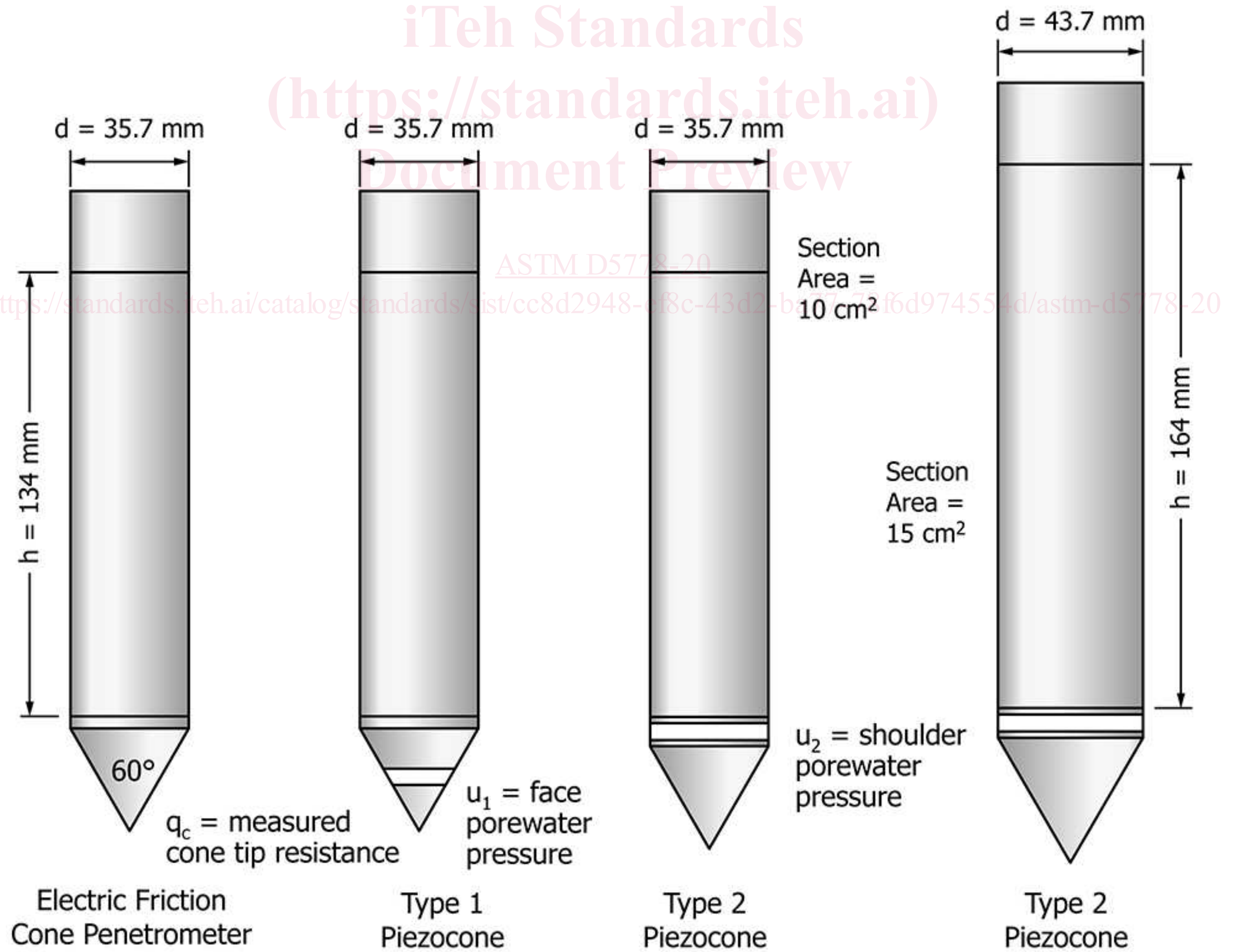

FIG. ~~3~~4 ~~Penetrometer~~Cone Design Configurations: (a) Electronic Friction-type, (b) Type 1 Piezocone, (c) Standard 10-cm^2 Type 2 Piezocone, and (d) 15-cm^2 Type 2 Version (7) (courtesy ConeTec Data Services)

and sleeve load cells are independent and operate in compression (**1**). These penetrometer designs result in a higher degree of accuracy in friction sleeve measurement, however, may be more susceptible to damage under extreme loading conditions.

7.1.1.2 Typical general purpose cone penetrometers are manufactured to full scale outputs (FSO) equivalent to net loads of 10 to 20 tons. Often, weak soils are the most critical in an investigation program, and in some cases, very accurate friction sleeve data may be required. To gain better resolution, the FSO can be lowered or the independent type penetrometer design can be selected. A low FSO subtraction cone may provide more accurate data than a standard FSO independent type cone depending on such factors as system design and thermal compensation. If the FSO is lowered, this may place electrical components at risk if overloaded in stronger soils. Expensive preboring efforts may be required to avoid damage in these cases. The selection of penetrometer type and resolution should consider such factors as practicality, availability, calibration requirements, cost, risk of damage, and preboring requirements.

7.1.1.3 The user or client should select the cone design requirements by consulting with experienced users or manufacturers. The need for a specific cone design depends on the design data requirements outlined in the exploration program.

7.1.1.4 Regardless of penetrometer type, the friction sleeve load cell system must operate in such a way that the system is sensitive to only shear stresses applied to the friction sleeve and not to normal stresses.

7.1.2 *Cone*—Nominal dimensions, with manufacturing and operating tolerances, for the cone are shown on Fig. 2. The cone has a diameter d = 35.7 mm, projected base area A_c = 1000 mm^2, + 2 %–5 % with an apex angle of 60°. A cylindrical extension, h_e, of 5 mm should be located behind the base of the cone to protect the outer edges of the cone base from excessive wear. The 10 cm^2 cone is considered the reference standard for which results of other penetrometers with proportionally scaled dimensions can be compared.

7.1.2.1 In certain cases, it may be desirable to increase the cone diameter in order to add room for sensors or increase ruggedness of the penetrometer. The standard increase is to a base diameter of 43.7 mm which provides a projected cone base area of 1500 mm^2 while maintaining a 60° apex angle. Nominal dimensions, with manufacturing and operating tolerances for the 15 cm^2 cone, are shown in Fig. 2, based on the international guides (**5**).

7.1.2.2 The cone is made of high strength steel of a type and hardness suitable to resist wear due to abrasion by soil. Cone tips which have worn to the operating tolerance shown in Fig. 2 should be replaced. Piezocone tips should be replaced when the tip has worn appreciably (as shown) and the height of the cylindrical extension has reduced considerably (as shown).

NOTE 4—In some applications it may be desirable to scale the cone diameter down to a smaller projected area. Cone penetrometers with 5 cm^2 projected area find use in the field applications and even smaller sizes (1 cm^2) are used in the laboratory for research purposes. These cones should be designed with dimensions scaled in direct proportion to standard 10-cm^2 penetrometers. In thinly layered soils, the diameter affects how accurately the layers may be sensed. Smaller diameter cones may sense thinner layers more accurately than larger cones. If there are questions as to the effect of scaling the penetrometer to either larger or smaller size, results can be compared in the field to the 10-cm^2 penetrometer for soils under consideration. This is because the 10-cm^2 cone is considered the reference penetrometer for field testing.

7.1.3 *Friction Sleeve*—The outside diameter of the manufactured friction sleeve and the operating diameter are equal to the diameter of the base of the cone with a tolerance of +0.35 mm and −0.0 mm. The friction sleeve is made from high strength steel of a type and hardness to resist wear due to abrasion by soil. Chrome-plated steel is not recommended due to differing frictional behavior. The surface area of the friction sleeve is 150 cm^2 ± 2 %, for a 10-cm^2 cone. If the cone base area is increased to 15 cm^2, as provided for in 7.1.2.1, the surface area of the friction sleeve should be adjusted proportionally, with the same length to diameter ratio as the 10-cm^2 cone. With the 15-cm^2 tip, a sleeve area of 225 cm^2 is similar in scale.

7.1.3.1 The top diameter of the sleeve must not be smaller than the bottom diameter or significantly lower sleeve resistance will occur. During testing, the top and bottom of the sleeve should be periodically checked for wear with a micrometer. Normally, the top of the sleeve will wear faster than the bottom.

7.1.3.2 Friction sleeves must be designed with equal end areas which are exposed to water pressures (**1**, **5**, **6**, **7**, **8**). This will remove the tendency for unbalanced end forces to act on the sleeve. Sleeve design must be checked in accordance with A1.7 to ensure proper response.

7.1.4 *Gap*—The gap (annular space) between the cylindrical extension of the cone base and the other elements of the penetrometer tip should be kept to the minimum necessary for operation of the sensing devices and should be designed and constructed in such a way to prevent the entry of soil particles. Gap requirements apply to the gaps at either end of the friction sleeve and to other elements of the penetrometer tip.

7.1.4.1 The gap between the cylindrical extension of the cone base and other elements of the penetrometer tip, e_c, must not be larger than 5 mm for the friction cone penetrometer.

7.1.4.2 If a seal is placed in the gap, it should be properly designed and manufactured to prevent entry of soil particles into the penetrometer tip. It must have a deformability at least two orders of magnitude greater than the material comprising the load transferring components of the sensing devices in order to prevent load transfer from the tip to the sleeve.

7.1.4.3 *Filter Element in the Gap*—If a filter element for a piezocone is placed in the gap between cone and sleeve the sum of the height of cylindrical extension, h_e, plus element thickness filling the gap, e_c, can range from 8 to 20 mm (see 7.1.8 for explanation).

7.1.5 *Diameter Requirements*—The friction sleeve should be situated within 5 to 15 mm behind the base of the cone tip. The annular spaces and seals between the friction sleeve and other portions of the penetrometer tip must conform to the same specifications as described in 7.1.4. Changes in the diameter of the penetrometer body above the friction sleeve should be such that tip or sleeve measurements are not influenced by increases in diameter. International reference test procedures require that the penetrometer body have the same diameter as the cone for the complete length of the penetrometer body (**5**, **9**, **10**).

7.1.5.1 For some penetrometer designs, it may be desirable to increase the diameter of the penetrometer body to house additional sensors or reduce friction along push rods. These diameter changes are acceptable if they do not have significant influence on tip and sleeve data. If there is question regarding a specific design with diameter increases, comparison studies can be made to a penetrometer with constant diameter. Information on diameters of the complete penetrometer body should be reported.

NOTE 5—The effects caused by diameter changes of the penetrometer on tip and sleeve resistance are dependent on the magnitude of diameter increase and location on the penetrometer body. Most practitioners feel that diameter increases equivalent to addition of a friction reducer with area increases of 15 to 20 % should be restricted to a location at least eight to ten cone diameters behind the friction sleeve.

7.1.6 The axis of the cone, the friction sleeve (if included), and the body of the penetrometer tip must be coincident.

7.1.7 *Force Sensing Devices*—The typical force sensing device is a strain gauge load cell that contains temperature compensated bonded strain gages. The configuration and location of strain gages should be such that measurements are not influenced by possible eccentricity of loading.

7.8.2 *Electronic Piezocone Penetrometer*—A piezocone penetrometer can contain porous filter element(s), pressure transducer(s), and fluid filled ports connecting the elements to the transducer to measure pore water pressure. Fig. 3 shows the common design types used in practice including: 10-cm^2 friction-type, type 1 and type 2 piezocone, and 15-cm^2 size. The standard penetrometer should be the type 2 piezocone with filter located at the shoulder (both 10-cm^2 and 15-cm^2) to allow correction of tip resistances. The electric friction penetrometer without porewater transducers can be used in soils with minor porewater pressure development, such as clean sands, granular soils, as well as soils and fills well above the groundwater table. The type 1 with face filter element finds use in fissured geomaterials and materials prone to desaturation, as well as dissipation readings. Numerous design and configuration aspects can affect the measurement of dynamicpore water pressures. Variables such as the element location, design and volume of ports, and the type and degree of saturation of the fluids, cavitation of the element fluid system and resaturation lag time, depth and saturation of soil during testing all affect the dynamic porewaterpore water pressure measured during testing and dissipation tests of dynamic pore water pressures (**2**, **3**, **4**, **8**). It is beyond the scope of the procedure to address all of these variables. As a minimum, complete information shouldshall be reported as to the design, configuration, and the preparation of the piezocone system that is used for the particular sounding.

7.1.8.1 Measurement of hydrostatic water pressures during pauses in testing are more straightforward. The presence of air entrained in the system only affects dynamic response. In high permeability soils (that is, clean sands), hydrostatic pressures will equalize within seconds or minutes. In low permeability materials such as high plasticity clays, equalization can take many hours. If the goal of the exploration program is only to acquire hydrostatic pressures in sands, some of the preparation procedures for dynamic pressure measuring can be relaxed, such as deairing fluids.

7.1.8.2 The porewater pressure measurement locations of the porous element are limited to the face or tip of the cone, u_1, directly behind the cylindrical extension of the base of the cone, u_2, or behind the sleeve, u_3. Some penetrometers used for research purposes may have multiple measurement locations.

7.1.8.3 There are several advantages to locating the porous element immediately behind the tip of the cone in location u_2, primarily the required correction of measured q_c to total tip stress, q_t, as detailed extensively (**4-8**). Also, the element is less subject to damage and abrasion, as well as fewer compressibility effects (**4**, **8**). Elements located in the u_2 location may be subject to cavitation at shallow depths in dense sands because the zone behind the height of cylindrical extension is a zone of dilation in drained soils. Similar response can occur in stiff fissured clays and crusts (**4**). Porewater pressure measurements obtained at the u_1 face location are more effective for compressibility determinations and layer detection, particularly in fissured soils, but are more subject to wear (**3**, **11**). At the u_2 location, a minimum 2-mm cylindrical extension of the cone tip (h_e) should be maintained for protection of the cone. Typical filter element thickness at all locations in the horizontal plane ranges from 5 to 10 mm.

7.1.8.4 The miniature diaphragm-type electronic pressure transducer is normally housed near the tip of the cone. For dynamic pressure measurements, the filter and ports are filled with deaired fluid to measure dynamic porewater pressure response. The volume of connecting ports to the transducer should be minimized to facilitate dynamic pressure response. These electronic transducers are normally very reliable, accurate, and linear in response. The transducer shall have a precision of at least ±14 kPa (±2 psi). The porewater pressure transducer must meet requirements given in 10.2.

7.1.8.5 *Element*—The element is a fine porous filter made from plastic, sintered steel or bronze, or ceramic. Typical pore size is between 20 to 200 microns (**8**, **11**). Different materials have different advantages. Smearing of metallic element openings by hard soil grains may reduce dynamic response of the system, thus normally not used for face elements but best suited for shoulder filter positions. Ceramic elements are very brittle and may crack when loaded, but perform well on the cone face as they reduce compressibility concerns. Polypropylene plastic elements are most commonly used in practice, particularly at the shoulder. Plastic filters (as high-density polyethylene, HDPE, or high-density polypropylene, HDPP) may be inappropriate for environmental type CPTs where contaminant detection is sought. Typically, the filter element is wedged at the tip or midface (u_1) location, or located at the shoulder in the gap immediately above the cone extension (designated u_2) location. At these locations, it is important to design the penetrometer such that compression of the filter elements is minimized.

~~7.1.8.6 *Fluids for Saturation*—Glycerine, or alternatively silicone oil, is most often used for deairing elements for dynamic response. These stiff viscous oils have less tendency to cavitate, although cavitation may be controlled by the effective pore size of the element mounting surfaces. Water can be used for the fluid if the entire sounding will be submerged, or if dynamic response is not important. The fluids are deaired using procedures described in 11.2.~~

7.8.3 Measurement of equilibrium pore water pressures during pauses in testing are more straightforward. The presence of air entrained in the system only affects dynamic response. In high permeability soils (for example, clean sands or gravel), the pore water pressure will equalize the equilibrium pore pressure within seconds or minutes. In low permeability materials such as high plasticity clays, equalization can take many hours. If the goal of the exploration program is only to acquire equilibrium pore water pressures in sands, some of the preparation procedures for pore water pressure measuring can be relaxed, such as deairing fluids. However, such relaxation shall be reported in detail, including on each pore pressure graph generated with such relaxed preparation procedures.

7.8.4 The pressure transducer is normally housed near the cone tip. For dynamic pressure measurements, the filter and ports are filled with deaired fluid and the volume of connecting ports to the transducer should be minimized. The transducer shall have an accuracy of at least 25 kPa or 3 % of the reading (whichever is larger).

7.8.5 *Element*—The element is a fine porous filter made from plastic, sintered steel or bronze, or ceramic. The pore size should be less than 100 micron. Different materials have different advantages. Smearing of metallic element openings by hard soil grains may reduce dynamic response of the system, thus these elements are normally not used for Type 1 cones, but best suited for Type 2 or Type 3 cones. Ceramic elements are very brittle and may crack when loaded, but perform well for Type 1 cones as they reduce compressibility concerns. Polypropylene plastic elements are most commonly used in practice, particularly for Type 2 and Type 3 cones, but they may be inappropriate for environmental type CPTs where contaminant detection is sought.

7.8.6 *Fluids for Saturation*—Pure glycerine or silicone oil is most often applied for deairing elements that are used to measure the dynamic response. These stiff viscous oils have less tendency to cavitate, although cavitation may be controlled by the effective pore size of the element mounting surfaces. Water or water mixtures can be used for the fluid if the entire sounding will be submerged, or if the dynamic response is not important. The fluids are deaired using procedures described in 11.1.

7.9 ~~*Measuring*~~ Data Acquisition *System*—The signals from the ~~penetrometer~~cone transducers are to be displayed at the surface during testing as a continuously updated plot against ~~depth.~~ penetration length. The data are also to be recorded electronically ~~for subsequent processing. Electronic recording shall be digital and use at least twelve bit (one part in 4096) resolution in the analog to digital conversion, although 16-bit resolution and higher may be preferable in very soft ground. Either magnetic (disk or tape) or optical (disk) non-volatile storage may be used. In analog systems, the temperature stability and accuracy of the A-to-D converter shall be such that the overall cone-transmission-recording system complies with calibration requirements set forth in the annex.~~on the same data acquisition system for subsequent processing.

7.9.1 ~~Use of analog systems is acceptable but the system resolution may be lower than requirements in the annex and Section~~The electronic data files shall include project, location, operator, and data ~~10. Use of an analog recorder as a supplement to digital system is advantageous because it can provide system backup.~~format information (for example, channel, units, corrected or uncorrected, etc.) so that the data can be understood when reading the file with a text editor.

~~NOTE 6—Depending upon the equipment, data stored digitally on magnetic drives, tapes, floppy disks, or other media are often used. The data files should include project, location, operator, and data format information (for example, channel, units, corrected or uncorrected, etc.) so that the data can be understood when reading the file with a text editor.~~

7.10 *Push Rods*—Steel rods are required having a cross sectional area adequate to sustain, without buckling, the thrust required to advance the ~~penetrometer tip. For penetrometers using electrical~~cone. For systems that use cables, the cable is prestrung through the rods prior to testing. Push rods are typically supplied in 1-meter ~~lengths.~~ lengths, although other lengths are used as well. The push rods must be secured together to bear against each other at the joints and form a rigid-jointed string of push rods. ~~The deviation of push rod alignment from a straight axis should be held to a minimum, especially in the push rods near the penetrometer tip, to avoid excessive directional penetrometer drift. Generally, when a 1-m long push rod is subjected to a permanent circular bending resulting in 1 to 2 mm of center axis rod shortening, the push rod should be discarded. This corresponds to a horizontal deflection of 2 to 3 mm at the center of bending. The locations of push rods in the string should be varied periodically to avoid permanent curvature.~~Before a test is carried out, the linearity of the push rods should be checked. If any indications of bending appear, the use of the rods should be suspended.

7.10.1 For the 10-cm^2 ~~penetrometer, standard 20-metric ton high tensile strength~~ cone steel push rods are typically 36-mm outside diameter, 16-mm inside diameter, and have a mass per unit length of 6.65 kg/m. For 15-cm^2 ~~penetrometers,~~cones, the test ~~may be pushed~~is typically performed with 44.5-mm outside diameter rods or with standard rods used for the 10-cm^2 ~~penetrometer.~~cones, although other diameters are used as well.

7.11 *Friction Reducer*—Friction reducers are normally used on the push rods to reduce rod friction. If a friction reducer is used, it ~~should~~shall be located on the push rods no closer than ~~0.5 m~~400 mm behind the cone tip base of the 10-cm^2 cone and 500 mm behind the cone tip base of a 15-cm^2 cone. Friction reducers, that increase push rod outside diameter by approximately 25 %, are typically used for 10-cm^2 cones. If a 15-cm^2 ~~penetrometer~~cone is advanced with 36-mm push rods there may be no need for friction reducers since the ~~penetrometer~~cone itself will open a larger hole. The type, size, amount, and location of friction reducer(s) used during testing must be reported.