Designation: 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 resistance of a friction cone or a piezocone as it is advanced into subsurface soils at a steady rate.

1.2 This test method applies to 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 cones are covered elsewhere by Test Method D3441.

1.3 This test method can be used to determine pore water pressures developed during the 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 (Test Methods D7400), resistivity, electrical conductivity, dielectric, and temperature sensors, may be included in the cone to provide additional information. The use of an inclinometer is recommended since it will provide information on potentially damaging situations during the sounding process.

1.5 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. 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

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values shall conform to the guidelines for significant digits and rounding established in Practice D6026, unless superseded by this test method.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

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, health, and 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

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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.

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

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

D7400 Test Methods for Downhole Seismic Testing

3. Terminology

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, n*—resistance measured on either the tip or friction sleeve of a friction cone while that element is in a no-load condition but the other element is loaded.

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

3.2.3 *cone tip, n*—the conical point of a cone on which the end bearing resistance is developed.

3.2.4 *cone penetration test, n*—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, n*—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 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 13.1.1).

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 *electronic cone, n*—a cone that uses transducers to obtain the measurements.

3.2.9 *electronic piezocone, n*—an electronic cone that can measure the pore water pressure simultaneously with the cone tip resistance and the friction sleeve resistance.

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, n*—pore water pressure in excess of the equilibrium pore water pressure caused by the penetration of the cone into the ground.

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).

3.2.12 *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 the depth for the middle of the friction 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, n*—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, n*—an isolated cylindrical section of a cone upon which the friction component of penetration resistance develops.

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

3.2.16 *full-scale output, n*—the output of an electronic transducer when loaded to 100 % rated capacity.

3.2.17 *measuring system, n*—all sensors and auxiliary parts used 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.

3.2.18 *penetration depth, n*—vertical depth of the base of the cone, relative to a fixed point.

3.2.19 *penetration length, n*—sum of the lengths of the push rods and the cone.

3.2.20 *piezocone porewater pressure measurement location: u_1, u_2, u_3, n*—fluid pressure measured by the piezocone at specific locations (**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 in the cylindrical extension of the cone tip (standard location) and, u_3—porous filter location behind the friction sleeve.

3.2.21 *pore water pressure, n*—pore water pressure measured during penetration.

3.2.22 *pore water pressure ratio, B_q, n*—the ratio of excess 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}.

3.2.23 *push rods, n*—the tubes or rods used to advance the cone.

3.3 *Abbreviations:*

3.3.1 *CPT*—cone penetration test.

3.3.2 *FSO*—full scale output.

3.3.3 *MO*—measured output.

4. Summary of Test Method

4.1 A cone is advanced through the soil at a constant rate of 20 mm/s. The force on the cone tip required to penetrate the soil is measured using an electric transducer. The cone tip resistance q_c is calculated by dividing the vertical force applied to the cone tip by the cone base area.

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

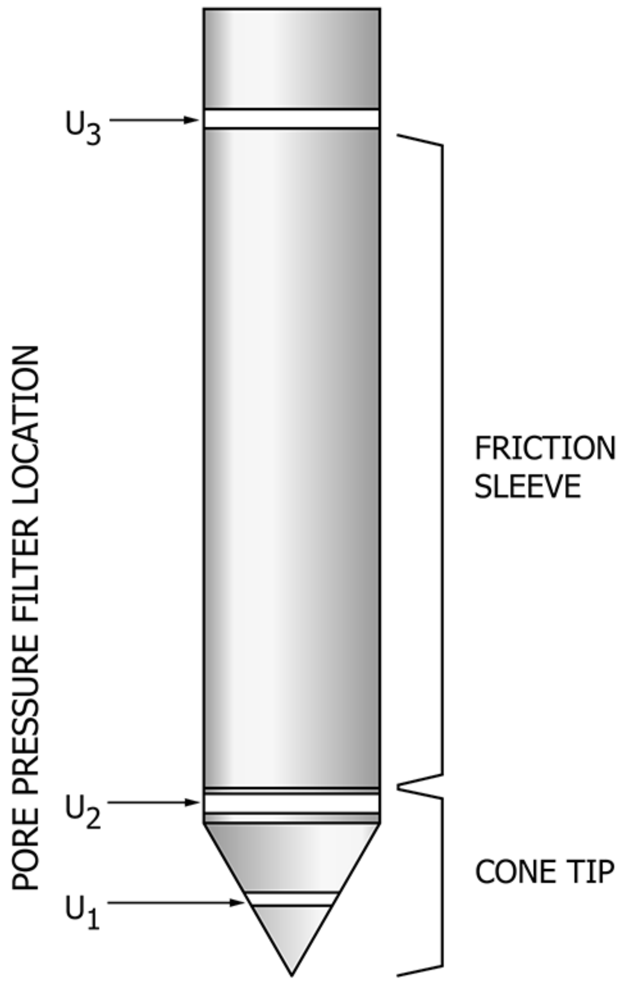


FIG. 1 Piezocone Pore Water Pressure Measurement Locations (courtesy ConeTec Data Services)

4.2 A friction sleeve is present on the cone immediately behind the cone tip, and the force exerted on the friction sleeve is measured using an electric transducer. The friction sleeve resistance, f_s is calculated by dividing the shear force applied to the friction sleeve by the surface area of the friction sleeve.

4.3 Most modern cones are capable of registering pore water pressure induced during advancement of the cone using an electric pressure transducer. These cones are formally called "electronic piezocones," but given their prevalence they are often simply referred to as "cones." The dissipation of either positive or negative excess pore water pressure can be monitored by stopping penetration, unloading the push rods, and recording pore water pressure as a function of time. When pore water pressure becomes constant it is measuring the equilibrium value (designated u_0) 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 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 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 and soil samples are not 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 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 cone.

6.3 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 string, such as push rod joints and push 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 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

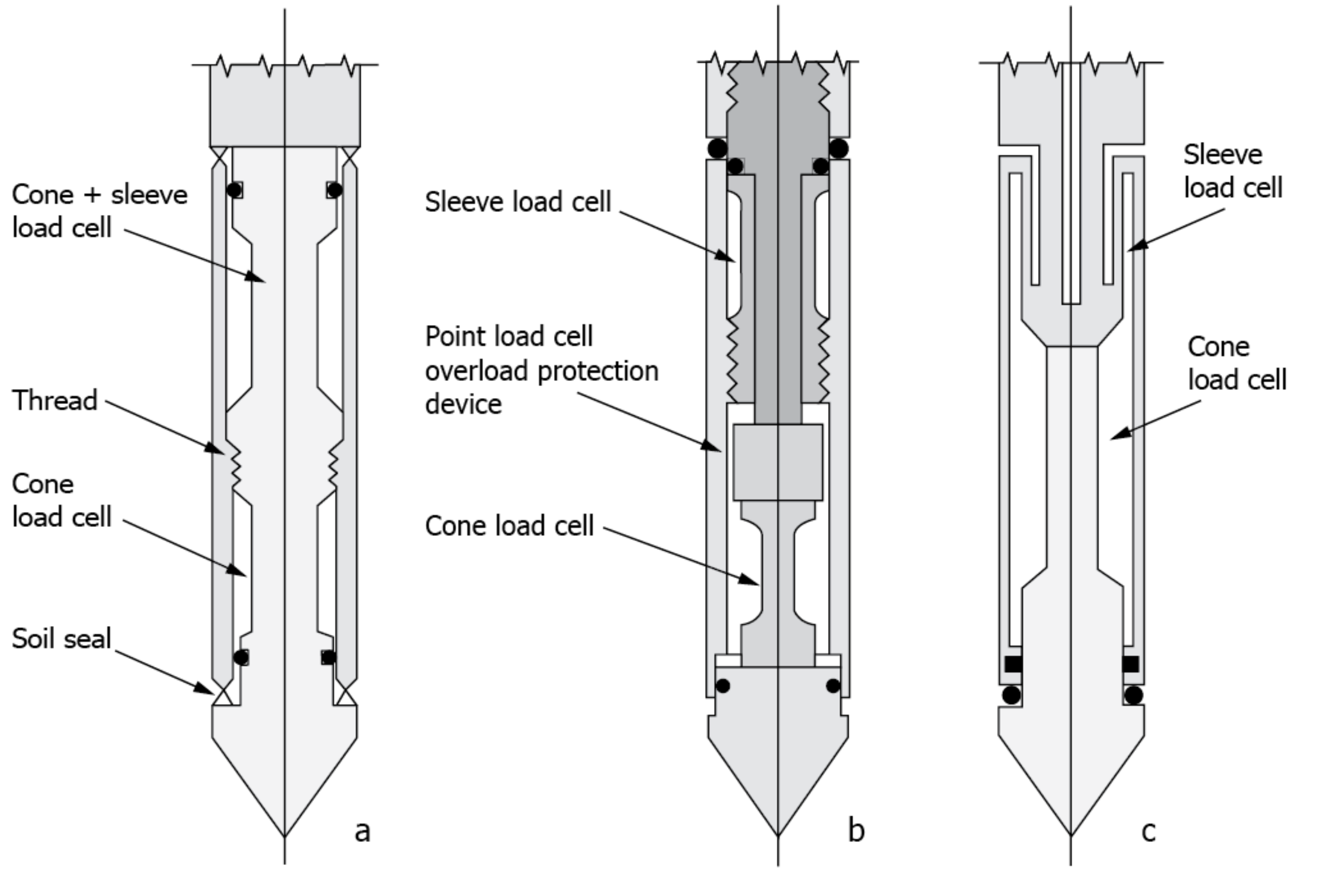


FIG. 2 Configurations for Electric Friction-Cone Penetrometers (1) Showing: (a) Subtraction type, (b) Compression type, and (c) Tension type (courtesy ConeTec Data Services)

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 %.

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.

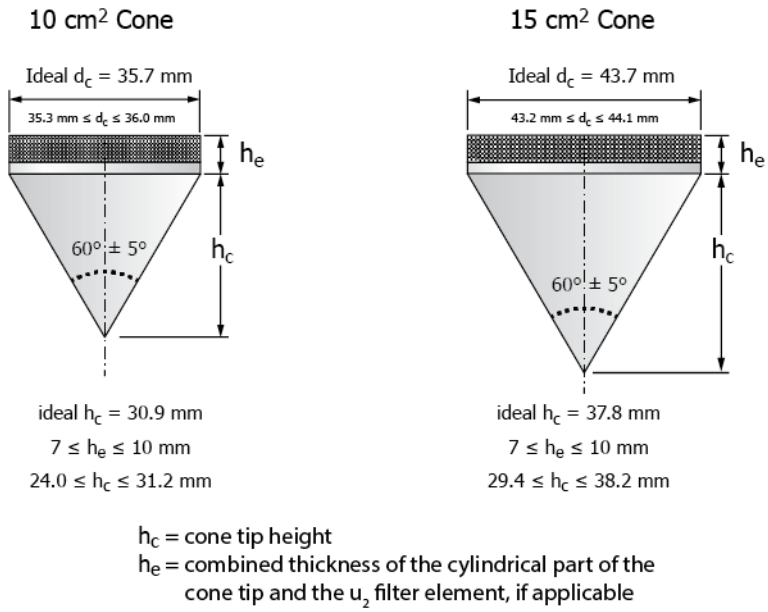


FIG. 3 Manufacturing and Operating Tolerances of Cone Tips (5) (courtesy ConeTec Data Services)

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 *Electronic Piezocone*—A piezocone 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. 4 shows some common design types used in practice for 10-cm^2 and 15-cm^2 piezocones (with ideal dimensions).

7.8.1 The pore water pressure measurement location of the porous element shall be either in the cone tip (Type 1 or u_1), immediately behind the cone tip (Type 2 or u_2) or immediately behind the friction sleeve (Type 3 or u_3). Some piezocones used for research purposes may 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**). However, Type 2 cones may be subject to cavitation at shallow depths in dense soils because the zone behind the

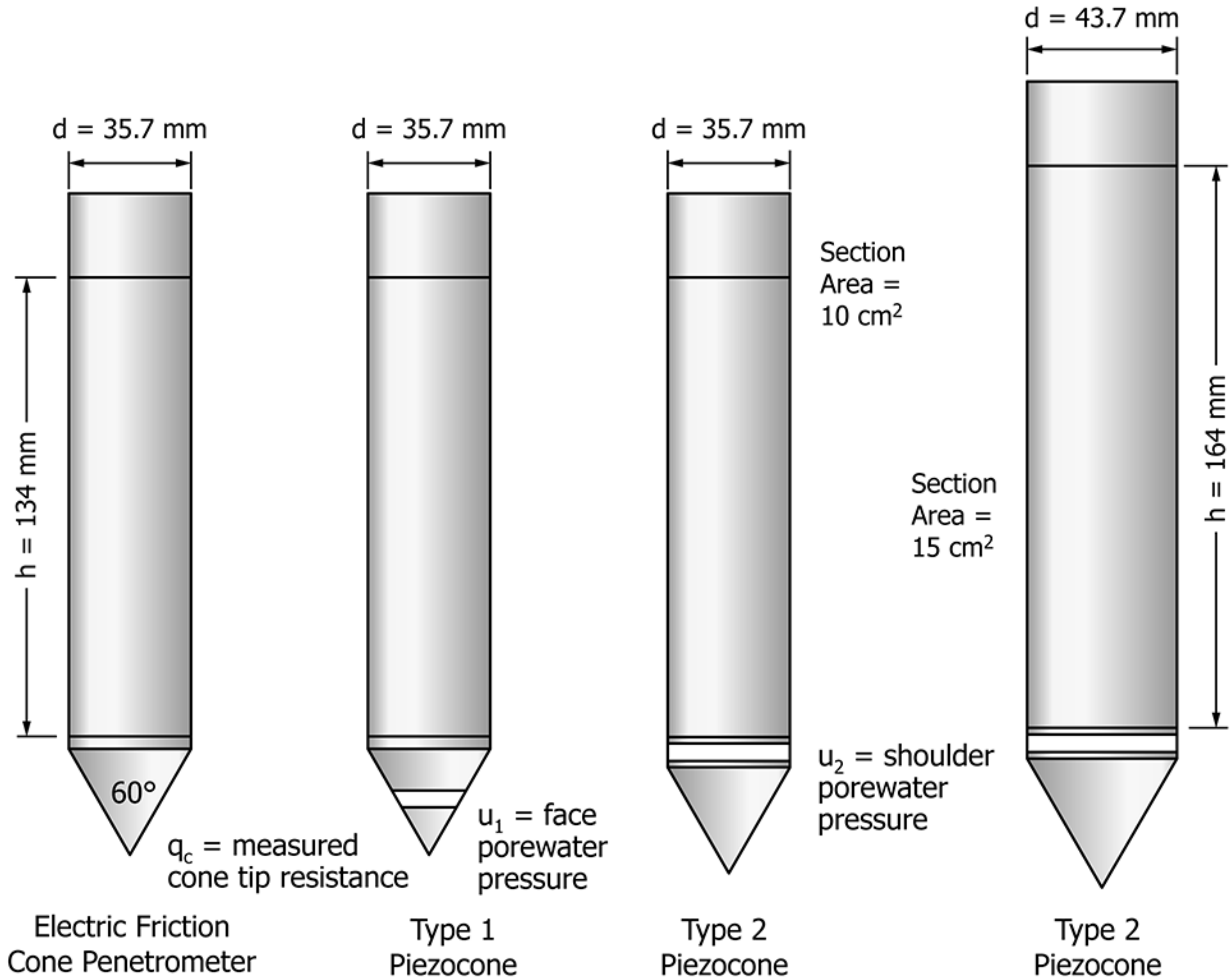


FIG. 4 Cone Design Configurations: (a) Electronic Friction-type, (b) Type 1 Piezocone, (c) Standard 10-cm^2 Type 2 Piezocone, and (d) 15-cm^2 Type 2 Version (7) (courtesy ConeTec Data Services)

height of cylindrical extension is a zone of dilation in drained soils. Similar response can occur in stiff fissured clays and crusts (**1**). Pore water pressure measurements obtained at the u_1 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 (**4, 11**).

7.8.2 Numerous design and configuration aspects can affect the measurement of pore 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 pore water pressure measured during testing and dissipation tests of 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 shall be reported as to the design, configuration, and the preparation of the piezocone system that is used for the particular sounding.

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 *Data Acquisition System*—The signals from the cone transducers are to be displayed at the surface during testing as a continuously updated plot against penetration length. The data are also to be recorded electronically on the same data acquisition system for subsequent processing.

7.9.1 The electronic data files shall 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 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, 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. 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 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 cones, the test is typically performed with 44.5-mm outside diameter rods or with standard rods used for the 10-cm^2 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 shall be located on the push rods no closer than 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 cone is advanced with 36-mm push rods there may be no need for friction reducers since the cone itself will open a larger hole. The type, size, amount, and location of friction reducer(s) used during testing must be reported.

7.12 *Thrust Machine and Reaction*—The thrust machine will provide a continuous stroke, preferably over a distance greater than 1 m. The thrust machine should be capable of adjusting push direction through the use of a leveling system such that push initiates in a vertical orientation. The machine must advance the cone and push rods at a smooth, constant rate (see 12.1.2) while the magnitude of thrust can fluctuate. The thrust machine must be anchored or ballasted, or both, so that it provides the necessary reaction for the cone and does not move relative to the soil surface during thrust.

NOTE 6—Cone penetration soundings usually require thrust capabilities ranging from 100 to 200 kN for full capacity. High mass ballasted vehicles can cause soil surface deformations, which may affect cone resistance(s) measured in near surface layers. Anchored or ballasted vehicles, or both, may induce changes in ground surface reference level. If these conditions are evident, they should be noted in reports.

7.13 *Other Sensing Devices*—Other sensing devices can be included in the cone to provide additional information during the sounding. These instruments are normally read at the same continuous rate as tip, sleeve, and pore water pressure sensors, or alternatively, during pauses in the push (often at 1-m rod breaks). Typical sensors are inclinometer, temperature, resistivity (or its reciprocal, electrical conductivity), or seismic sensors. The use of an inclinometer is highly recommended since it will provide information on potentially damaging situations during the sounding process. An inclinometer can provide a useful depth reliability check because it provides information on verticality. In addition, it will allow for correction of the penetration length to the penetration depth during post-processing of the data.

8. Reagents and Materials

8.1 *O-Ring Compound*—A petroleum or silicon compound for facilitating seals with O-rings. Use of silicon compounds may impede repair of strain gages if the strain gauge surface is exposed to the compound.

8.2 *Silicone Oil, Glycerine, or water,* for use in pore water pressure measurement systems.

NOTE 7—Detailed comparisons and discussions on the use of these fluids can be found elsewhere (**8, 11**).

9. Hazards

9.1 *Technical Precautions—General:*

9.1.1 Use of components that do not meet required tolerances or show visible signs of non-symmetric wear can result in erroneous cone resistance data.

9.1.2 The application of thrust in excess of rated capacity of the equipment can result in damage to equipment (see Section 6).

9.1.3 A cone sounding must not be performed any closer than 10 borehole diameters from any existing unbackfilled or uncased bore hole.

9.1.4 When performing cone penetration testing in prebored holes, the depth and diameter of the prebored hole shall be reported and shown on the sounding plot.

NOTE 8—Usually it is assumed that the soil is disturbed at least three borehole diameters below the bottom of the borehole, and this should be taken into account when evaluating the penetration resistance data.

9.1.5 If obstructions are encountered and normal advance of the sounding is stopped to bore through the obstructions, the depth and thickness of obstructions shall be recorded.

9.1.6 Significant bending of the push rods can influence penetration resistance data. The use of a tubular rod guide is recommended at the base of the thrust machine and also in prebored holes to help prevent push rod bending.

9.1.7 Bent push rods may result in excessive directional penetrometer drift and possibly unreliable penetration resistance values.

9.1.8 The cone may drift directionally from vertical alignment and these deviations in inclination can create nonuniform loading resulting in unreliable penetration resistance data as well as damage. Passing through or alongside obstructions (such as boulders, cobbles, coarse gravel, soil concretions, thin rock layers, or inclined dense layers) may deflect the cone and also induce directional drift. Therefore, limitations on inclination in the system should be imposed. Generally, a 1° change in inclination over 1 m of penetration can impose detrimental push rod bending, while a total drift of over 15° imposes non-symetric loading and possible unreliable penetration resistance data.

9.1.9 If the proper rate of advance of the cone is not maintained for the entire stroke through the measurement interval, penetration resistance data may be erroneous.

9.2 *Technical Precautions—Electronic Friction Cone:*

9.2.1 Failure of seals can result in damage to or inaccurate readings from electronic transducers. The seals should be inspected regularly for overall condition, cleanliness, and water tightness, and replaced when necessary.

9.2.2 Soil ingress between different elements of a cone can result in unreliable data. Specifically, soil ingress will detrimentally affect sleeve resistance data. Seals should be inspected and maintained regularly, and replaced when necessary. If very accurate sleeve resistance data is required, it is recommended to clean all seals after each sounding.

9.2.3 Electronic cones shall be temperature compensated. If extreme temperatures outside of the range established in A1.3.1 are to be encountered, the cone shall be checked for the required temperature range to establish it can meet the calibration requirements. Also, harsh environments may severely affect the data acquisition system or power supplies, notebook or field computers, and other electronics.

9.2.4 If the shift in baseline reading after extracting the cone from the soil is so large that the conditions of accuracy as defined in 10.1.2.3 are no longer met, penetration resistance data shall be noted as unreliable. If baseline readings do not conform to allowable limits established by accuracy requirements in 10.1.2.3, the cone must be repaired, and recalibrated or replaced.

9.2.5 Friction sleeve design shall be checked in accordance with A1.6 to ensure balanced response. The response is also dependent on location of water seals. If water seals are damaged during testing, and sleeve data appear affected, the sounding data shall be noted as unreliable and the seals shall be repaired.

9.3 *Technical Precautions—Piezocone:*

9.3.1 The electronic piezocone measures pore water pressures on the exterior of the cone by transferring the pressure through a de-aired fluid system to a pressure transducer in the cone interior. For proper dynamic response, the measurement system (consisting of fluid ports and porous element) must be completely saturated prior to testing. Entrained air must be removed from the fluid-filled system or pore water pressure fluctuation during cone advancement will be incorrect due to response lag from compression of air bubbles.

10. Calibration and Standardization

10.1 *Electronic (Piezo) Cones:*

10.1.1 Newly manufactured or repaired cones are to be checked to meet the minimum calibration requirements described in the annex. These calibrations include load tests, thermal tests, and mechanical tests for effects of imbalanced hydrostatic forces. The calibration records must be certified as correct by a registered professional engineer or other responsible engineer with knowledge and experience in materials testing for quality assurance.

10.1.2 *Baseline Readings*—Baseline or zero-load readings for the load cells and pore water pressure transducers must be taken before and after each sounding. The baseline reading is a reliable indicator of output stability, temperature-induced apparent load, soil ingress, internal friction, threshold sensitivity, and unknown loading during zero setting.

10.1.2.1 The initial baseline reading shall be taken in a temperature environment as close as possible to that of the material to be sounded. If temperature is a concern, the cone shall be immersed in a bucket of fresh tap water or inserted in the ground to stabilize its temperature and then extracted for rapid determination of initial baseline. The change in initial baseline and calibration values shall not exceed 5 % FSO for the load cells and pressure transducer.

10.1.2.2 After a sounding is completed, a final baseline reading shall be taken. The change in initial and final baseline values shall not exceed 2 % FSO for the load cells and pore water pressure transducers.

10.1.2.3 A continuous record of initial and final baselines readings shall be kept during production testing.

10.1.2.4 If a baseline reading exceeds the above criteria, the cone shall be inspected for damage. If there is apparent damage, the cone shall be cleaned and any damaged parts shall be replaced, after which a new baseline shall be obtained. If this value agrees with the initial baseline within the above criteria, recalibration is not required. However, if the initial and final baselines are still not within the above criteria then it is likely that the shift was caused by an obstacle or obstruction, and the cone shall no longer be used until it has been repaired and recalibrated.

10.1.2.5 Data for a sounding where unacceptable final baseline shift has occurred shall be reported as unreliable. In some cases, it may be obvious where the damage occurred and data prior to that point may be considered reliable. In that case, the location where obvious damage occurred must be clearly noted in the sounding logs and duly reported.

10.1.3 *Cone Wear and Usage:*

10.1.3.1 For cones used regularly, periodic calibrations should be performed. The calibration period can be based on production footage, such as once every 3000 m of soundings, or time period. If calibration equipment is not available in the field, the cone may be checked in the laboratory at the end of the project during which the calibration period ended.

10.1.3.2 Cones that are used infrequently should be calibrated based on a time period. If a cone has not been used for a long period of time, checking it before use is advisable.

10.1.3.3 For projects requiring a high level of quality assurance, it may be required to do a calibration before the project.

10.1.3.4 Calibrations are required if an initial or a final baseline reading does not meet the requirements given in 10.1.2.3 and whenever a cone has been repaired.

10.1.3.5 Records documenting the history of an individual cone shall be maintained for evaluation of performance.

10.1.3.6 If it appears from a track record or the baseline readings that no significant deviations are registered, a longer period between calibrations can be applicable.

10.2 *Calibrations of Other Sensing Devices*—Other sensors in the cone may require calibrations using procedures similar to those given in the annex for load cells and pressure transducers. The need for calibration depends on the requirements of the individual investigation program. For noncritical programs, the occurrence of reasonable readings may be sufficient. In critical programs, it may be necessary to load the sensor through the range of interest with reference standards to ensure accurate readings.

11. Conditioning

11.1 Piezocones used for pore water pressure readings require special preparation such that entrained air is removed from the system. In addition the filter element should be replaced after every sounding and the ports should be flushed after every sounding. However, for soundings where dynamic response is important, the prepared filter elements shall be replaced after every sounding.

11.1.1 Field or laboratory tests can be performed to evaluate assembled system response, if desired by placing the cone tip and the filter element in a pressurized chamber and subject them to rapid pressure change. If the responses match, the system is properly prepared.

11.1.2 To condition the filter elements, they shall be placed in a pure glycerine or silicone oil bath under a vacuum of at least 90 % of one atmosphere (–90 kPa). Vacuum shall be maintained until air bubble generation is reduced to a minimum. Application of ultrasonic vibration and low heat (T < 50°C) will assist in removal of air. Generally with use of combined vacuum, ultrasonic vibration, and low heat, filter elements can be deaired in about 4 h, although it is best to allow for 24 h to ensure best performance. Results will depend upon the viscosity of the fluid and pore size of the filter element.

11.1.3 Alternatively, elements can be prepared in water by boiling the elements while submerged in water for at least 4 h, although damage may result from prolongued exposure in this approach (**4**), or commercially-purchsed pre-saturated filter elements may be used..

11.1.4 Prepared elements must be kept submerged in the prepared fluid in closed containers until ready for use, whereby the allowable storage length depends on the fluid. If elements are prepared in water, they must be deaired again one day after containers are opened and exposed to air. Elements stored in pure glycerine or silicone may be stored for longer periods, but not to exceed one month after storage containers are opened and exposed to air.

12. Procedure

12.1 *General Requirements:*

12.1.1 Prior to beginning a sounding, site surveys shall be performed to ensure hazards such as overhead and underground utilities will not be encountered. Next, the thrust machine shall be positioned over the location of the sounding, and either the leveling jacks shall be lowered to raise the machine mass off the suspension system (in case the dead weight of the thrust machine is used to generate the required reaction) or the ground anchors shall be placed (in case they are used to generate the required reaction). Afterwards it shall be ensured that the hydraulic rams of the penetrometer thrust system are set as near vertical as possible.

12.1.2 The hydraulic ram feed rate shall be set to advance the cone at a rate of 20 ± 5 mm/s. This rate must be maintained during the entire stroke during downward advance of the rods while taking readings.

NOTE 9—In practice the penetration speed is reduced whenever the recorded data imply a precarious situation (sudden dramatic increase in tip resistance, bending, or overall inclination). Those deviations must be clearly indicated in the report.

12.1.3 The push rods shall be checked for straightness and permanent bending (See Section 7.10). Push rods are assembled and tightened by hand or by an automatic tightening device, but care must be taken and threads may need cleaning to ensure that the shoulders are tightly butted to prevent damage to the push rods. For cones using cables, the cable is prestrung through the push rods. A friction reducer shall be added to the string of push rods as required, usually as the first push rod behind the cone.

12.1.4 The cone shall be inspected before and after soundings for damage, soil ingress, and wear. In very soft and sensitive soils where accurate sleeve data is required, the cone shall be cleaned and lubricated in accordance with the manufacturer's recommendations after each sounding. If damage is found after a sounding, this information shall be recorded.

12.2 *Electronic Cones:*

12.2.1 The cone and the data acquisition system shall be powered up according to the manufacturer's recommendations.

12.2.2 An initial baseline reading shall be obtained for the cone in an unloaded condition at a temperature as close as possible to ground conditions. This baseline reading shall be compared with the calibration values for the requirements given in 10.1.2.1. If thermal stability needs to be assured, the cone shall be submerged in water at temperature close to ground; or an initial short penetration test hole shall be performed to allow the cone to reach soil temperature.

12.2.3 The depth at which readings were taken shall be measured with an accuracy of at least ±25 mm or 1 % of the reading (whichever is larger) from the ground surface.

12.2.4 The cone tip resistance and friction sleeve resistance shall be measured continuously with depth, and recorded at depth intervals not exceeding 50 mm. Improved resolution may often be obtained at 20- or 10-mm interval readings.

12.2.5 During the sounding, the cone tip and friction sleeve resistance shall be monitored continuously for signs of proper operations. It is helpful to monitor other indicators such as ram pressure or inclination to ensure that damage may not occur if highly resistant layers or obstructions are encountered. Inclination is a particularly useful indicator of imminent danger to the system (see 12.4).

12.2.6 After attaining the final sounding depth the push rods and the cone shall be withdrawn as soon as possible and a final baseline reading shall be obtained for the cone in an unloaded condition. This baseline reading shall be compared with the initial baseline values for the requirements given in 10.1.2.2. The initial and final baseline values shall be recorded on all documents related to the sounding.

12.2.7 Upon complete withdrawal of the cone, inspect the cone for proper operation.

12.3 *Electronic Piezocones:*

12.3.1 The cone and the data acquisition system shall be powered up according to the manufacturer's recommendations.

12.3.2 The piezo elements shall be assembled according to the manufacturer's recommendations. Typically, the piezo elements are assembled with all fluid chambers submerged in the de-aired medium used to prepare the elements (see Fig. 5) and all confined areas flushed with fluid to remove air bubbles. Next, the cone tip is tightened to effectively seal the flat surfaces of the porous element, after which it is suggested that the assembled system is protected from evaporation by enclosing the porous element inside a (fluid-filled) plastic membrane.

12.3.3 If unsaturated soil is first penetrated and it is desired to obtain accurate pore water pressure response once below the ground water, it may be necessary to prebore or sound a pilot hole to the water table. In many cases, the piezocone fluid system may desaturate during penetration through unsaturated soil or in dilating sand layers below the water table and this can adversely affect dynamic response. As the cone is advanced deeper, the saturation levels may recover as air bubbles are driven back into solution according to Boyles Law. Evaluation of proper interpretation of dynamic response requires experience (**4, 5, 8, 12**). Pre-punching or pre-boring with a two-level phase approach to soundings may help alleviate desaturation problems.

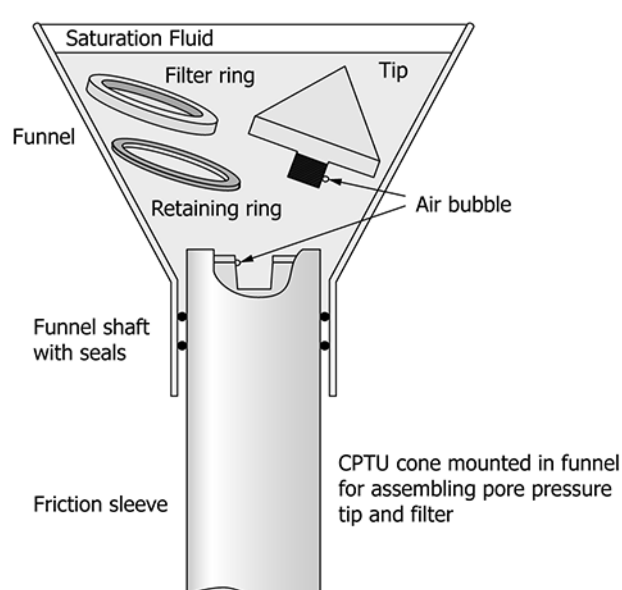


FIG. 5 Typical Example of Piezocone Preparation Set-up (courtesy ConeTec Data Services)

12.3.4 Procedures similar to electric friction cone in 12.2.4 – 12.2.6 shall be followed with the addition of recording pore pressure readings. Baseline values for the pore pressure transducer shall not be obtained with protective membranes in place as these may induce pressure in the system.

12.3.5 *Dissipation Tests*—If dissipation tests are to be conducted during progress of the sounding, penetration is temporarily stopped at the location of interest. If pore water pressures are measured at the u_2 or u_3 locations, it is common practice to release the force on the push rods, but if pore water pressures are measured at the u_1 location, the force on the push rods should be maintained. Pore water pressure and if the u_1 location is used also the cone tip resistance shall be displayed and recorded on the data acquisition system during conduct of the dissipation test. The test shall be conducted until equilibrium pore water pressure is reached or 50 % of the initial excess pore water pressure has dissipated. In fine grained soils of very low conductivity, very long times may be required to reach the 50 % dissipation. Depending on the requirements of the program, and any concern of friction buildup on the push rods, dissipation testing may be terminated prior to reaching the 50 % level.

12.3.6 *Equilibrium Pore Water Condition*—If full dissipations are carried out, then the pore water transducer will eventually record the equilibrium condition, thus providing an evaluation of the position of the groundwater table or phreatic surface.

12.4 *Penetrometer Operation and Data Interpretation-Guidelines:*

12.4.1 *Push Rod Addition Interruptions*—Short duration interruptions in the penetration rate during addition of each new push rod can affect initial cone and friction sleeve readings at the beginning of the next push. If necessary, the depths at which push rods are added and where long pauses may have affected initial startup resistances should be recorded.

12.4.2 *Piezocone Pore Water Pressure Dissipation Interruptions*—Pore water pressure dissipation studies, for which soundings are stopped and rod load is released for varying time durations, can affect the initial cone, friction sleeve, and dynamic pore water pressure readings at resumptions of cone penetration. If dissipation tests are performed, be aware of possible rebound effects on initial excess pore water pressures. If necessary, the depth and duration for which dissipation values are taken should be recorded.

12.4.3 *Excessive Thrust Capacity*—If excessive thrust pressure begins to impede the progress of the sounding, it may be necessary to withdraw and install or change friction reducers or install casing. Alternately, sometimes friction may be reduced by withdrawing the cone and rods up to one third to one half of the penetration length and then repushing to the depth at which the friction caused stopping. Collection of sounding data should be continued from the point of stopping and the delay time and depths to which the cone was moved should be recorded. Long delays and pauses may cause buildup of friction on the rods and therefore delays should be kept to a minimum (for example, to perform dissipation tests or equipment repairs).

12.4.3.1 If a high resistance layer is encountered, and the hydraulic thrust machine is physically moved during penetration, the sounding shall be terminated. Another indicator of reaching thrust capacity is the rebound of rods after they are released. The magnitude of rebound depends on the flexibility of the thrust machine and the push rods. An operator must become familiar with the safe deflection of the system and decide when excessive deflections are being reached.

12.4.4 *Unusual Occurrences*—As data are recorded, it is important to note unusual occurrences in testing. When penetrating gravels, it is important to note "crunching" sounds that may occur when particle size and percentage of coarse particles begin to influence penetration.

12.5 *Hole Closure*—In certain cases, it may be prudent or required by law or specifications, that the cone hole be filled, sealed, or grouted and closed after the sounding is completed. For example, in complex groundwater regimes, hole closure should be made to protect the water aquifer. Details on various methods for hole closure are provided elsewhere (**13**).

13. Calculations

13.1 *Cone Tip Resistance, q_c:*

$$q_c = Q_c / A_c \quad (1)$$

where:

q_c = cone tip resistance, kPa,
Q_c = force on cone tip, kN, and
A_c = cone tip base area, m^2.

13.1.1 *Corrected Total Cone Resistance:*

$$q_t = q_c + u_2 (1 - a_n) \quad (2)$$

where:

q_t = corrected total cone tip resistance, kPa,
u_2 = pore water pressure generated immediately behind the cone tip, kPa, and
a_n = net area ratio (see A1.6).

13.1.1.1 The correction to the total cone tip resistance is particularly important when pore water pressures are generated during penetration (for example, in saturated clays, silts, and soils with appreciable fines). Generally, the correction is not so significant for CPTs in clean sands, dense to hard geomaterials, and dry soils. The correction is due to pore water pressures acting on opposing sides of both the face and joint annulus of the cone tip (**4**, **1**, **6**, **8**).

NOTE 10—Some methods to interpret CPT data use q_t rather than q_c. It is not within the scope of this standard to recommend which methods of interpretation are to be used or how to determine qt for other filter locations.

13.2 *Friction Sleeve Resistance, f_s:*

$$f_s = Q_s / A_s \quad (3)$$

where:

f_s = friction sleeve resistance, kPa,
Q_s = force on friction sleeve, kN, and
A_s = area of friction sleeve, m^2.

NOTE 11—A corrected sleeve friction resistance may also be obtained (f_t), yet this requires both u_2 and u_3 measurements simultaneously (**2**, **3**, **1**, **5**, **6**, **8**). Thus, the raw f_s has been accepted for practical reasons.

13.3 *Friction Ratio, R_f:*

$$R_f = (f_s / q_c) \cdot 100 \quad (4)$$

where:

R_f = friction ratio, %,
f_s = friction sleeve resistance, kPa,
q_c = cone tip resistance, kPa, (see Note 1 for use of q_t), and
100 = conversion from decimal to percent.

13.3.1 Determination of the friction ratio requires obtaining a cone resistance and friction sleeve resistance at the same point in the soil mass. The point of the cone tip is taken as the reference depth. Typically, a previous cone tip resistance reading at friction sleeve midpoint depth is used for the calculations. If an offset other than midheight is used it must be reported.

NOTE 12—In some cases, if readings are compared at the same point in a soil mass which has alternating layers of soft and hard materials erratic friction ratio data will be generated. This is because cone resistance is sensed, to varying degrees, ahead of the cone. The erratic data may not be representative of soils actually present.

NOTE 13—The friction sleeve resistance and friction ratio obtained from the mechanical friction cones will differ considerably from values obtained from electronic friction cones. When using soil classification charts that use R_f and q_c, it is important to use charts based on correlations for the type of cone being used.

13.4 *Pore Water Pressure Data:*

13.4.1 SI units for reporting pore water pressure data are kPa.

13.4.2 *Conversion of Measured Pore Water Pressures to Equivalent Height of Water*—If it is desired to display pore water pressure in equivalent height of water, the dynamic or static water pressures shall be converted to height by dividing pressure by the unit weight of freshwater, $\gamma_w = 9.8\ kN/m^3$. For salt water, use $\gamma_w = 10.0\ kN/m^3$.

13.4.3 *Estimate of Equilibrium Pore Water Pressure*—Excess pore water pressure can only be calculated by knowing equilibrium pore water pressure, u_o (see 3.2.10). The equilibrium water pressure can be measured by dissipation test or estimated by calculation as follows:

$$u_o = \text{estimated equilibrium water pressure} = h_w \cdot \gamma_w \quad (5)$$

In saturated soils below the groundwater level, the hydrostatic case is obtained from:

$$u_o = (z - z_w)\, \gamma_w \quad (6)$$

For soils above the groundwater table that are saturated due to full capillarity, Eq 6 is also applicable. For dry soils above the groundwater table, it is commonly adopted that $u_o = 0$. In partially-saturated soils (vadose zone), there can be great transient variations and variability in the u_o profile.

where:

h_w = height of water, m, evaluate from site conditions,
γ_w = unit weight of water, kN/m^3,

z = depth of interest, m, and
z_w = depth to the groundwater table (phreatic surface), m.

In layered soils with multiple perched aquifers the assumption of a single height of water may be in error.

13.5 *Normalized CPT Measurements* In soil behavioral classification charts and CPT interpretation methods, normalized readings for cone tip resistance, sleeve friction, and pore water pressure are utilized (**1, 6, 14**), as defined below.

13.5.1 Normalized cone tip resistance:

$$Q_t = (q_t - \sigma_{vo})/\sigma_{vo}' \quad (7)$$

13.5.2 *Normalized Pore Water Pressure Parameter, B_q*—This parameter is normally calculated with the pore water pressure measurement (immediately behind the cone tip).

$$B_q = \Delta u_2/(q_t - \sigma_{vo}) \quad (8)$$

13.5.3 Normalized friction ratio:

$$F_r = f_s/(q_t - \sigma_{vo}) \quad (9)$$

where:

Δu_2 = excess pore water pressure $(u_2 - u_o)$ (see 3.2.11),
u_o = estimated equilibrium water pressure, or hydrostatic pore water (see 13.4.3),
σ_{vo} = total vertical overburden stress, and
σ_{vo}' = effective overburden stress = $\sigma_{vo} - u_o$.

The total overburden stress is calculated:

$$\sigma_{vo} = \sum (\gamma_{ti}\,\Delta z_i) \quad (10)$$

where:

Δz_i = layer thickness, and
γ_{ti} = total soil unit weight for layer.

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

14.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in Practice D6026.

14.2 Record as a minimum the following general information (data):

14.2.1 *General*—Each sounding log should provide as a minimum:

14.2.1.1 Operator name or initials,

14.2.1.2 Project designation,

14.2.1.3 Ground surface elevation and water surface elevation (if available),

14.2.1.4 Sounding location, including coordinates

14.2.1.5 Sounding number,

14.2.1.6 Sounding date.

14.2.1.7 Sounding plot (see Fig. 6 and Fig. 7),

1. Each sounding plot shall show as a function of penetration length,

(a) the cone tip resistance q_c, and preferably the total cone tip resistance, q_t,

(b) the friction sleeve resistance, f_s, and friction ratio, R_f,

(c) in case of a piezocone, the pore water pressure or alternatively, the pressure may be converted to equivalent heights of water.

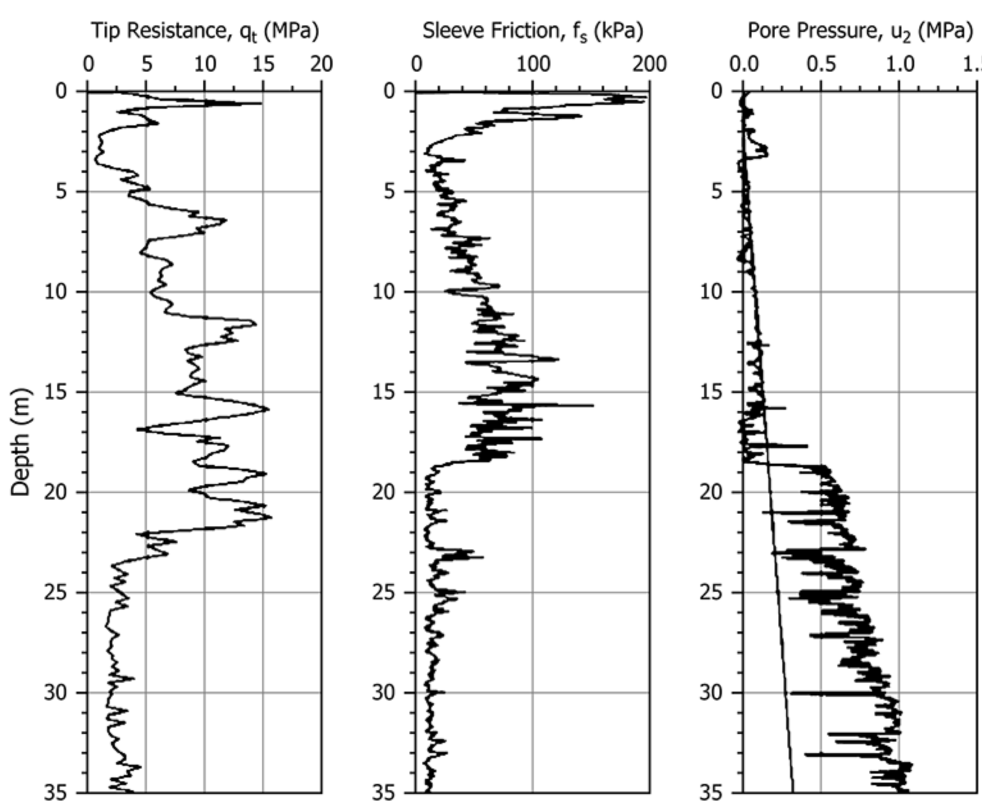


FIG. 6 Example Graph Presentation Results from a Conventional Piezocone Penetration Test (courtesy ConeTec Data Services)

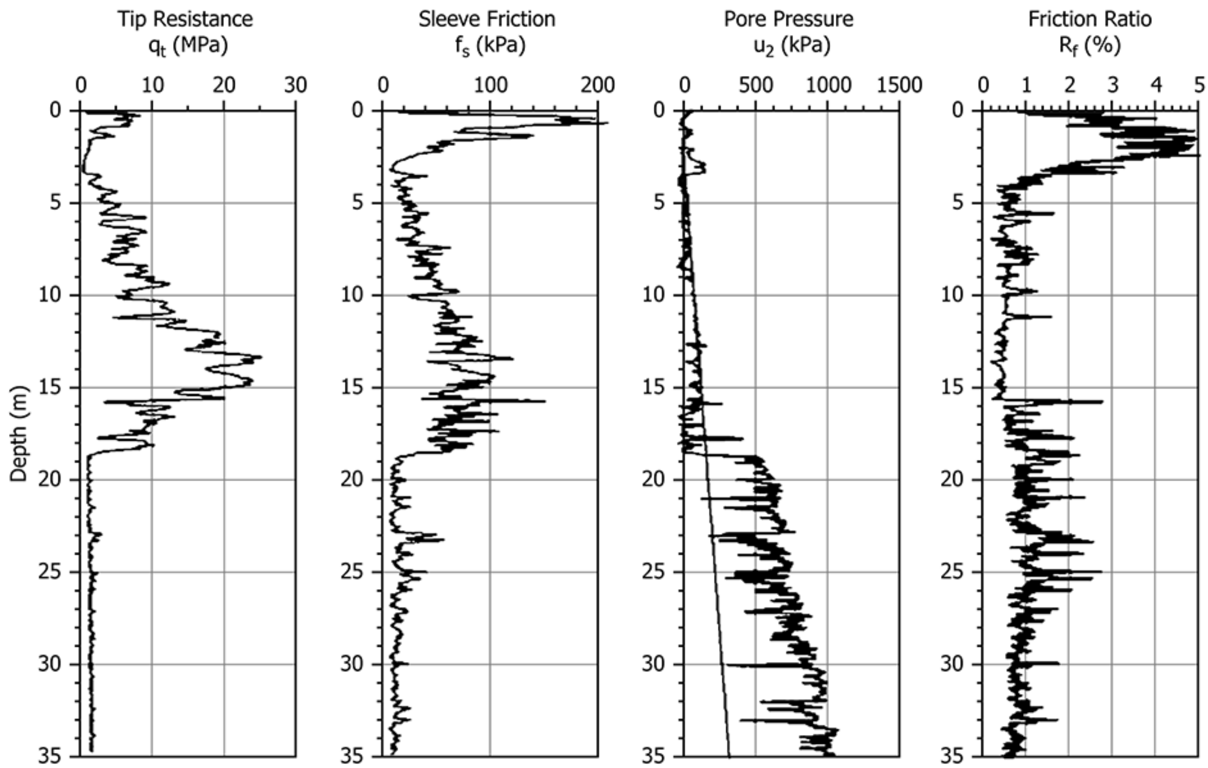


FIG. 7 Illustrative Piezocone Graph Showing Tip Resistance, Sleeve Friction, Penetration Porewater Pressure, and Friction Ratio (courtesy ConeTec Data Services)

2. Each plot shall provide the general information as outlined in 14.2.1.4 – 14.2.1.7, and

3. For uniform presentation of data, the vertical axis (ordinate) should display depth and the horizontal axes should display the test values.

14.2.1.8 Initial and final baseline readings.

14.2.2 Reports should contain information concerning:

14.2.2.1 *Equipment Used:*

(a) Cone manufacturer,

(b) Cone type used,

(c) Cone details such as cone base area, friction sleeve area, net area ratio, friction sleeve end areas,

(d) Offset between tip and sleeve resistance used for friction ratio determination,

(e) Cone serial numbers,

(f) Type of thrust machine,

(g) Method used to provide reaction force—with notes as to possible surface deformations,

(h) Location and type of friction reduction system (if any),

(i) Any special difficulties or other observations concerning performance of the equipment,

(j) Information on other sensing devices used during the sounding,

(k) Any observations concerning the quality of the recorded data.

14.2.2.2 *Calibration Information*—For all sensors, information required in Section 10.

14.2.2.3 *Computer Data Files with Recorded Raw Data—in Open Format*—(for example, ASCII format or spreadsheet file).

15. Precision and Bias

15.1 *Precision*—There are little direct data on the precision of this test method, in particular because of the natural variability of the ground. Committee D-18 is actively seeking comparative studies. Judging from observed repeatability in approximate uniform deposits, persons familiar with this test estimate its precision as follows:

15.1.1 *Cone Tip Resistance*—Provided that compensation is made for the net area ratio as described in 13.1.1, a standard deviation of approximately 2 % FSO (that is, comparable to the basic electromechanical combined accuracy, nonlinearity, and hysteresis).

15.1.2 *Sleeve Friction—Subtraction Cones*—Standard deviation of 15 % FSO.

15.1.3 *Sleeve Friction—Compression and Tension Cones*—Standard deviation of 5 % FSO.

15.1.4 *Dynamic Pore Water Pressure*—Strongly dependent upon operational procedures and adequacy of saturation as described in 11.1. When carefully carried out a standard deviation of 2 % FSO can be obtained.

15.2 *Bias*—This test method has no bias because the values determined can be defined only in terms of this test method.

NOTE 14—Jefferies and Davies (**14**) report q_t repeatability of the two different soundings in compact clean sand using two different cones by the same manufacturer. Approximately 50 % of the data lay within 8 % of the average of the two tests, and 90 % of the data lay within 15 % of the average. In this trial the transducers (that conformed to the requirements in A1.4) were loaded to between one tenth and one fifth of their rated FSO, so confirming a standard deviation of better than 2 % FSO.

16. Keywords

16.1 cone penetration test; cone penetrometer; explorations; field test; friction resistance; geotechnical test; in situ testing; penetration tests; penetrometer; piezocone; point resistance; pore water pressures; resistance; site characterization; sleeve friction; soil investigations

ANNEX

(Mandatory Information)

A1. CALIBRATION REQUIREMENTS ON NEWLY MANUFACTURED OR REPAIRED ELECTRONIC CONES

A1.1 *Introduction:*

A1.1.1 This annex describes procedures and requirements for calibrating newly manufactured and repaired cones.

A1.1.2 Calibrations should be performed with the complete penetrometer system to be used in the field, but depending on the components of the system some components may be substituted with acceptable replacements. Each individual cone must be tested over a range of loads to assure adequate performance.

A1.1.3 *Thermal Stability*—Newly manufactured cones are first cycled to a minimum of 80 % of FSO five times at room temperature, to remove any residual nonlinearity. After cycling an initial baseline reading shall be obtained at room temperature. To evaluate the thermal stability, the cone shall then be stabilized at temperatures of 10°C or below and 30°C or above and new baseline readings shall be obtained. The change in baseline readings must be less than 1.0 % FSO for load cells and pore water pressure transducers.

A1.2 *Terms Related to Force Transducer Calibrations:*

A1.2.1 Fig. A1.1 is a graphical depiction of terms related to transducer calibrations and defines the concepts of zero-load error, nonlinearity, hysteresis, and calibration error (**3**, **1**, **10**).

A1.2.2 To evaluate several of these values, the FSO (full scale output) of the cone is needed.

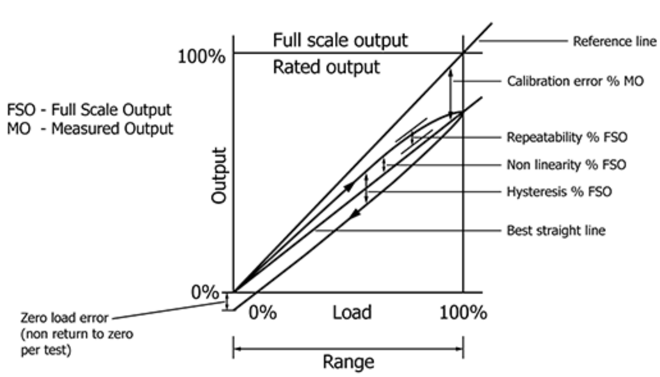


FIG. A1.1 Definition of Calibration Terms for Load Cells and Transducers (1, 10) (courtesy ConeTec Data Services)

A1.2.3 The FSO parameter is also important to avoid overloading and damaging cones.

A1.3 *Force Transducer Calibrations:*

A1.3.1 Newly manufactured or repaired cones shall be calibrated over a range of loads after production or repair using a universal testing machine or specially designed cone calibration device capable of independently loading each load cell. The universal testing machine or cone calibration device must be capable of loading the cone to 100 % FSO and certified within a year to a national standard.

A1.3.2 Before calibrating a new cone, the sensors should be subjected to 15 to 20 repeated loading cycles up to the maximum load at room temperature, before the actual calibration is carried out. When a cone has been repaired five cycles shall suffice.

A1.3.3 For the actual calibration the cone tip is loaded in a minimum of six increments at forces equivalent to 0, 2, 5, 10, 25, 50, and 75 % FSO. At each increment of force, the cone tip and the sleeve resistance shall be recorded. The actual cone tip resistance shall be calculated by dividing the applied force by the cone base area. Using linear regression the linearity shall be determined as a percentage of the cone's FSO, and by comparing the difference between cone resistance at the same level of applied force in loading and unloading the hysteresis shall also evaluated, again as a percentage of the cone's FSO. Finally for each data point the calibration error shall be calculated by taking the difference between the best-fit-straight line cone resistance and actual cone resistance and dividing it by the actual cone resistance. Since calibration errors can become larger with smaller measured outputs, it is not evaluated at loadings equivalent to less than 20 % of cone FSO.

A1.3.3.1 When loading the cone tip the friction sleeve resistance is monitored to evaluate apparent load transfer.

A1.3.4 The friction sleeve is then loaded in a minimum of six increments at forces equivalent to 0, 2, 5, 10, 25, 50, and 75 % FSO. At each increment of force, the cone tip and the sleeve resistance shall be recorded. Nonlinearity, hysteresis, and calibration error are evaluated in the same manner as calibrations for the cone tip reading. During friction sleeve calibration, monitor cone tip resistance to evaluate apparent load transfer that was not apparent in this calibration.

A1.4 *Force Transducer Calibration Requirements:*

A1.4.1 Newly manufactured or repaired electronic cones shall meet the manufacturer's stated tolerances. Minimum requirements are:

Calibration Parameter	Element	Requirement
Zero-load error	Cone tip and sleeve	≤ ± 0.5 % FSO
Zero-load thermal stability	Cone tip and sleeve	≤ ± 1.0 % FSO
Nonlinearity	Cone tip	≤ ± 0.5 % FSO
	Sleeve	≤ ± 1.0 % FSO
Hysteresis	Cone tip and sleeve	≤ ± 1.0 % FSO
Calibration error	Cone tip	≤ ± 1.5 % MO at >20 % FSO
	Sleeve	≤ ± 1.0 % MO at >20 % FSO
Apparent load	While loading cone tip	≤ ± 1.5 % FSO of sleeve transfer
	While loading sleeve	≤ ± 0.5 % FSO of cone tip

A1.4.2 In cases where a higher level of precision than stated in 7.1 is required, stricter calibration requirements are required.

A1.5 *Pressure Transducer Calibrations:*

A1.5.1 Newly manufactured or repaired pressure transducers shall be calibrated by the manufacturer using equipment certified within a year to a national standard. The calibration shall consist of a minimum of six points of loading to at least 75 % of FSO. The calibration shall meet the manufacturer's stated tolerances. Minimum requirements are linearity better than 1 % of FSO and zero load error less than ±7 kPa.

A1.6 Correction of Tip and Sleeve Areas:

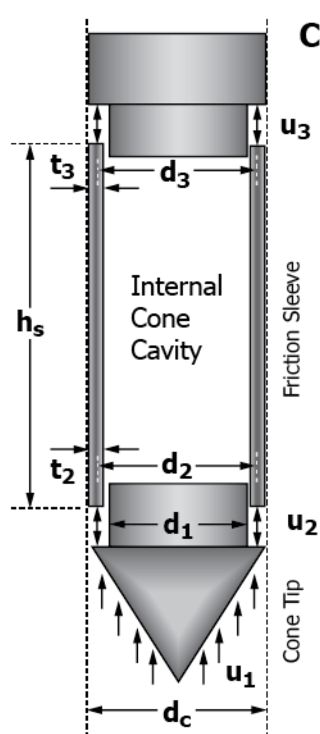
A1.6.1 The conceptual regions where water pressures can act on the cone tip and sleeve elements are shown in Fig. A1.2. Water pressure that acts behind the cone tip will reduce measured cone resistance, q_c, by the magnitude of water pressure acting on unequal areas of the tip geometry.

A1.6.2 In order to calculate the corrected total cone resistance, q_t, it will be necessary to determine the area ratio of the cone. The penetrometer should be enclosed in a specially designed pressure chamber so that the lower part of the cone is mounted in the chamber and be sealed above the friction sleeve. The enclosed part of the cone should then be subjected to an incrementally increasing chamber pressure, and cone tip resistance, sleeve friction and pore pressure are recorded. In this way a calibration curve for the pore pressure transducer is obtained and the net area ratio can be determined from the response curves for cone as shown in the example in Fig. A1.3. The net area ratio is then used in computing the corrected total tip resistance.

A1.7 *Other Calibrations*—Other sensors such as inclination, temperature, etc. may require calibration depending on the requirements of the investigation. Such calibrations shall be performed using similar techniques given in this annex or by other reference procedures.

A1.8 *Documentation of Calibrations*—Calibration records shall be maintained for each cone. These records shall include:

- Description of the cone
- Name of manufacturer
- Serial number or unique identifier
- Date of calibration
- Reference standard, certified reference material or reference material used for calibration



Corrections for Tip and Sleeve Readings

d_j = diameter geometry (as shown)
t_j = thickness of friction sleeve
u_i = measured porewater pressure
q_c = measured cone tip resistance
f_s = measured sleeve friction
q_t = total corrected cone tip resistance
f_t = total corrected sleeve resistance
a_n = tip net area ratio from triaxial test
b_n = sleeve net ratio from triaxial test
h_s = height of sleeve

Sleeve Friction:

$$f_t = f_s - (\pi d_2 t_2 u_2 - \pi d_3 t_3 u_3)/(\pi d_c h_s)$$

$$f_t \approx f_s - b_n u_2$$

Tip Resistance:

$$q_t = q_c + (1 - a_n) u_2$$

FIG. A1.2 Schematic of Net Area Ratio (a_n) for Corrections of Cone Tip Resistances (6)

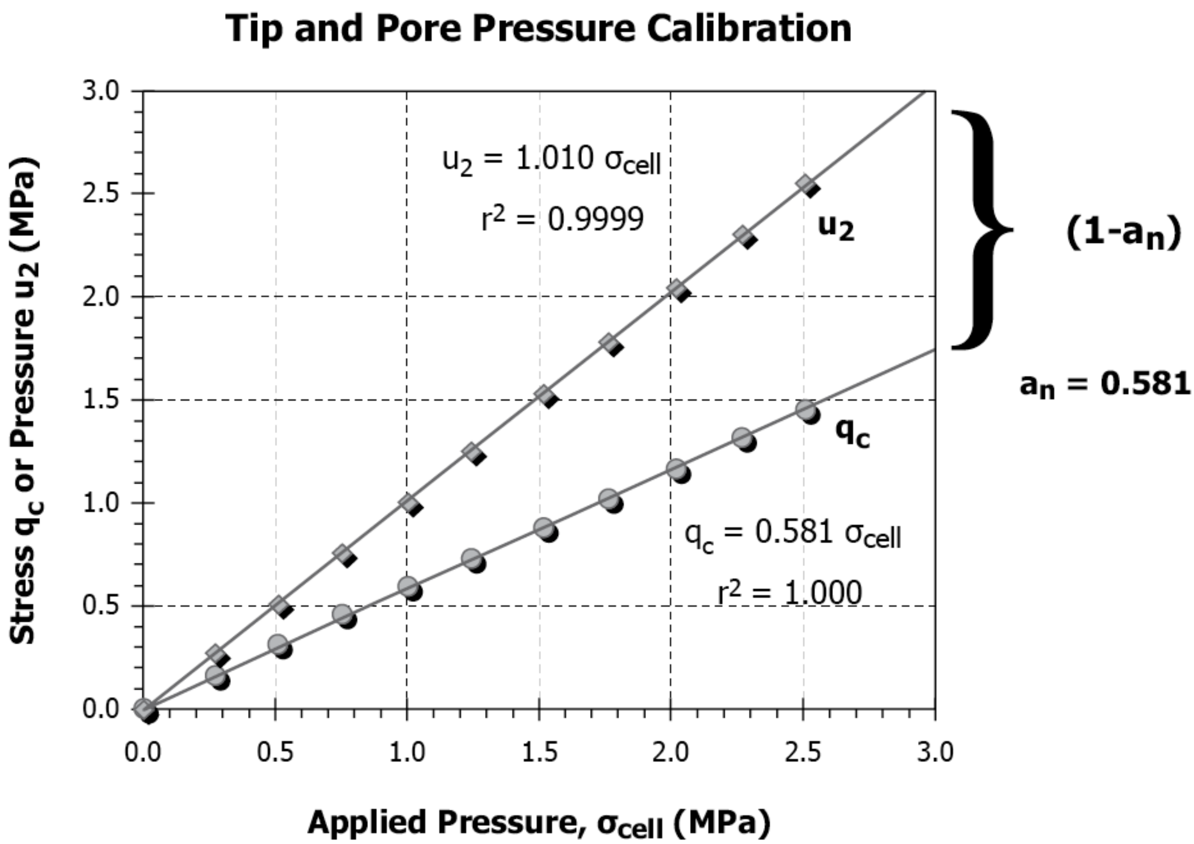


FIG. A1.3 Illustrative Example Determination of Unequal End Area for Correction of Tip Resistances Using Pressurized Triaxial Cell Calibration

- Results of calibration

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SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this test method since the last issue, D5778–12 that may impact the use of test method. (June 1, 2020)

(1) Extensive revisions were made throughout the standard.