Designation: D 5778 – 95 (Reapproved 2000)

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

This standard is issued under the fixed designation D 5778; 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 to penetration of a conical pointed penetrometer as it is advanced into subsurface soils at a slow, 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 slow, steady rate.

1.3 This test method applies to friction-cone penetrometers of the electronic type.

1.4 This test method can be used to determine pore pressure development during push of a piezocone penetrometer. Pore pressure dissipation, after a push, can also be monitored for correlation to soil compressibility and permeability.

1.5 Other sensors such as inclinometer, seismic, and temperature sensors may be included in the penetrometer to provide useful information. The use of an inclinometer is highly recommended since it will provide information on potentially damaging situations during the sounding process.

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

1.7 The values stated in SI units are to be regarded as standard. Within Section 13 on Calculations, SI metric 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 centimetres for convenience. The values stated in each system are not equivalents; therefore, each system must be used independently of the other.

NOTE 1—This test method does not include hydraulic or pneumatic penetrometers. However, many of the procedural requirements herein could apply to those penetrometers.

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

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

E 4 Practice for Force Verification of Testing Machines[3]

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions are in accordance with Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *apparent load transfer*—apparent resistance measured on either the cone or friction sleeve of an electronic 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*—a set of zero load readings, expressed in terms of apparent resistance, that are used as reference values during performance of testing and calibration.

3.2.3 *cone*—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 projected (horizontal plane) surface area or cone base area of 10 or 15 cm^2, and a cylindrical extension behind the cone base.

3.2.4 *cone penetration test*—a series of penetration readings performed at one location over the entire depth when using a cone penetrometer. Also referred to as cone sounding.

3.2.5 *cone penetrometer*—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.

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

3.2.7 *corrected total cone resistance, q_t*—tip resistance

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

[3] *Annual Book of ASTM Standards*, Vol 03.01.

corrected for water pressure acting behind the tip (see 13.2.1). Correction for water pressure requires measuring water pressures with a piezocone element behind the tip at location u_2. The correction results in estimated total tip resistance.

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

3.2.9 *electronic cone penetrometer*—a friction cone penetrometer that uses force transducers, such as strain gage load cells, built into a non-telescoping penetrometer tip for measuring, within the penetrometer tip, the components of penetration resistance.

3.2.10 *electronic piezocone penetrometer*—an electronic cone penetrometer equipped with a low volume fluid chamber, porous element, and pressure transducer for determination of pore pressure at the porous element soil interface.

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

3.2.12 *equilibrium pore water pressure,* u_0—at rest water pressure at depth of interest. Same as hydrostatic pressure (see Terminology D 653).

3.2.13 *excess pore water pressure,* Δu—the difference between pore pressure measured as the penetration occurs, u, and estimated equilibrium pore water pressure ($u_0 - u$). Excess pore pressure can either be positive or negative.

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

3.2.15 *friction ratio,* R_f—the ratio of friction sleeve resistance, f_s, to cone resistance, q_c, measured at where the middle of the friction sleeve and cone point are at the same depth, expressed as a percentage.

3.2.16 *friction reducer*—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.

3.2.17 *friction sleeve*—an isolated cylindrical sleeve section on a penetrometer tip upon which the friction component of penetration resistance develops. The friction sleeve has a surface area of either 150 for 10 cm^2 cone tip.

3.2.18 *friction sleeve resistance,* f_s— the friction component of penetration resistance developed on a friction sleeve, equal to the shear force applied to the friction sleeve divided by its surface area.

3.2.19 *FSO*—abbreviation for full-scale output. The output of an electronic force transducer when loaded to 100 % rated capacity.

3.2.20 *local side friction*—same as friction sleeve resistance.

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.

3.2.22 *penetrometer*—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.

3.2.23 *penetrometer tip*—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.

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

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

3.2.26 *piezocone pore pressure measurement locations,* u_1, u_2, u_3—fluid pressure measured by the piezocone penetrometer at specific locations on the penetrometer as follows: u_1—pore pressure filter location on the face or tip of the cone, u_2—pore pressure filter location immediately behind the cone tip (standard location) and, u_3—pore pressure filter location behind the friction sleeve.

3.2.27 *pore pressure ratio*—the ratio of excess pore pressure, Δu, to cone resistance, q_c, expressed as a percentage (see 13.5.3).

3.2.28 *pore pressure ratio parameter,* B_q—the ratio of excess pore pressure at measurement location Δu_2, to corrected total cone resistance q_t, minus the total vertical stress, σ_v (see 13.5.4.1).

3.2.29 *push rods*—the thick-walled tubes or rods used to advance the penetrometer tip.

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 *CPTu*—abbreviation for the piezocone penetration test.

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^2 is advanced through the soil at a constant rate of 20 mm/s. The force on the conical point (cone) required to penetrate the soil is measured by electrical methods, at a minimum of every 50 mm of penetration. Stress is calculated by dividing the measured force (total cone force) by the cone base area to obtain cone resistance, q_c.

4.2 A friction sleeve is present on the penetrometer immediately behind the cone tip, and the force exerted on the friction sleeve is measured by electrical methods at a minimum of every 50 mm of penetration. Stress is calculated by dividing the measured force by the surface area of the friction sleeve to determine friction sleeve resistance, f_s.

4.3 Many penetrometers are capable of registering pore water pressure induced during advancement of the penetrometer tip using an electronic pressure transducer. These penetrometers 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. The dissipation of either positive or negative excess pore water pressure can be monitored by stopping penetration, unloading the push rod, and recording pore pressure as a function of time. When pore pressure becomes constant it is measuring the equilibrium value or piezometric level at that depth.

5. Significance and Use

5.1 Tests performed using this test method provide a detailed record of cone resistance which is useful for evaluation of site stratigraphy, homogeneity and depth to firm layers, voids or cavities, and other discontinuities. The use of a friction sleeve and pore 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 test method tests the soil in situ and soil samples are not obtained. 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.

6. Interferences

6.1 Refusal, deflection, or damage to the penetrometer 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.

6.3 Standard 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 such as push rod joints and push rod-penetrometer tip 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 *Friction Cone Penetrometer*—The penetrometer tip should meet requirements as given below and in 10.1. In a typical friction cone penetrometer tip (as shown on Fig. 1 **(1)**),[4] the forces produced by friction sleeve resistance and cone resistance during penetration are measured by two load cells within the electronic friction cone penetrometer. Either independent or subtraction-type electronic friction cone penetrometer tips are acceptable for use.

7.1.1 In the subtraction-type friction cone penetrometer, the cone and sleeve both produce compressive forces on the load cells. The load cells are joined together in such a manner that the cell nearest the cone (the "C" cell on Fig. 1(*b*)) measures the compressive force on the cone while the second cell (the "C + S" cell on Fig. 1(*b*)) measures the sum of the compressive forces on both the cone and friction sleeve. The compressive force from just the friction sleeve is computed then by subtraction. This cone design finds the most common use in industry. It is preferred because of its rugged design. This design forms the basis for minimum performance requirements for electronic penetrometers.

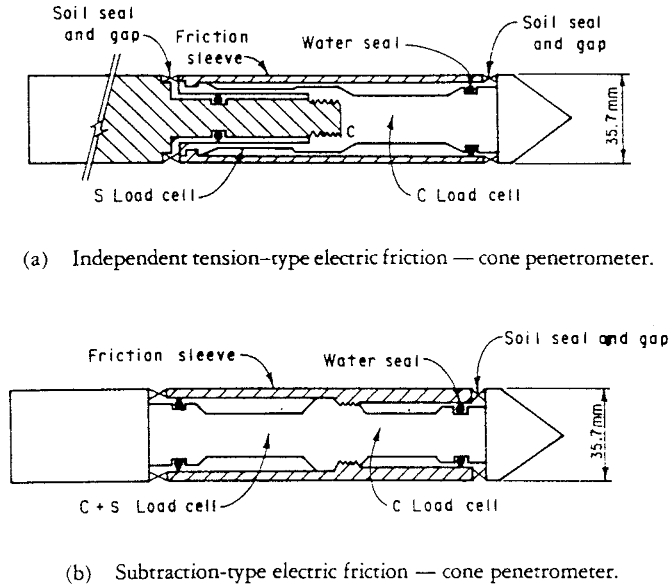


FIG. 1 Typical Electric Friction—Cone Penetrometer Tip Configurations (1)

7.1.1.1 In the independent tension-type cone penetrometer tip, the cone produces a compression force on the cone load cell (the "C" cell on Fig. 1(*a*)) while the friction sleeve produces a tensile force on the independent friction sleeve load cell (the "S" cell on Fig. 1(*a*)). Designs are also available where the independent sleeve element is placed in compression. This penetrometer tip design results in a higher degree of accuracy in friction sleeve measurement, but, depending on the design, it is more susceptible to damage under extreme loading conditions.

7.1.1.2 Typical general purpose cone penetrometers are manufactured to full scale outputs 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 independent type penetrometers 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.

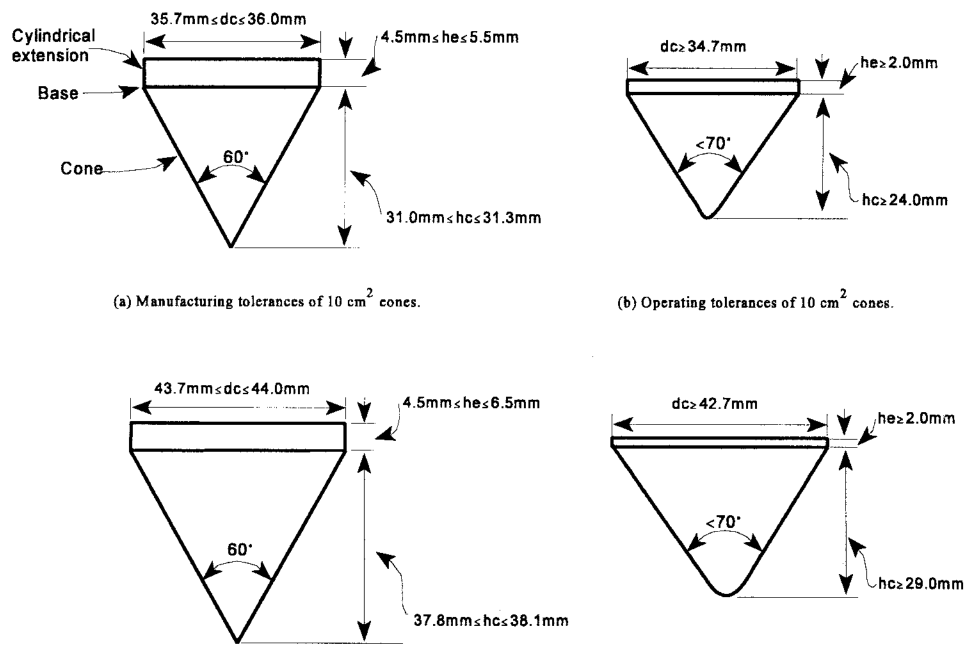
7.1.1.3 The user or client should select the cone design requirements by consulting with experienced users or manufacturers. The need for a specific cone design depends on the design data needs outlined in the exploration program.

7.1.1.4 Regardless of penetrometer type, the friction sleeve

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

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 tips which have worn to the operating tolerance shown on Fig. 2(*b*) and (*d*) should be replaced. Piezocone tips should be replaced when the height of cylindrical extension has worn to approximately 1.5 mm.



(a) Manufacturing tolerances of 10 cm² cones. (b) Operating tolerances of 10 cm² cones.

(c) Manufacturing tolerances of 15 cm² cones. (d) Operating tolerances of 15 cm² cones.

CONE BASE AREA	NOMINAL			TOLERANCE MANUFACTURED (OPERATIONS)		
	BASE DIAMETER	CONE HEIGHT	EXTENSION			
cm²	dc mm	hc mm	he mm	dc mm	hc mm	he mm
10	35.7	31.0	5.0	+0.3 - 0.0 (≥34.7)	+0.3 - 0.0 (≥24.0)	+0.0 - 0.5 (≥2.0)
15	43.7	37.8	5.0 - 6.0	+0.3 - 0.0 (≥42.7)	+0.3 - 0.0 (≥29.0)	+0.0 - 0.5 (≥2.0)

FIG. 2 Manufacturing and Operating Tolerances of Cones (2)

cone has a projected base area, $A_c = 1000$ mm², + 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 cm² 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 which provides a projected cone base area of 15 cm² while maintaining a 60° apex angle. Nominal dimensions, with manufacturing and operating tolerances for the 15 cm² cone, are shown on Fig. 2.

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

NOTE 2—In some applications it may be desirable to scale the cone diameter down to a smaller projected area. Cone penetrometers with 5 cm² projected area find use in the field applications and even smaller sizes are used in the laboratory for research purposes. These cones should be designed with dimensions scaled in direct proportion to 10 cm² 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 cm² penetrometer for soils under consideration. This is because the 10 cm² 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 suitable 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 1.5×10^4 mm$^2 \pm$ 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, sleeve areas of 2.0 to 3.0×10^4 mm^2 have been used successfully in practice. This indicates that acceptable sleeve length to tip diameter ranges from three to five.

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. 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*—Fig. 3(*a*) and (*b*) illustrate penetrometer requirements immediately above the cone tip for the friction cone penetrometer. 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.

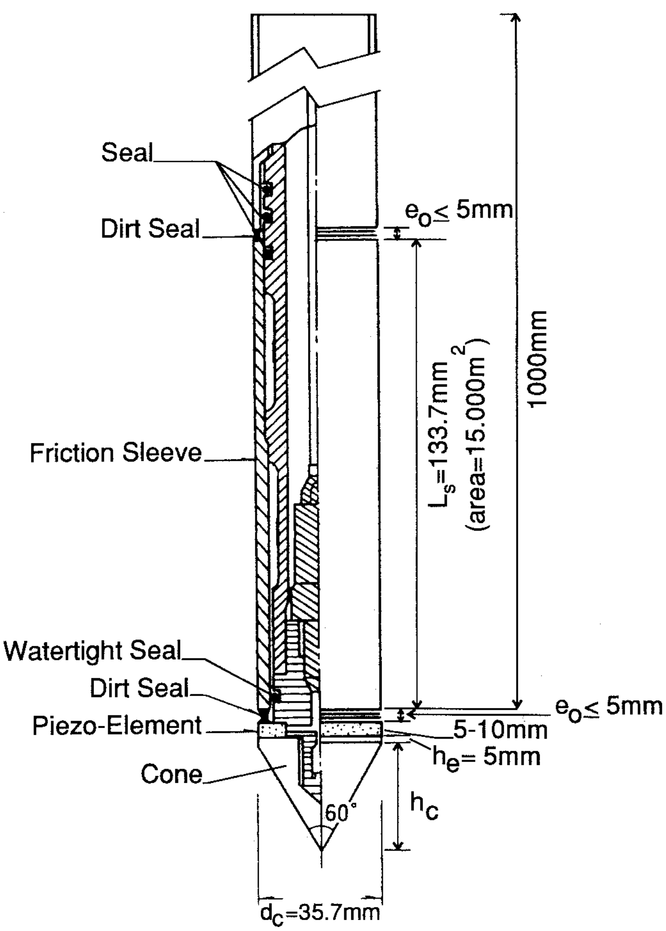


FIG. 3 Example of a Reference Penetrometer With a Fixed Cone and With Friction Sleeve

7.1.4.1 The gap between the cylindrical extension of the cone base and other elements of the penetrometer tip, e_0, 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_o, can range from 8 to 20 mm (see 7.1.8 for explanation).

7.1.5 *Diameter Requirements*—The penetrometer tip is the terminal body housing all sensors to be monitored during testing (see 3.2.25). The penetrometer tip includes the cone tip, friction sleeve, and other sensors normally located just above the friction sleeve. The friction sleeve should be located within 5 to 15 mm behind the base of the cone. The friction sleeve diameter tolerance is given in 7.1.3. 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 has the same diameter as the cone for the complete length of the penetrometer body **(2)**.

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 3—The effects 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 practioners 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 gage 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.

7.1.8 *Electronic Piezocone Penetrometer*— A piezocone penetrometers can contain porous element(s), pressure transducer(s), and fluid filled ports connecting the elements to the transducer to measure pore water pressure. Numerous design and configuration aspects can affect the measurement of dynamic 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 pore pressure measured during testing and dissipation tests of dynamic pressures **(3)**. It is beyond the scope of the procedure to address all of these variables. As a minimum, complete information should be reported as to the design, configuration, and the preparation of the piezocone system.

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 hydrostatic pressures will equalize within 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 pore 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. The element is less subject to damage and abrasion, there are less compressibility effects, and the data can be used for corrected total tip pressure, q_t **(3)**. Elements located in the u_2 location may be subject to cavitation at shallow depths in sands because the zone behind the height of cylindrical extension is a zone of dilation in drained soils. In some cases, the corrected total cone resistance, q_t, can be estimated with pore pressures measured in the u_1 position through empirical correlation with soil type. Some piezometer elements are housed within the height of cylindrical extension of the cone tip itself. Pore pressure measurements obtained in the u_1 location are more effective for compressibility determinations and layer detection but are more subject to wear **(3)**. In the u_2 location a minimum 2.5-mm cylindrical extension of the cone tip, h_e, should be maintained for protection of the cone. Typical element thickness in 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 pore 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. The pore 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 200 µm or smaller. Different materials have different advantages. Smearing of the element openings by hard soil grains may reduce dynamic response of the system. Problems have been experienced with smearing of sintered metal elements. Ceramic elements are very brittle and often crack when loaded. Polypropylene plastic elements are most commonly used in practice. Typically, the filter element is wedged in the tip, U_1 location, or located in the gap immediately above the cone extension, U_2 location. In 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*—Silicon oil or glycerin is most often used for deairing elements for dynamic response. The 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 dynamic response is not important. The fluids are deaired using procedures described in 11.2.

7.2 *Measuring System*—The signals from the penetrometer transducers are to be displayed at the surface during testing as a continuously updated plot against depth. 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 analogue to digital conversion. Either magnetic (disk or tape) or optical (disk) non-volatile storage may be used. The temperature stability and accuracy of the analogue to digital converter shall be such that the overall cone/transmission/recording system complies with calibration requirements set forth in the annex.

7.2.1 Use of analog systems is acceptable but the system resolution may be lower than requirements in the annex and Section 10. Use of an analog recorder as a supplement to digital system is advantageous because it can provide system backup.

NOTE 4—Present practice is to use ASCII formatted data on magnetic floppy disks readable by MS-DOS compatible computers. The data files should include project, location, operator, and data format information so that the data can be understood when reading the file with a text editor.

7.3 *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 cables the cable is prestrung through the rods prior to testing. Push rods are supplied in 1-meter lengths. 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.

7.3.1 For the 10 cm^2 penetrometer, standard 20-metric ton high tensile strength steel push rods are 36-mm outside diameter, 16-mm inside diameter, and have a mass per unit length of 6.65 kg/m. 15 cm^2 penetrometers may be pushed with 44.5 mm outside diameter rods or with standard rods used for the 10 cm^2 penetrometer.

7.4 *Friction Reducer*—Friction reducers are normally used on the push rods to reduce rod friction. If a friction reducer is used, it should be located on the push rods no closer than 0.5 m behind the base of the 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 is advanced with 36 mm push rods there may be no need for friction reducers. The type, size, amount, and location of friction reducer(s) used during testing must be reported.

7.5 *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 penetrometer tip 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 penetrometer and does not move relative to the soil surface during thrust.

NOTE 5—Cone penetration soundings usually require thrust capabilities ranging from 98 to 196 kN (10 to 20 metric tons). High mass ballasted vehicles can cause soil surface deformations which may affect penetrometer 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.

7.6 *Other Sensing Devices*—Other sensing devices can be included in the penetrometer body to provide additional information during the sounding. These instruments are normally read at the same rate as tip, sleeve and pore pressure sensors or during pauses of push. Typical sensors are inclinometer, temperature, or seismic sensors. These sensors should be calibrated if their use is critical to the investigation program. 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. The configuration and methods of operating such sensors should be reported.

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 gage surface is exposed to the compound.

8.2 *Glycerin* $CHOH(CH_2OH)_2$, for use in pore pressure measurement system. 95 % pure glycerin can be procured from most drug stores.

8.3 *Silicon Oil*, for use in pore pressure measurement system. This material is available in varying viscosities ranging from 400 to 10 000 CP. More viscous versions may provide better response.

9. Hazards

9.1 *Technical Precautions—General*:

9.1.1 Use of penetrometer components that do not meet required tolerances or show visible signs of non-symmetric wear can result in erroneous penetration 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 25 borehole diameters from any existing unbackfilled or uncased bore hole.

9.1.4 When performing cone penetration testing in prebored holes, an estimate of the depth below the prebored depth which is disturbed by drilling, should be made and penetration resistance data obtained in this zone should be noted. Usually, this depth of disturbance is assumed to be equal to at least three borehole diameters.

9.1.5 Significant bending or buckling 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.

9.1.6 Push rods not meeting requirements of 7.3 may result in excessive directional penetrometer drift and possibly unreliable penetration resistance values.

9.1.7 Passing through or alongside obstructions may deflect the penetrometer and induce directional drift. Note any indications of encountering such obstructions, and be alert for possible subsequent improper penetrometer tip operation.

9.1.8 If the proper rate of advance of the penetrometer is not maintained for the entire stroke through the measurement interval, penetration resistance data will be erroneous.

9.2 *Technical Precautions—Electronic Friction Cone Penetrometer*:

9.2.1 Failure of O-ring seals can result in damage to or inaccurate readings from electronic transducers. The O-ring seals should be inspected regularly, after each sounding, for overall condition and watertightness.

9.2.2 Soil ingress between different elements of a penetrometer tip can result in unreliable data. Specifically, soil ingress will detrimentally affect sleeve resistance data. Seals should be inspected after each sounding, 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 cone penetrometer tips should be temperature compensated. If extreme temperatures outside of the range established in A1.3.3 are to be encountered, the penetrometer should be checked for the required temperature range to establish they can meet the calibration requirements.

9.2.4 If the shift in baseline reading after extracting the penetrometer tip from the soil is so large that the conditions of accuracy as defined in 10.1.2.1 are no longer met, penetration resistance data should be noted as unreliable. If baseline readings do not conform to allowable limits established by accuracy requirements in 10.1.2.2, the penetrometer tip must be repaired, and recalibrated or replaced.

9.2.5 Electronic friction cone penetrometer tips having an unequal friction sleeve end area ratios will yield friction sleeve resistance data that are erroneous because of unequal dynamic pore pressures encountered along the length of the sleeve during penetrometer tip advancement. Friction sleeve design should be checked in accordance with A1.7 to ensure balanced response. The response is also dependent on location of water seals. If O-ring water seals are damaged during testing, and sleeve data appear affected, the sounding data should be noted as unreliable and the seals should be repaired.

9.3 *Piezocone Penetrometer*—The electronic piezocone penetrometer tip easures pore water pressures on the exterior of the penetrometer tip by transferring the pressure through a de-aired fluid system to a pressure transducer in the interior of the tip. 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 pressure fluctuation during penetrometer tip advancement will be incorrect due to response lag from compression of air bubbles (see 11.2, 12.3.1, and 12.3.2). For soundings where dynamic response is important, the prepared filter elements should be replaced after every sounding.

10. Calibration and Standardization

10.1 *Electronic Friction Cone Penetrometers*:

10.1.1 The requirements for newly manufactured or repaired cone penetrometers are of importance. Newly manufactured or repaired electronic cone penetrometers 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. Calibration procedures and requirements given in the annex are for subtraction-type cone penetrometers. Calibration requirements for independent-type cone penetrometers should equal or exceed those requirements. 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. Applied forces or masses must be traceable to calibration standard forces or masses retained by the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards. For description of calibration terms and methods for calibrating, refer to the annex.

10.1.2 Field calibration of electronic cone penetrometers is required. Field calibration requires use of a loading device, calibrated to traceable calibration standards, that can independently apply forces up to 50 % of rated capacity on the cone and friction sleeve load cells.

10.1.2.1 *Baseline Readings*—Baseline or zero-load readings for both cone and friction sleeve load cells 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. Take the initial baseline reading after warming electrical circuits according to the manufacturer's instructions, generally for 15 to 30 min, and in a temperature environment as close as possible to that of the material to be sounded. If temperature is of concern, immerse the penetrometer tip in a bucket of fresh tap water, or insert the penetrometer tip in the ground while electrically warming circuits to stabilize its temperature and then extracted for rapid determination of initial baseline. After a sounding is completed, take a final baseline. The change in initial and final baseline values should not exceed 1 % FSO for the cone and 2 % FSO for the sleeve.

10.1.2.2 Maintain a continuous record of initial and final baselines during production testing. After each sounding, compare the final baseline to the initial baseline for agreement within the tolerances noted above. In some cases during heavy production testing where the cone is not disassembled and cleaned after each sounding, the initial baseline for the next sounding can serve as the final baseline to the previous sounding as long as agreement is within allowable limits.

10.1.2.3 If the post sounding baseline shift exceeds above criteria, inspect the cone for damage by inspecting the tip and checking to see that the sleeve can be rotated by hand. If there is apparent damage replace parts as required. Clean the cone and allow temperatures to equalize to presounding conditions, and obtain a new baseline. If this value agrees with the initial baseline within the above criteria, a load range calibration check is not required. If the pre and post baselines are still not within the above criteria then it is likely that the shift was caused by an obstacle or obstruction and linearity should be checked with a load range calibration.

10.1.2.4 If the baseline shift still exceeds the above criteria, perform a load range calibration as described in 10.1.2.1. If the cone load cell baseline shift exceeds 2 % FSO, the cone is likely damaged and will not meet load range criteria in 10.1.2.3. Sleeve load cell baseline shifts for subtraction-type penetrometers usually can exceed 2 % FSO and still meet load range criteria.

10.1.2.5 Report data for the sounding where unacceptable baseline shift occurs as unreliable. In some cases it may be obvious where the damage occurred and data prior to that point may be considered reliable. The location where obvious damage occurred should be clearly noted in reports.

10.1.3 *Load Range Calibrations*—For penetrometers used in production, it is recommended to have a plan for performing linearity checks at regular periodic intervals or when baseline information may indicate damage. Load range calibrations can be performed either in the field or in the laboratory. Conditions where load range checks should be performed are listed in 10.1.3.1, 10.1.3.2, and 10.1.3.4. Perform calibrations with all O-rings and seals in place. Working load range calibrations are to consist of a minimum of 6 points at 0, 2, 5, 10, 25, and 50 % of full-scale loading for cone and friction sleeve load cells independently. Field load range calibrations may be performed with maximum load increments less than 50 % FSO if safety is a concern. During load range calibrations, the amount of apparent load transfer during cone or friction sleeve loading must also be monitored. Penetrometers that do not meet the requirements given below or in 10.1.2.1 must be discarded, recalibrated, or sent to the manufacturer for repair.

Calibration Parameter	Element	Requirement
Zero load shift	Cone	$\leq \pm 0.5$ % FSO
Zero load shift	Sleeve	$\leq \pm 1$ % FSO
Linearity	Cone	$\leq \pm 1$ % FSO
Linearity	Sleeve	$\leq \pm 2$ % FSO
Apparent load transfer	Cone	Maximum sleeve value $\leq \pm 2.0$ % FSO
Apparent load transfer	Sleeve	Maximum cone value $\leq \pm 0.5$ % FSO
Calibration error	Cone	$\leq \pm 2$ % of Measured output at loads greater than 20 % of FSO
Calibration error	Sleeve	$\leq \pm 3$ % of Measured output at loads greater than 20 % of FSO

10.1.3.1 For penetrometers used regularly during production, regular periodic load range checks should be performed. The period can be based on production footage such as once every 1500 m. If field load range equipment is not available, the penetrometer may be checked in the laboratory at the end of a project.

10.1.3.2 For penetrometers that are infrequently used a periodic check may be based on time period, such as once every year. If a penetrometer 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 load range checks before and after the project.

10.1.3.4 Load range calibrations are required if the initial and final baselines for a sounding do not meet requirements given in 10.1.2.1.

10.1.3.5 Records documenting the history of an individual penetrometer should be maintained for evaluation of performance.

10.2 *Pore Pressure Transducer*—Calibrate newly manufactured or repaired transducers in accordance with requirements in the annex. During production, the transducer should be calibrated at regularly scheduled intervals (as in 10.1.3.1) and whenever linear performance is suspect. A load range calibration to 50 % of FSO with a minimum of five equally spaced points should result in pressure readings within ± 14 kPa of reference gage values. The reference gage can be a bourden tube pressure gage, or electronic pressure transducer that is calibrated annually to NIST traceable loading device (dead weight testing apparatus).

10.2.1 Prior to testing, baseline values or initial zeroing of the transducer is performed on the pore pressure transducer at ambient air pressures at the surface. Maintain records as to the baseline values for the transducer in similar fashion to those for tip and sleeve resistance. If significant changes in baseline values occur, normally 1 to 2 % FSO, perform load range tests to check for possible damage and nonlinear response.

10.3 *Calibrations of Other Sensing Devices*—Calibration data for other sensors in the penetrometer body 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 minimum important 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 Power electronic cone penetrometer and data acquisition systems for a minimum time period to stabilize electric circuits before performing soundings. Power the system to manufacturer's recommendations prior to obtaining reference baselines. For most electronic systems this time period is 15 to 30 min.

11.2 Electronic piezocone penetrometer soundings require special preparation of the transmitting fluid and porous elements such that entrained air is removed from the system. For soundings where dynamic response is important, replace the prepared filter elements and the ports flushed after every sounding. Some of the techniques discussed below have been successful for preparation of elements. Regardless of the techniques used, report the equipment and methods.

11.2.1 Field or laboratory tests can be performed to evaluate assembled system response. Place the cone tip and element in a pressurized chamber and subject to rapid pressure change. Compare the response of the system to the applied pressure changes and if responses match, the system is properly prepared. These tests are not routinely performed in practice as long as proven preparation methods such as those listed below are followed.

11.2.2 Place elements in a pure glycerin or silicon oil bath under a vacuum of almost one atmosphere. Maintain vacuum until air bubble generation is reduced to a minimum. Application of ultrasonic vibration and low heat, <50°C, will assist in removal of air. Generally with use of combined vacuum, ultrasonic vibration, and low heat, elements can be deaired in 3 to 4 h.

11.2.3 Elements can be prepared in water by boiling the elements while submerged in water for 4 to 5 h.

11.2.4 *Other Suitable Means*—Report other techniques.

11.2.5 *Storage*—Store prepared elements submerged in the prepared fluid until ready for use. Fill the containers and evacuate during storage. 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 glycerin or silicon may be stored for longer periods, up to one month, after storage containers have been exposed to air.

12. Procedure

12.1 *General Requirements*:

12.1.1 Prior to beginning a sounding, perform site surveys to ensure hazards such as underground utilities will not be encountered. Position the thrust machine over the location of the sounding, and lower leveling jacks to raise the machine mass off the suspension system. Set the hydraulic rams of the penetrometer thrust system to as near vertical as possible. The axis of the push rods must coincide with the thrust direction.

12.1.2 Set the hydraulic ram feed rate to advance the penetrometer at a rate of 20 ± 5 mm/s for all electronic cone penetrometers. This rate must be maintained during the entire stroke during downward advance of the rods while taking readings.

12.1.3 Check push rods for straightness as required in 7.3. Push rods are assembled and tightened by hand, 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 electronic cone penetrometers using cables, the cable is prestrung through the push rods. Add friction reducer to the string of push rods as required, usually the first push rod behind the penetrometer tip and other rods as required.

12.1.4 Inspect penetrometer tips before and after soundings for damage, soil ingress, and wear. In very soft and sensitive soils where accurate sleeve data is required, dismantle electronic cone penetrometer tips after each sounding to clean and lubricate as required. If damage is found after a sounding, note and record this information on the sounding data record or report.

12.2 *Friction Cone Penetrometers*:

12.2.1 Power up the penetrometer tip and data acquisition system according to the manufacturer's recommendations, typically 15 to 30 min, prior to use.

12.2.2 Obtain an initial baseline reading for the penetrometer in an unloaded condition at a temperature as close as possible to ground conditions. Obtain baseline readings with the penetrometer tip hanging freely in air or in water, out of direct sunlight. Compare baseline readings with the previous baseline reading for the requirements given in 10.1.2.1. If thermal stability needs to be assured, immerse the penetrometer tip in a bucket of water at temperature close to ground; or perform an initial short penetration test hole, stop penetration and allow the penetrometer tip to reach soil temperature, and withdraw the penetrometer.

12.2.3 Measure the depth at which readings were taken with an accuracy of at least ±100 mm from the ground surface.

12.2.4 Determine the cone resistance and friction sleeve resistance, continuously with depth, and record the data at intervals of depth not exceeding 50 mm.

12.2.5 During the progress of sounding, monitor tip and sleeve forces 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 At the end of a sounding, extract the penetrometer tip, obtain a final set of baseline readings with the penetrometer tip hanging freely in air or in water, and check them against the initial baseline. Record initial and final baselines on all documents related to the sounding.

12.3 *Electronic Piezocone Penetrometers*:

12.3.1 Assemble the piezo elements with all fluid chambers submerged in the de-aired medium used to prepare the elements. Flush all confined areas with fluid to remove air bubbles. Tighten the cone tip to effectively seal the flat surfaces. For water fluid systems, protect the assembled system from evaporation by enclosing the porous element inside a fluid-filled plastic bag or cap sealed to the penetrometer tip.

12.3.2 If unsaturated soil is first penetrated and it is desired to obtain accurate dynamic pore 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 be cavitated during penetration through unsaturated soil or in dilating sand layers below the water table which 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 **(3)**.

12.3.3 Record baseline readings with the penetrometer tip hanging freely in air, or in water, out of direct sunlight. Compare baseline readings with reference baseline readings for requirements given in 10.1.2.1 and 10.2. A baselines for the pore pressure transducer is obtained for immediately after assembly to avoid evaporation effects. If evaporation is a problem, temporarily immerse the penetrometer in a bucket of water until ready for baseline. Do not obtain transducer baselines with protective caps or covers in place as these may induce pressure in the system. Note the pressure from the pressure transducer to see if it is a reasonable value for the equipment and assembly technique used.

12.3.4 Follow procedures in 12.2.4-12.2.6 with the addition of recording pore pressure.

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 pressures are measured at the u_2 or u_3 locations it is common practice to release the force on the push rods. If pore pressures are measured at location u_1, maintain the force on the push rods. Record pore pressure versus time during conduct of the dissipation test. Monitor pressures until equilibrium pore pressure is reached or 50 % of the initial pore 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. Report dissipation test data as a record of pressure versus time.

12.4 *Penetrometer Operation and Data Interpretation-Guidelines*:

12.4.1 *Directional Drift of Penetrometer*:

12.4.1.1 The penetrometer may drift directionally from vertical alignment. Large deviations in inclination can create nonuniform loading and result in unreliable penetration resistance data. Reduce drift by accurately setting thrust alignment and using push rods which meet tolerances given in 7.3.

12.4.1.2 Passing through or alongside obstructions such as boulders, cobbles, coarse gravel, soil concretions, thin rock layers, or inclined dense layers will deflect the penetrometer tip and induce drifting. Note and record any indication of encountering such obstructions, and be alert for possible subsequent improper penetrometer tip operations as a sign of serious directional drift.

12.4.1.3 Penetrometer inclination is typically monitored in cone penetrometers. Impose limitations on inclination in the system to prevent damage to push rods and non-symmetric loading of the penetrometer tip. Generally, a 5° change in inclination over 1 m of penetration can impose detrimental push rod bending. Total drift of over 12° in 10 m of penetration imposes non-symetric loading and possible unreliable penetration resistance data.

12.4.2 *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, note and record the depths at which push rods are added and where long pauses may have affected initial startup resistances.

12.4.3 *Piezocone Pore Pressure Dissipation Interruptions*—Pore 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 pressure readings at resumptions of cone penetration. If dissipation tests are performed, be aware of possible rebound effects on initial excess pore pressures. Note and record the depth and duration for which dissipation values are taken.

12.4.4 *Interruptions Due to Obstructions*— If obstructions are encountered and normal advance of the sounding is stopped to bore through the obstructions, obtain further penetration resistance data only after the penetrometer tip has passed through the estimated zone of disturbance due to drilling. As an alternative, readings may be continued without first making the additional penetration and the disturbed zone evaluated from these data. Note and record the depth and thickness of obstructions and disturbed zones in areas where obstructions are drilled through.

12.4.5 *Excessive Thrust Capacity*—If excessive thrust pressure begins to impede the progress of the sounding, it may be necessary to withdraw and change friction reducers. Alternately, sometimes friction may be reduced by withdrawing the penetrometer and rods up to one third to one half of the penetration depth and then repushing to depth at which the friction caused stopping. Continue collection of sounding data from the point of stopping. Note and record the delay time and depths to which the penetrometer was moved. Long delays and pauses may cause buildup of friction on the rods. Hold delays to the minimum required to perform dissipation tests or equipment repairs.

12.4.5.1 If a high resistance layer is encountered, and the truck is physically moved during penetration, terminate the sounding. 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.

12.4.6 *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. Note and report all occurrences of coarse gravels.

12.5 *Withdrawal*:

12.5.1 Withdraw the push rods and penetrometer tip as soon as possible after attaining complete sounding depth.

12.5.2 Upon complete withdrawal of the penetrometer, inspect the penetrometer tip for proper operation. The friction sleeve should be able to be rotated through 360° by hand without detectable binding.

12.5.3 Record baseline readings with the penetrometer tip hanging freely in air, or in water, out of direct sunlight. Compare baseline readings with initial baseline reading for requirements given in 10.1.2.1.

13. Calculation

13.1 *Friction Cone Penetrometers*—Most electronic cone penetrometers in use at the present time measure a change in voltage across a strain gage element to determine change in length of the strain element. Using known constitutive relationships between stress and strain for the strain element, the applied force may be determined for the cone or friction sleeve. The applied force may then be converted to stresses using the basic equations given in 13.2 and 13.3. Since there are a wide variety of additional, optional measurements currently being obtained with electronic cone penetrometers and new ones being continually developed, it is beyond the scope of this procedure to detail the makeup, adjustments, and calculations for these optional measurements.

13.2 *Cone Resistance, q_c—Required*:

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

where:

q_c = cone resistance MPa (ton/ft^2, kg$_f$/cm^2, or bar),
Q_c = force on cone kN (ton, or kg$_f$), and
A_c = cone base area, typically 10 cm^2, or 15 cm^2.

13.2.1 *Corrected Total Cone Resistance (Optional)*—Calculation of corrected total cone resistance requires measurement of dynamic pore pressures measured cone tip. This correction is most readily performed with water pressure measured in the u_2 position. Empirical adjustment factors based on soil types have been developed for some pressure elements in the u_1 position.

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

where:

q_t = corrected total cone resistance, MPa (ton/ft^2, kg$_f$/cm^2, or bar),
u_2 = pore pressure generated immediately behind the cone tip, kPa (lb$_f$/in.^{2}, kg$_f$/cm^2, bar), and
a = net area ratio (see A1.7).

13.3 *Friction Sleeve Resistance, f_s—Required*:

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

where:

f_s = friction sleeve resistance kPa (ton/ft^2, kg$_f$/cm^2, or bar),
Q_s = force on friction sleeve kN (ton, kg$_f$), and
A_s = area of friction sleeve, typically 150 cm^2, or 225 cm^2.

13.4 *Friction Ratio, R_f—Required*:

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

where:

R_f = friction ratio, %,
f_s = friction sleeve resistance kPa (ton/ft^2, kg$_f$/cm^2, or bar),
q_c = cone resistance kPa (ton/ft^2, kg$_f$/cm^2, or bar), and
100 = conversion from decimal to percent.

13.4.1 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 is taken as the reference depth. Typically, a previous cone resistance reading at friction sleeve midpoint depth is used for the calculations. For the 10 cm^2 cone the standard offset is 100 mm. If an offset other than midheight is used it must be reported.

NOTE 6—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 7—The friction sleeve resistance and friction ratio obtained from the mechanical friction cone penetrometers will differ considerably from values obtained from electronic friction cone penetrometers. 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 penetrometer being used.

13.5 *Pore Pressure Data*:

13.5.1 SI metric units for reporting pore pressure data are kPa.

13.5.2 *Conversion of Measured Pore Pressures to Equivalent Height of Water—Optional*—If it is desired to display pore pressure in equivalent height of water, convert the dynamic or static water pressures to height by dividing pressure by the unit weight of water—9.8 kN/m^3(62.4 lb$_f$/ft^3).

13.5.3 *Pore Pressure Ratio—Optional*— Some reports may require a plot of pore pressure ratio. This is ratio of excess pore pressure, Δu, to cone resistance, q_c, expressed as a percentage. Excess pore pressure can only be calculated by knowing equilibrium pore water pressure, u_o (see 3.2.14). The equilibrium water pressure can be measured by dissipation test or estimated by calculation as follows (see Terminology D 653):

$$u_o = \text{estimated equilibrium water pressure} = h_i \cdot \gamma_w \tag{5}$$

where:
h_i = height of water, m, estimated from site conditions, and
γ_w = unit weight of water = 9.8 kN/m^3.

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

13.5.4 *Normalized Pore Pressure Parameters—Optional*—Several researchers have proposed normalized penetration resistance parameters to more accurately predict soil properties such as overconsolidation ratio **(3, 4)**. Some of the parameters listed below may be calculated depending on requirements of the investigation program.

13.5.4.1 *Pore Pressure Parameter Ratio, B_q*—This parameter is normally calculated with the pore pressure measurement location immediately behind the cone tip, u_2.

$$B_q = \Delta u_2/(q_t - \sigma_{vo}) \tag{6}$$

where:
Δu = excess pore water pressure ($u - u_o$) (see 3.2.15),
u_o = estimated equilibrium water pressure (see 13.5.3), and
σ_{vo} = total vertical overburden stress =

$$\Sigma h_i \cdot \gamma_i \tag{7}$$

where:
h_i = layer thickness, and
γ_i = total unit weight of soil for layer thickness, estimated from penetration data or site conditions.

13.5.4.2 *Revised Friction Ratio—F*— This parameter is normally calculated with the pore pressure measurement location immediately behind the cone tip, u_2. This parameter is calculated as:

$$F = f_s/(q_t - \sigma_v) \tag{8}$$

Where f_s, q_t, and σ_v are defined above.

14. Report

14.1 Report the following information:

14.1.1 General—Each sounding log should provide as a minimum:

14.1.1.1 Operator name,

14.1.1.2 Project information,

14.1.1.3 Feature notes,

14.1.1.4 Water surface elevation (if available),

14.1.1.5 Sounding location,

14.1.1.6 Sounding number, and

14.1.1.7 Sounding date.

14.1.2 Reports should contain information concerning:

14.1.2.1 *Equipment Used*—Design drawings and data on all sensors,

14.1.2.2 Graphical data,

14.1.2.3 Tabular data (optional),

14.1.2.4 Procedures followed, and

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

14.1.3 The report should contain a text that discusses items required in 14.2 and 14.3. Each sounding should be documented with:

14.1.3.1 Sounding plot.

14.1.3.2 *Accompanying Tabular Output*—Tabular output is considered optional due to its bulk. It is optional as long as computer data files are preserved and archived for later use.

14.1.3.3 *Computer Data Files*—Preferably in ASCII format. Computer data files must contain header as required in 14.1, sounding log information. Certain interpretation programs require data to be in a particular format. It is the responsibility of the user to determine acceptable formats.

14.1.3.4 The comments should contain notes on equipment and procedures, particular to the individual sounding.

14.2 *Equipment*—The report should include notes concerning:

14.2.1 Penetrometer manufacturer,

14.2.2 Types of penetrometer tips used,

14.2.3 Penetrometer details such as friction sleeve end areas, location and types of sensors, location and type of friction reducers,

14.2.4 Offset between tip and sleeve resistance used for friction ratio determination,

14.2.5 Serial numbers of penetrometer tips,

14.2.6 Type of thrust machine,

14.2.7 Method used to provide reaction force—with notes as to possible surface deformations,

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

14.2.9 Method of recording data,

14.2.10 Condition of push rods and penetrometer tip after withdrawal,

14.2.11 Any special difficulties or other observations concerning performance of the equipment,

14.2.12 Details on piezocone design, filter elements, and fluid conditioning procedures, and

14.2.13 Information on other sensing devices used during the sounding.

14.3 *Calibration Certifications*—For each project the report should include the load range calibrations of the cones used that were performed in accordance with Section 10. The report should include the initial and final baseline readings for each sounding. Calibration records for the pore pressure transducers are required as given in 10.2. If the project requires calibrations of other sensors they should also be submitted in final reports.

14.4 *Graphs*—Every report of friction cone penetration sounding is to include a cone resistance plot, q_c, MPa (ton/ft^2, kg$_f$/cm^2, or bar) with depth below ground surface m (ft), friction sleeve resistance, f_s, kPa (ton/ft^2, kg$_f$/cm ^{2}, or bar), and friction ratio, *Rf* (%), on the same plot. (See Fig. 4 and Fig. 5 for example plots.) As a minimum, the plot should provide general information as outlined in 14.1. Electronic piezocone penetrometer soundings should provide an additional plot of pore pressure kPa (lb$_f$/in.^{2}, kg$_f$/cm^2, or bar) versus depth m (ft). Pore pressures can be plotted or the pressure may be converted to equivalent heights of water.

14.4.1 Symbols q_c and f_s for tip and sleeve resistance are accepted by the International Society for Soil Mechanics and Foundation Engineering **(2)**. Some plotters are not capable of plotting subscript symbols. In these cases it would be acceptable to have plots displayed in terms of q_c and f_s.

14.4.2 For uniform presentation of data, the vertical axis (ordinate) should display depth and the horizontal axis (abscissa) should display the test values. There are many preferences in plotting such that uniform plotting scales and presentation will not be required.

15. Precision and Bias

15.1 *Precision*—There is 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:

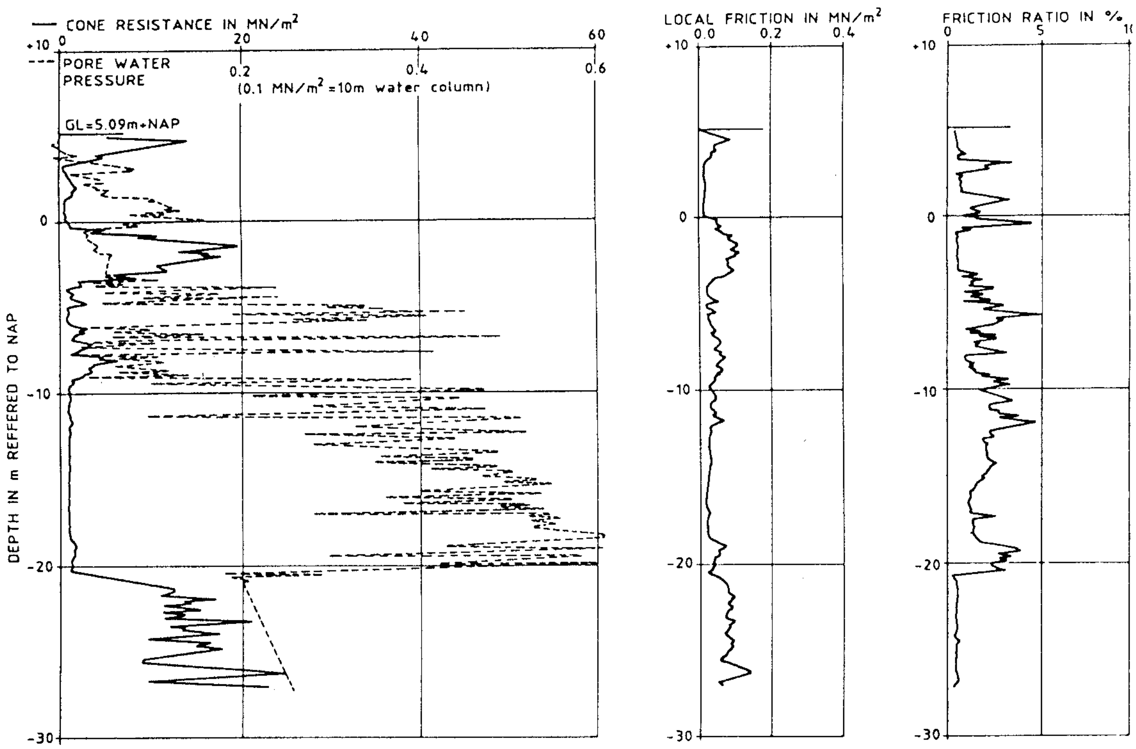
15.1.1 *Cone Resistance*—Provided that compensation is made for unequal area effects as described in 13.2.1, a standard deviation of approximately 2 % FSO (that is, comparable to the basic electromechanical combined accuracy, nonlinearity, and hysteresis).

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

15.1.3 *Sleeve Friction—Independent 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 11.2. 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.



Piezo cone nr : 10/1-355
size of filter : heigth 3,0mm, thickness 3,0mm
location of filter : directly above the cone
material of filter : sintered stainless steel

zero-reading:		before test	after test	capacity
	cone	0	-0,010 MN/m²	100 MN/m²
	friction sleeve	0	-0,0001MN/m²	0,7 MN/m²
	piezo meter	0	+0,008 MN/m²	1 MN/m²

Remarks:
friction reducer : not applied
abnormal interruptions : none
observations : no special observations
fill/excavation : old fill 4m thickness
inclinometer : no readings taken
condition of push rods/penetrometer tip after test : gooc
waterlevel in sounding hole : hole collapsed near surface
backfilling : none

WONINGEN TE MAASSLUIS *date of test : 87-02-19*
CONE PENETRATION TEST GD. 02(RE) *time : 14-15 hrs*

FIG. 4 Example of the Presentation of the Test Results on a Graph

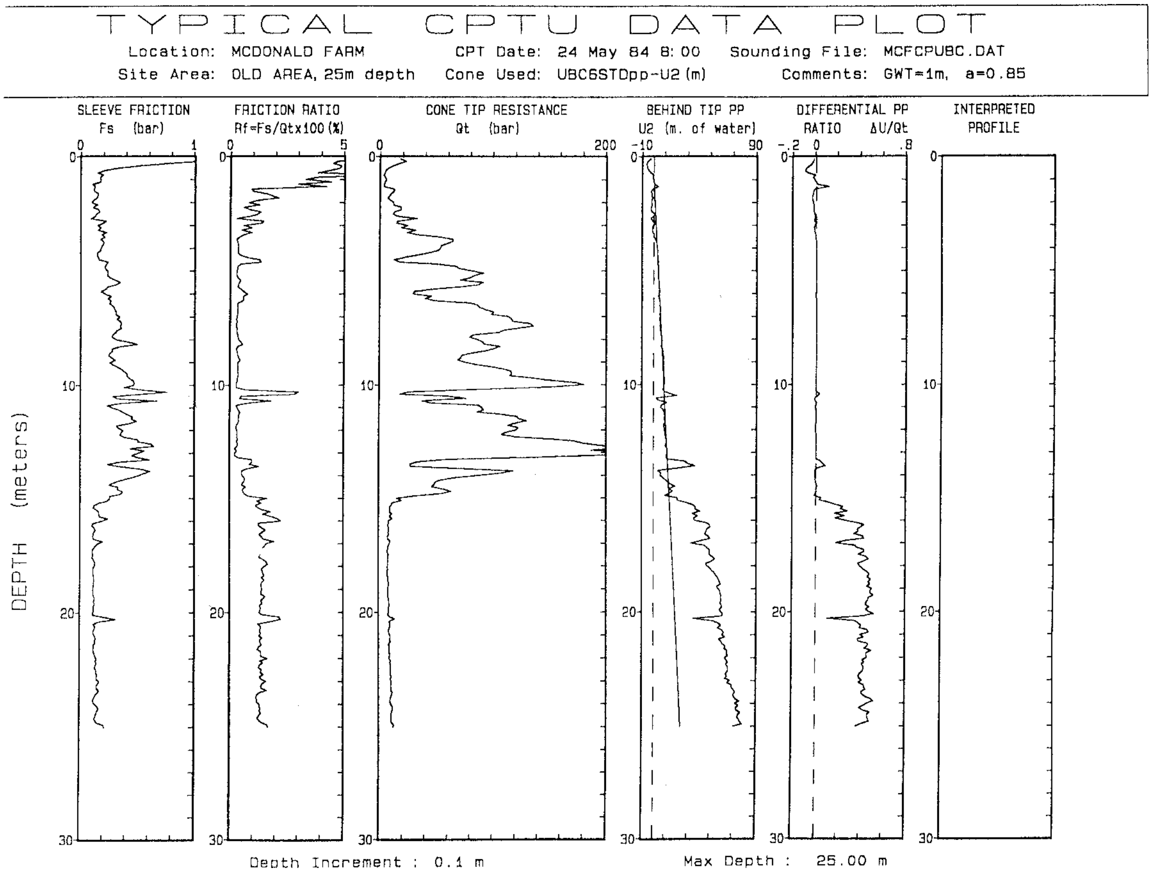


FIG. 5 Example Piezocone Graph

NOTE 8—Jefferies and Davies **(5)** 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 A1.5) 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; penetration tests; piezocone; soil investigations

ANNEX

(Mandatory Information)

A1. CALIBRATION REQUIREMENTS ON NEWLY MANUFACTURED OR REPAIRED ELECTRONIC FRICTION CONE AND PIEZOCONE PENETROMETERS

A1.1 *Introduction:*

A1.1.1 This annex describes procedures and requirements for calibrating electronic cone penetrometers. The evaluation of cone penetrometer calibration as described in this annex is a quality assurance standard for newly manufactured and repaired penetrometer tips. Many of the standards may be impractical to evaluate under field operating conditions. Therefore, determination of these calibration errors for any individual penetrometer tip should be performed in a laboratory environment under ideal conditions by the manufacturer or other qualified personnel with necessary knowledge, experience, and facilities.

A1.1.2 The electronic cone penetrometer is a delicate instrument subjected to severe field conditions. Proper use of such an instrument requires detailed calibration after manufacture and continuous field calibrations. Years of cone penetrometer design and performance experience have resulted in refined cone designs and calibration procedures which make the electronic cone penetrometer a highly reliable instrument. Reports of these experiences form the basis for requirements in this annex **(1, 6)**.

A1.1.3 The required calibration tolerances developed in this annex are based on subtraction type electronic cone penetrometers. These penetrometers are more robust than electronic cone penetrometers with independent tip and sleeve load cells and are the most widely used design. The subtraction type penetrometer, however, has less precision due to the subtraction process **(1, 6)**. As a result, calibration tolerances given here are considered maximum values and requirements for more sensitive cone penetrometers imply smaller tolerances having greater precision. The calibration process consists of loading the penetrometer tip with reference forces and pressures and then comparing measured output to the reference.

A1.1.4 Calibrations in the laboratory environment should be performed with the complete penetrometer system to be used in the field. The same make and model computer, cable, signal conditioning system, and penetrometer to be used in the field shall be calibrated in the laboratory. Depending on the components of the system some components may be substituted with acceptable replacements. Each individual penetrometer must be tested over a range of loads to assure adequate performance.

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

A1.2.1 Fig. A1.1 is a graphical depiction of terms related to transducer calibrations as set forth by the Instrument Society of America **(1)**. The example calibration that follows deals with zero-load error, nonlinearity, hysteresis, and calibration error.

A1.2.2 To evaluate several of these values, the FSO (full scale output) of the penetrometer tip is needed. The manufacturer shall provide full scale output information for the system. Cone penetrometer tips usually are available in nominal capacities of 5, 10, and 15 metric tons. Typical full-scale outputs for these penetrometer tips follow:

Nominal Capacity, metric tons	Full-Scale Output of Cone, q_c		Full-Scale Output of Friction Sleeve, f_s	
	ton/ft^2	MPa	ton/ft^2	kPa
5	500	50	5	500
10	1000	100	10	1000
15	1000	100	10	1000

A1.2.3
It is important to check with the manufacturer on the full scale output of electronic cone penetrometer tips to avoid overloading and damaging penetrometer tips.

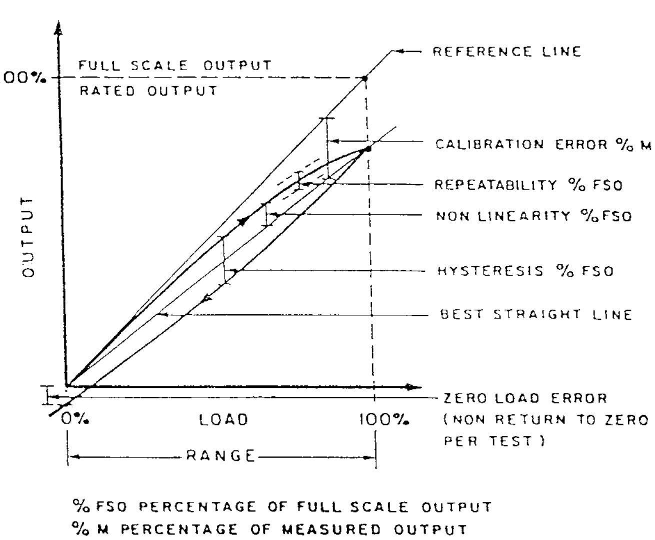


FIG. A1.1 Definition of Terms Related to Calibration (1)

A1.3 *Zero Load Baseline Values:*

A1.3.1 Zero-load output variation of the cone penetrometer during testing and calibration is a reliable indicator of output stability, internal O-ring friction, and temperature-induced apparent load. The variation in zero load output is affected by temperature fluctuation because temperature compensated strain gages do not compensate for material effects and system component effects **(1, 6)**.

A1.3.2 Systems with microprocessors provide "reference baseline" values for the transducers that are not equal to zero but are measured positive or negative values depending on the electronics of the system. For the particular penetrometer and penetrometer system used, the baseline values should remain relatively constant through the life of the penetrometer. As testing is performed in the field, the baseline resistances are monitored for changes. If large changes are noted the penetrometer should be loaded to check for linearity and possible damage. Evaluate the zero-load error during load range calibration by taking the difference between initial and final baseline values.

A1.3.3 *Thermal Stability*—For ensurance of thermal stability, evaluate a particular design of a newly manufactured cone under a range of temperature conditions. Newly manufactured penetrometer tips are first cycled to a minimum of 80 % of FSO five times at room temperature, to remove any residual nonlinearity. After cycling, establish an initial reference baseline value at room temperature after the cone has been electrically powered for about 30 min. To evaluate thermal stability, stabilize the penetrometer tip at temperatures of 10 and 30°C and new baseline values are obtained. The change in baseline values must be ≤ 1.0 % FSO of either cone or friction sleeve resistances.

A1.4 *Load Range Calibration:*

A1.4.1 Calibrate newly manufactured or repaired cone penetrometers over a range of loads after production or repair. Load test the cone penetrometer system in a universal testing machine or specially designed cone penetrometer calibration device capable of independently loading the cone and friction sleeve. If a universal testing machine is used, a calibration certificate (current within the last year) in accordance with Practice E 4 must be available. If a cone calibration apparatus is used, it should also have a calibration document current within the last year. The calibration document shows that applied forces or masses are traceable to standard forces or masses retained by the National Institute of Standards and Technology (National Bureau of Standards). The universal testing machine or cone calibration devices must be capable of loading the penetrometer tip to 100 % FSO.

A1.4.2 Example calibrations of an electronic cone penetrometer are shown in Table A1.1 and Table A1.2. The calibrations were performed on a 10-ton subtraction-type electronic cone penetrometer. The measured output was a readout of cone and friction sleeve resistance obtained through a microprocessor based data acquisition system. An initial baseline was taken and then subtracted to obtain zero resistance at zero load. Selection of loading steps and maximum loading varies depending on need and application. Select the load steps

TABLE A1.1 Calibration of Cone Penetrometer—Cone Tip Calibration

				m	b
DATE:	CALIBRATED BY:		CALIBRATOR DATA:	0.04971	-0.07911
PROJECT:	CONE #:	361	CALIBRATOR SETTING:	100KN	
FEATURE:	FSO TIP:	100 MPA			
CLIENT:	FSO SLEEVE:	1000 KPA			
	TIP AREA:	10 CM^2			
	SLEEVE ARE	150 CM^2			

TARGET GAUGE READING	ACTUAL GAUGE READING	APPLIED FORCE X kN	FULL SCALE OUTPUT FSO - %	MEASURED CONE RESISTANCE Y qc - mPA	MEASURED SLEEVE RESISTANCE fs - kN/M^2	ACTUAL CONE RESISTANCE qca mPa	BEST STRAIGHT LINE* Y'=mX+b mPA	LINEARITY Y-Y'/FSO % FSO	CALIBRATION ERROR qca-Y'/qca % MO
0.000	BASELINE			-0.2	-10.3				
0	0	-0.079	-0.1	-0.0	-0.2	-0.1	0.034	0.04	
40	40	1.909	1.9	2.1	-0.2	1.9	2.053	0.00	
100	100	4.892	4.9	5.1	0.2	4.9	5.081	0.04	
200	200	9.862	9.9	10.2	0.3	9.9	10.128	0.03	
500	507	25.122	25.1	25.5	1.2	25.1	25.623	0.08	1.99
1000	1001	49.678	49.7	50.6	0.6	49.7	50.556	0.02	1.77
500	499	24.725	24.7	25.2	0.3	24.7	25.219	0.01	
200	198	9.763	9.8	10.0	0.3	9.8	10.027	0.01	
100	100	4.892	4.9	5.1	0.4	4.9	5.081	0.03	
40	40	1.909	1.9	2.1	0.4	1.9	2.053	0.08	
0	0	-0.079	-0.1	0.0	0.0	-0.1	0.034	0.03	
0.000	BASELINE			-0.3	-9.8				

		RESULT	UNIT	ALLOWABLE	APPROVAL
*BEST FIT STRAIGHT LINE (Y=mX+b	m=	1.015			
	b=	0.114			
MAXIMUM LOAD TRANSFER -SLEEVE		0.1	%FSO	2.000	YES
MAXIMUM LINEARITY ERROR		0.1	%FSO	1.0	YES
MAXIMUM CALIBRATION ERROR		1.99	%MO	2.0%MO>20%FSO	NO
MAXIMUM ZERO LOAD ERROR -CONE		0.0	%FSO	0.5	YES
MAXIMUM ZERO LOAD ERROR - SLEEVE		0.1	%FSO	1.0	YES

COMMENTS:

and maximum load to cover the range of interest and not necessarily the maximum capacity of the cone. Some calibrations stress more frequent load steps at lower loads to evaluate weaker materials. Selection of more frequent lower load steps may result in higher levels of calibration error since the best fit line is more influenced by the low range data.

A1.4.3 As shown in Table A1.1, the cone tip is first loaded. Perform this loading after the cone is subjected to five cycles of compressive loading and reference baselines, or internal zeroing, have been obtained at room temperature. The cone is loaded in a minimum of six increments at forces equivalent to 0, 2, 5, 10, 25, 50, and 75 % FSO for the cone. At each increment of force, record both cone and sleeve resistance. Compute the actual cone resistance by dividing the applied force by the cone base area. Determine the "best fit straight line" by linear regression of applied force and measured output. The linearity is the difference between measured cone resistance and best-straight line cone resistance divided by the cone FSO. Evaluate hysteresis by comparing the difference between cone resistance at the same level of applied force in loading and unloading and dividing by cone FSO. Calculate calibration error by taking the difference between the best-fit-straight line cone resistance and actual cone resistance and dividing by the actual cone resistance. Calibration error can become larger with smaller measured outputs and, therefore, it is not evaluated at loadings equivalent to less than 20 % of cone FSO.

A1.4.3.1 When calibrating the cone, monitor the friction sleeve resistance to evaluate apparent load transfer. With a subtraction-type electronic cone penetrometer tip, the apparent friction sleeve resistance is caused by electrical subtraction error, crosstalk, and any load transferred mechanically to the sleeve. With a cone, that provides for independent cone and sleeve measurements, apparent friction sleeve resistances are caused by electrical crosstalk and mechanical load transfer. Apparent load transfer must be less than 1.5 % of FSO of the friction sleeve (1000 kPa).

A1.4.3.2 As shown in Table A1.1, maximum nonlinearity is 0.2 %, maximum calibration error is 0.5 %, and maximum apparent load transfer is 1.2 %. For this calibration, the zero load error was zero. Hysteresis was not evaluated in this example because the testing machine was incapable of producing the exact same force on the loading and unloading steps.

A1.4.4 Table A1.2 shows the calibration of the friction sleeve element, independent of cone loading. This is accomplished by removing the cone and loading the bottom edge of the friction sleeve. Again, apply the forces in seven increments at 0, 2, 5, 10, 25, 50, and 75 % of FSO, that is, approximately 1000 kPa. Nonlinearity, hysteresis, and calibration error are evaluated in the same manner as calibrations for the cone. During friction sleeve calibration, monitor cone resistance to evaluate apparent load transfer that was not apparent in this calibration.

TABLE A1.2 Calibration of Cone Penetrometer—Sleeve Calibration

					m	b
DATE:	CALIBRAT BY:		CALIBRATOR DATA:		0.00992	-0.012668
PROJECT:	CONE #:	361	CALIBRATOR SETTING:		20kN	
FEATURE:	FSO TIP:	100 MPA				
CLIENT:	FSO SLEEVE:	1000 KPA				
	TIP AREA:	10 CM^2				
	SLEEVE AREA:	150 CM^2				

TARGET GAUGE READING	ACTUAL GAUGE READING	APPLIED FORCE X kN	FULL SCALE OUTPUT FSO - %	MEASURED SLEEVE RESISTANCE Y fs - kPa	MEASURED CONE RESISTANCE qc - mPa	ACTUAL SLEEVE RESISTANCE fsa kPa	BEST STRAIGHT LINE* Y'=mX+b kPa	LINEARITY Y-Y'/FSO % FSO	CALIBRATION ERROR fsa-Y'/fsa % MO
0.000	BASELINE			-9.8	-0.3				
0	0	-0.013	-0.1	0.0	0.0	-0.8	3.113	0.31	
30	30	0.285	1.9	20.3	0.0	19.0	22.970	0.27	
75	75	0.731	4.9	51.2	0.0	48.7	52.757	0.16	
150	149	1.465	9.8	101.2	0.0	97.6	101.739	0.05	
375	378	3.735	24.9	249.1	0.0	249.0	253.320	0.42	1.73
750	749	7.414	49.4	495.3	0.0	494.2	498.893	0.36	0.94
375	375	3.705	24.7	260.2	0.1	247.0	251.334	0.89	
150	153	1.504	10.0	110.7	0.0	100.3	104.387	0.63	
75	77	0.751	5.0	57.7	0.0	50.1	54.081	0.36	
30	32	0.305	2.0	24.1	0.0	20.3	24.294	0.02	
0	0	-0.013	-0.1	0.2	0.0	-0.8	3.113	0.29	
0.000	BASELINE			-9.8	-0.3				

		RESULT	UNIT	ALLOWABLE	APPROVAL
*BEST FIT LINE (Y=mX+b)	m=	66.760			
	b=	3.958			
MAXIMUM LOAD TRANSFER -CONE		0.1	%FSO	0.5	YES
MAXIMUM LINEARITY ERROR		0.9	%FSO	2.0	YES
MAXIMUM CALIBRATION ERROR		1.73	%MO	3.0%MO>20%FSO	YES
MAXIMUM ZERO LOAD ERROR -CONE		0.0	%FSO	0.5	YES
MAXIMUM ZERO LOAD ERROR - SLEEVE		0.0	%FSO	1.0	YES

COMMENTS:

A1.5 *Force Transducer Calibration Requirements:*

A1.5.1 Calibration requirements developed for electronic cone penetrometers are based on past experience with subtraction-type electronic cone penetrometers and, as a result of this experience, represent the minimum precision requirement of electronic cone penetrometers. In cases where a higher level of precision is required, stricter calibration requirements would be required. Newly manufactured or repaired electronic cone penetrometers are required to meet the following requirements:

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

A1.6 *Pressure Transducer Calibrations:*

A1.6.1 Newly manufactured or repaired pressure transducers shall be supplied with a load range calibration provided by the manufacturer. The load range calibration shall consist of a minimum of six points of loading to at least 75 % of FSO. The applied pressures shall be traceable to reference forces maintained by NIST. The calibration shall meet the manufacturer's stated tolerances. Minimum requirements are linearity better than 1 % of FSO and zero load error less than ± 1.0 lb/in.^{2}(±7 kPa).

A1.6.2 The transducer shall be subjected to regular periodic inspection meeting requirements in A1.6.1.

A1.7 *Determination of Cone Area Ratio and Sleeve End Area Imbalance:*

A1.7.1 Fig. A1.2 illustrates the areas where water pressures can act on the cone tip and sleeve elements. Water pressure that acts behind the cone tip will reduce measured cone resistance, q_c, by the magnitude of water pressure multiplied by the net area ratio, a. Water pressure may also act on both ends of the sleeve, resulting in an imbalance of forces if the sleeve is not designed with equal effective end areas. The water pressure acting on the ends of the sleeve are not just a function of geometry; they are a function of the location of water seals. Water pressures during penetration are not often measured at both ends of the sleeve so a correction based on measurements is not possible.

A1.7.2 Equal end area friction sleeves are required for use and should be designed by the manufacturer. The best method for evaluating sleeve imbalance is to seal the penetrometer in a pressure chamber and apply forces to measure the sleeve

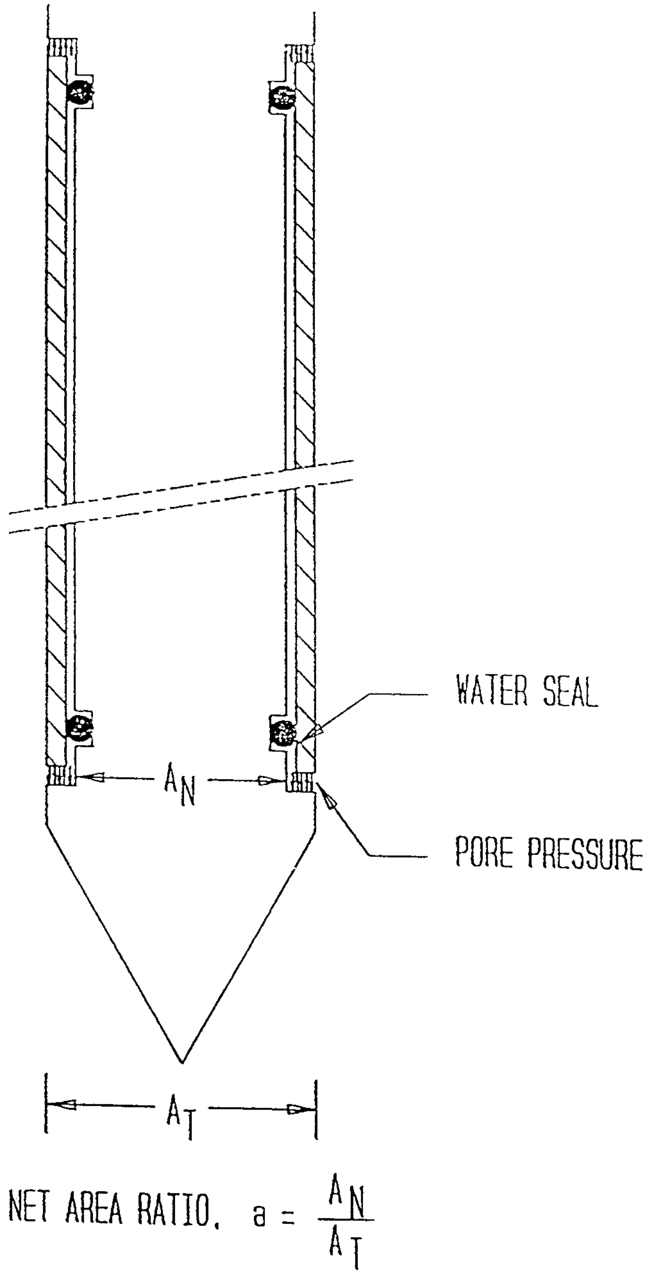


FIG. A1.2 Net Area Ratio, a

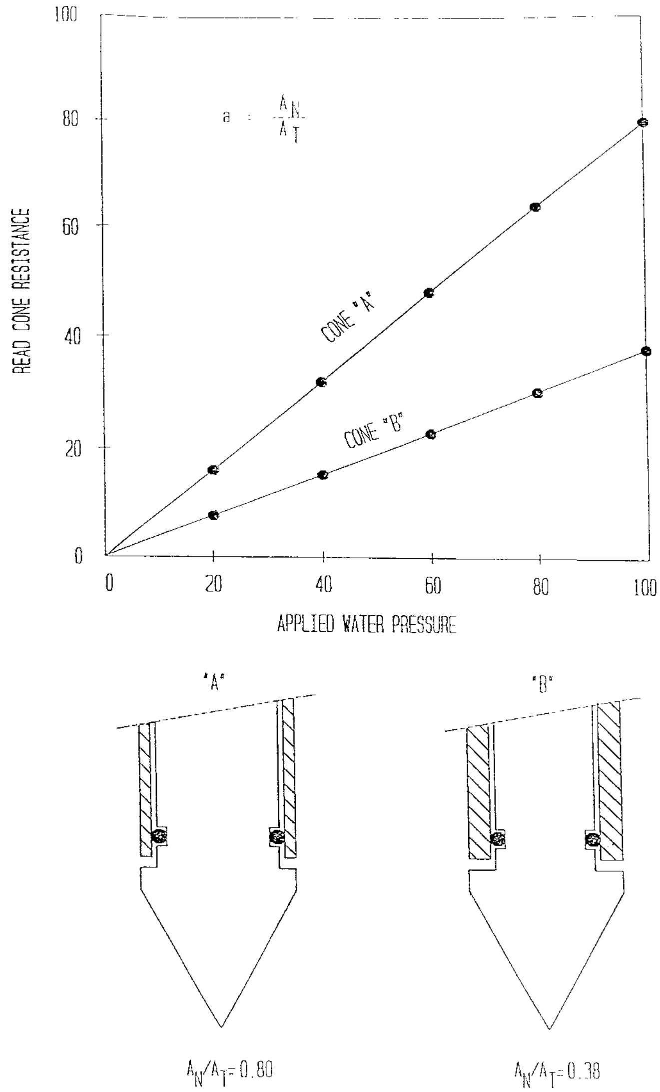


FIG. A1.3 Determination of Unequal End Area Correction

resistance after zeroing the system. Manufacturer's should perform this check for a particular design to assure minimal imbalance.

A1.7.3 If it is necessary to calculate the corrected total cone resistance, q_t , as shown in 13.2.1, it will be necessary to determine the area ratio of the cone. The penetrometer can be enclosed in a sealed pressure vessel and pressures should be applied as shown in the example in Fig. A1.3. The net area ratio is then used in computing the corrected total tip resistance.

A1.8 *Other Calibrations*—Other sensors such as inclination, temperature, etc. may require calibration depending on the requirements of the investigation. Perform such calibrations using similar techniques given in this annex or by other reference procedures. Report such calibrations when required.

A1.9 *Documentation of Calibrations:*

A1.9.1 Laboratory calibration documents consisting of a short report on the equipment and methods of testing, along with tables and figures similar to those in this annex, are required for the following occurrences:

A1.9.1.1 When new penetrometer tips are received,

A1.9.1.2 When damaged penetrometer tips are repaired, and

A1.9.1.3 In instances when qualifications or proposals are required for contract negotiations.

A1.9.2 The report must be certified by a registered professional engineer or other responsible engineer with knowledge and experience in materials testing for quality assurance. Calibration documents are retained on file by the offices responsible for performing soundings and should be updated at required intervals. For contract soundings, calibration documents should be obtained prior to contract acceptance and after testing on unaltered equipment.

A1.9.3 If the electronic cone penetrometer meets the field calibration requirements given in 10.1.3, it is only necessary to adjust the penetrometer tip to the laboratory requirements on a yearly basis. Cone penetrometers should be calibrated using laboratory procedures prior to use on each new project, but they do not need to meet calibration tolerances as required for newly manufactured cones.

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