# Part 631 Geology
# National Engineering Handbook

# Chapter 11 Cone Penetrometer

Issued January 2012

# Preface

This new chapter replaces Soil Mechanics Note 11 (SMN–11), which was originally issued in 1984.

Materials in this chapter were adapted from the following publications:

- ASTM D5778, Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils
- Cone Penetration Testing in Geotechnical Practice, 1997, Lunne, T., P.K. Robertson, and J.J.M Powell.
- Cone Penetration Testing State-of-Practice, Mayne, P.W., 2007, National Cooperative Highway Research Program (NCHRP) Project 20–05, Topic 37–14, Washington DC. http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_syn_368.pdf.
- Guide to Cone Penetration Testing for Geotechnical Engineering, 3rd Edition, 2010, Robertson P.K., and K.L. Cabal.

# Chapter 11 Cone Penetrometer

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## 631.1100 Purpose and scope

The cone penetrometer test (CPT) provides valuable information in geotechnical investigations when used in conjunction with other equipment and procedures. This chapter describes the CPT and explains the equipment, field procedures, and application. It also describes some procedures and guidance for interpreting and using the test results. The working end of a typical cone penetrometer is shown in figure 11–1.

This manual is not intended to provide full details of geotechnical analyses. The primary references generally accepted by industry are listed and shown in the references at the end of this chapter.

**Figure 11–1** Working end of cone penetrometer (*Photo courtesy of Gregg Drilling & Testing, Inc.)*

## 631.1101 Introduction

Cone penetrometer testing (CPT) is a fast, effective, and relatively inexpensive system for collecting important soils parameters during a geotechnical site investigation. When used in conjunction with conventional drilling and sampling methods, it provides a more complete description of the subsurface conditions, thereby reducing uncertainty in design and construction.

CPT methods can be divided into two basic groups:

- geophysical logging and stratigraphic profiling
- specific test methods

Testing equipment consists of a cone on the end of a series of rods that are pushed hydraulically into the ground. The typical rate of penetration is 2 centimeters per second (~1 in/s), or 91 meters per hour (~300 ft/h). CPTs can be performed to depths exceeding 100 meters (~300 ft) with large-capacity pushing equipment.

CPT logging is fast and economical, particularly in soft soils. CPTs can also provide preliminary evaluations of soil parameters and provide quantitative estimates of various geotechnical parameters based on empirical correlations.

Specific tests measure soil properties at a particular point, while some in situ CPTs can characterize specific engineering properties, including shear strength and modulus of elasticity. They require the use of specialized equipment, however, and can be slower and more expensive. Because of the increased cost, they are best used in critical areas that have been previously identified.

CPTs can be used to screen subsurface conditions during preliminary geologic investigations and locate borings for subsequent detailed geologic investigations (refer to NEM531 and NEH631.02). Soundings can be used to pinpoint changes in the lithology (stratigraphy) and identify areas to be sampled. CPT is particularly useful in nonuniform foundations and where undisturbed samples are difficult to obtain.

CPT with modern equipment provides continuous readings of:

- point load or tip resistance ($q_c$)
- friction ($f_s$)
- porewater pressure (u)

Tip resistance is theoretically related to the undrained shear strength of a saturated, cohesive material and measured with an embedded load cell. The sleeve friction is theoretically related to the friction of the horizon being penetrated and measured using tension load cells embedded in the sleeve.

After the initial information is collected, the digital data are post-processed to provide numerical values for engineering analysis. The use of computer processing during field investigations has enabled immediate interpretation of CPT results.

Results of CPT can be used to make reliable estimates of settlement and undrained shear strength in areas where some basic information about the engineering properties of the soil is available. Results, however, should always be confirmed or correlated with laboratory analyses of actual samples.

The cone itself does not produce a sample. Test results are nonunique and must be verified and calibrated to the specific site. Fewer physical samples are required if the geology of the area and some of the engineering properties of the soil are understood. While the CPT equipment cannot obtain a sample, some samplers can also be pushed into the ground using CPT equipment.

Undisturbed soil sampling is vital to the success of a geotechnical investigation and should be considered a companion of CPT. CPT data complement undisturbed sampling and provide a significant volume of in situ information that is difficult to achieve in the lab. Comparing lab results of both shear and consolidation tests with CPT data reduces the uncertainty of either set of data.

Most of the commercially operated CPT rigs use electronic friction cone and piezocone penetrometers as standard practice. Soundings are presented digitally. In the United States, most CPT is performed using electrical cones. The mechanical CPT is, however, manufactured and used in some parts of the world, particularly in developing countries, because of the equipment's low cost, simplicity, and sturdiness.

# 631.1102 Applications

CPT results have two fundamental uses requiring specific sensors and equipment:

- Direct measurements are used to estimate geotechnical parameters, which can then be used in an analysis.
- CPT results can also be directly applied into geotechnical engineering designs.

Although older CPT versions had previously only delivered readings for $q_c$, $f_s$, and u, recent improvements in the technology have greatly increased the CPT's utility in geotechnical investigations. Separate modules are now available with a wide range of sensors. The additional soundings generated are recorded simultaneously at the surface with the standard data in digital output. The new mechanical configurations are variable as well, with most added just behind the cone, some being retractable, and others with the capability to simultaneously measure porewater pressures. Separate modules that can be added to the cone include:

- temperature sensors, used to identify saturated zones
- video and still cameras
- microphones
- pH sensors, mounted either in the cone or on the surface of the probe
- pressure meters, which measure in situ (undrained) lateral stresses
- radioisotope detectors (gamma), used for determining density and water content

Modules used primarily for geoenvironmental investigations include:

- Oxygen exchange capacity, the electrical potential associated with the oxidation or reduction of a substance; or a measure of the tendency of a chemical species to acquire electrons in the reduction process.
- Laser/ultraviolet-induced fluorescence (LIF) measures hydrocarbons with polyaromatic constituents, such as benzene.

- Membrane interface probe (MIP) is used to locate volatiles in the subsurface. It has semi-quantitative capabilities and acts as an interface between contaminants in the subsurface, which diffuse across the membrane into an upward-moving gas stream, and the detector at the surface.
- Dielectric permittivity, which is based on the propagation of electromagnetic waves; indicate presence of organic contaminants in porewater with much more sensitivity than resistivity.

The common types of CPTs that are available for site characterization are listed in table 11–1.

The primary application of the CPT is for soil profiling and determining soil type using soil behavior type (SBT) graphs (fig. 11–2) that have been developed for this application. The numerical values are plotted on SBT graphs, from which the zone is identified. For example, cone resistance ($q_t$) is high in sands, and the friction ratio ($R_f$) is low, shown in zone 9 in figure 11–2. In soft clays, $q_t$ is low and $R_f$ is high, shown in zone 3.

CPT measures *state parameters* of the soil, which is one of a set of variables that describe the "state" of a dynamic system. They include void ratio ($e_0$), unit weight ($\gamma$), porosity (n), and relative density ($D_r$). These data are used to estimate the following geotechnical parameters of the materials, which then can be used in various geotechnical analyses:

- undrained shear strength ($S_u$)
- soil sensitivity ($S_t$)
- undrained shear strength ratio, $\frac{s_u}{\sigma'_{vo}}$
- stress history, overconsolidation ratio (OCR)

These data can also be applied directly to an engineering analysis, particularly in the analysis of load-settlement relationships and bearing capacity. CPT data can be used to develop factors for the bearing capacity analysis, including shape factors, load inclination factors, and the effects of groundwater and effective stress.

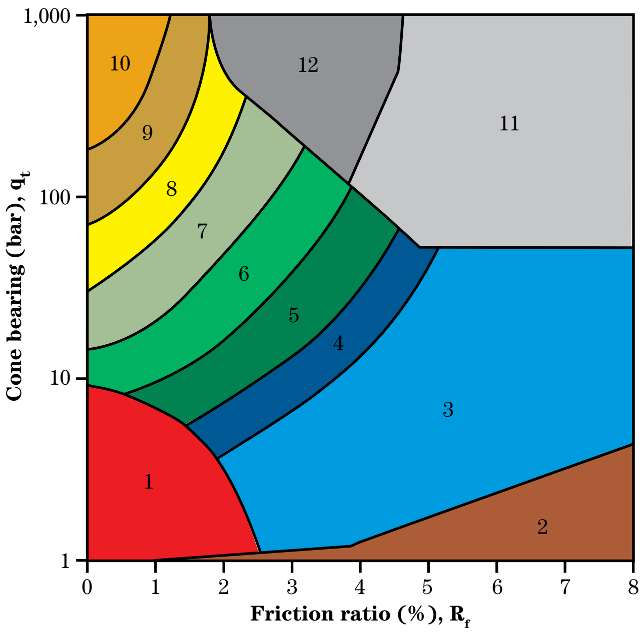
Table 11–2 shows reliability ratings of CPT data for design applications. The data presented are a synthesis on the state of practice in CPT undertaken during the National Cooperative Highway Research Program (Mayne 2007). A survey questionnaire was prepared for this program, directed at geotechnical engineers working for Departments of Transportation in 52 States and 12 provincial DOTs in Canada. Conclusions from this survey are summarized in table 11–3.

**Table 11–1** Basic CPTs used in site characterization (Mayne 2007)

| Type of CPT | Acronym | Measurements taken | Applications |
|---|---|---|---|
| Mechanical cone penetration test | MCPT | $q_c$ and $f_s$ at 20-cm intervals. Uses inner and outer rods to convey loads uphole | Stratigraphic profiling, fill control, natural sands, hard ground |
| Electrical friction cone | ECPT | $q_c$ and $f_s$ (taken at 1- to 5-cm intervals) | Fill placement, natural sands, and soils above the groundwater interface |
| Piezocone penetration test | CPTu and PCPT | $q_c$, $f_s$, and either face $u_1$ or shoulder $u_2$ (taken at 1- to 5-cm intervals) | All soil types. Note: Requires $u_2$ for correction of $q_c$ to q. |
| Piezocone with dissipation | CPTù | Same as CPTu with timed readings of $u_1$ or $u_2$ during decay, measured by stopping the penetration and measuring the decay of pore pressures with time | Normally conducted to 50% dissipation in silts and clays. Used to estimate compressibility and permeability |
| Seismic piezocone test with embedded geophones | SCPTu | Same as CPTu with downhole shear waves ($V_s$) at 1-m intervals | Provides fundamental soil stiffness with depth: $G_{max} = \rho_t V_s^2$ |
| Resistivity piezocone test | RCPTu | Same as CPTu with electrical conductivity or resistivity readings | Detect freshwater–saltwater interface, indicates contaminant plumes. |

**Notes:** $q_c$ = measured point stress or cone tip resistance
$f_s$ = measured sleeve friction
u = penetration porewater pressure ($u_1$ at face; $u_2$ at shoulder)
$q_t$ = total cone resistance, $V_s$ = shear wave velocity

**Figure 11–2** Soil behavior types (Robertson 1989)




| Zone | $q_t/N$ | | SBT |
|---|---|---|---|
| 1 | 2 | | Sensitive, fine grained |
| 2 | 1 | | Organic materials |
| 3 | 1 | | Clay |
| 4 | 1.5 | | Silty clay to clay |
| 5 | 2 | | Clayey silt to silty clay |
| 6 | 2.5 | | Sandy silt to clayey silt |
| 7 | 3 | | Silty sand to sandy silt |
| 8 | 4 | | Sand to silty sand |
| 9 | 5 | | Sand |
| 10 | 6 | | Gravelly sand to sand |
| 11 | 1 | | Very stiff fine grained* |
| 12 | 2 | | Sand to clayey sand* |

*Over consolidated or cemented

**Table 11–2** Perceived applicability of the CPT/CPTu for various design problems (Mayne 2007)

| Soil type | Pile design | Bearing capacity | Settlement* | Compaction control | Liquefaction |
|---|---|---|---|---|---|
| | CPT reliability rating | | | | |
| Sand | 1–2 | 1–2 | 2–3 | 1–2 | 1–2 |
| Clay | 1–2 | 1–2 | 2–3 | 3–4 | 1–2 |
| Intermediate soils | 1–2 | 2–3 | 2–3 | 2–3 | 1–2 |

Reliability rating: 1 = High; 2 = High to moderate; 3 = Moderate; 4 = Moderate to low; 5 = Low

**Table 11–3** Advantages and disadvantages of CPT

| | |
|---|---|
| **Advantages** | Provides fast and continuous profiling |
| | Equipment is economical and productive |
| | Generates repeatable and reliable data that are not dependent on the operator |
| | Can identify thin horizons of low strength |
| | Reduces contact between field personnel and contaminated soil |
| | Strong theoretical basis for interpretation |
| **Disadvantages** | High initial capital investment |
| | Skilled operators are required |
| | No drill cuttings or soil samples are produced |
| | Limited penetration in gravels or cemented materials |
| | Data are unreliable in unsaturated conditions, particularly in clayey soils |

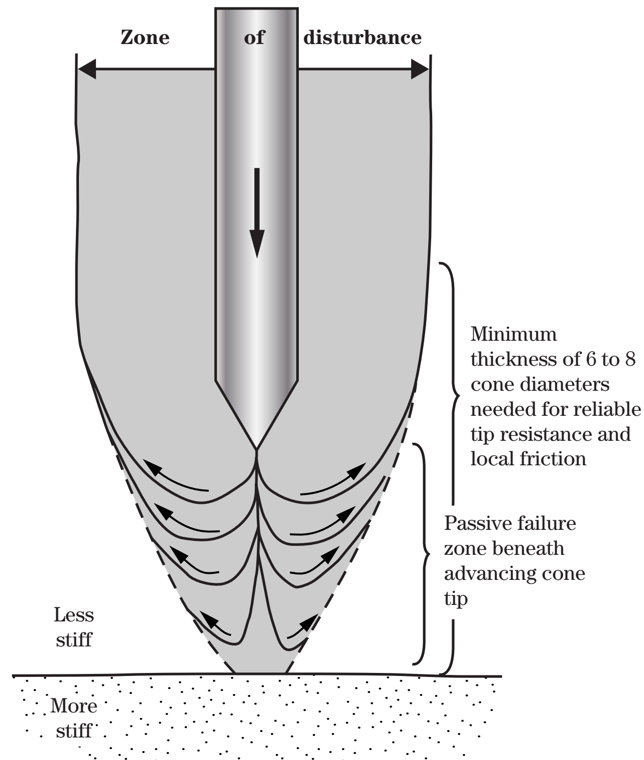
# 631.1103 Advantages, disadvantages, and cautions

The CPT was developed primarily for use in soft earth materials. The development of additional sensors and heavier equipment has extended the range of use. The advantages and disadvantages are shown in table 11–3.

The precise distance impacted below the cone tip depends on the stiffness and thickness of the units being penetrated and on the contrast in stiffness between adjacent beds (Rogers 2006; personal communication 2010). This influence varies between about 8 to 15 inches below the cone tip, so the soundings tend to overestimate unit strength parameters as the tip approaches a much stiffer horizon, such as the soil-bedrock contact (fig. 11–3).

The tip of the cone penetrometer senses out ahead of itself as it induces a local bearing failure of the soil through which it passes. The tip resistance recorded by the instrument is an average across this tip influence zone. Therefore, caution should be exercised when evaluating in situ strength parameters for horizons less than 14 to 28 inches (36–72 cm) thick, such as landslide slip surfaces (Rogers 2006).

**Figure 11–3** Zone of disturbance for cone penetrometer



# 631.1105 Equipment

A CPT system includes the following components (fig. 11–4):

- electronic penetrometer
- hydraulic pushing system with rods
- cable or transmission device
- depth recorder
- data acquisition unit

## (a) Penetrometers

The standard cone penetrometer consists of a three-channel-instrumented steel probe. The front end of the probe consists of a conical tip with a 60 degree apex. The tip typically has a 5-millimeter cylindrical extension, or lip, located at the upper portion to protect the outer edges of the cone base from excessive wear.

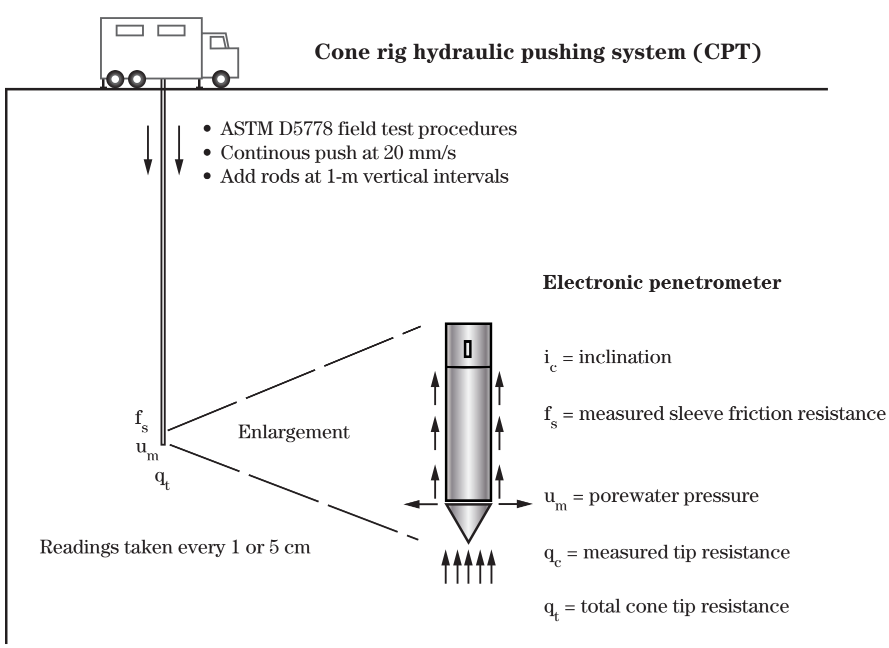
Penetrometers are normally available in two standard sizes:

- 35.7-millimeter diameter with a corresponding cross-sectional area of 10 square centimeters
- 44-millimeter diameter with a cross-sectional area of 15 square centimeters

The 10-square-centimeter size is the original standard size and remains in widespread use. However, the 15-square-centimeter version has some advantages and is specified in some standards. Being more robust, it can generally obtain soundings at greater depths and through coarser or harder materials. Also, as rods normally have a cross-sectional area of 10 square centimeters, the 44-millimeter-diameter cone produces a larger hole, reducing sleeve friction during pushing.

Figure 11–5 shows the basic styles of penetrometers in routine use. Detailed requirements and standards for the design, dimensions, and manufacturing and operating tolerances for the cone and sleeve are given in ASTM D5778.

**Figure 11–4** Configuration of the CPT, following ASTM D5778 (Mayne 2007, NCHRP Project 20–05)



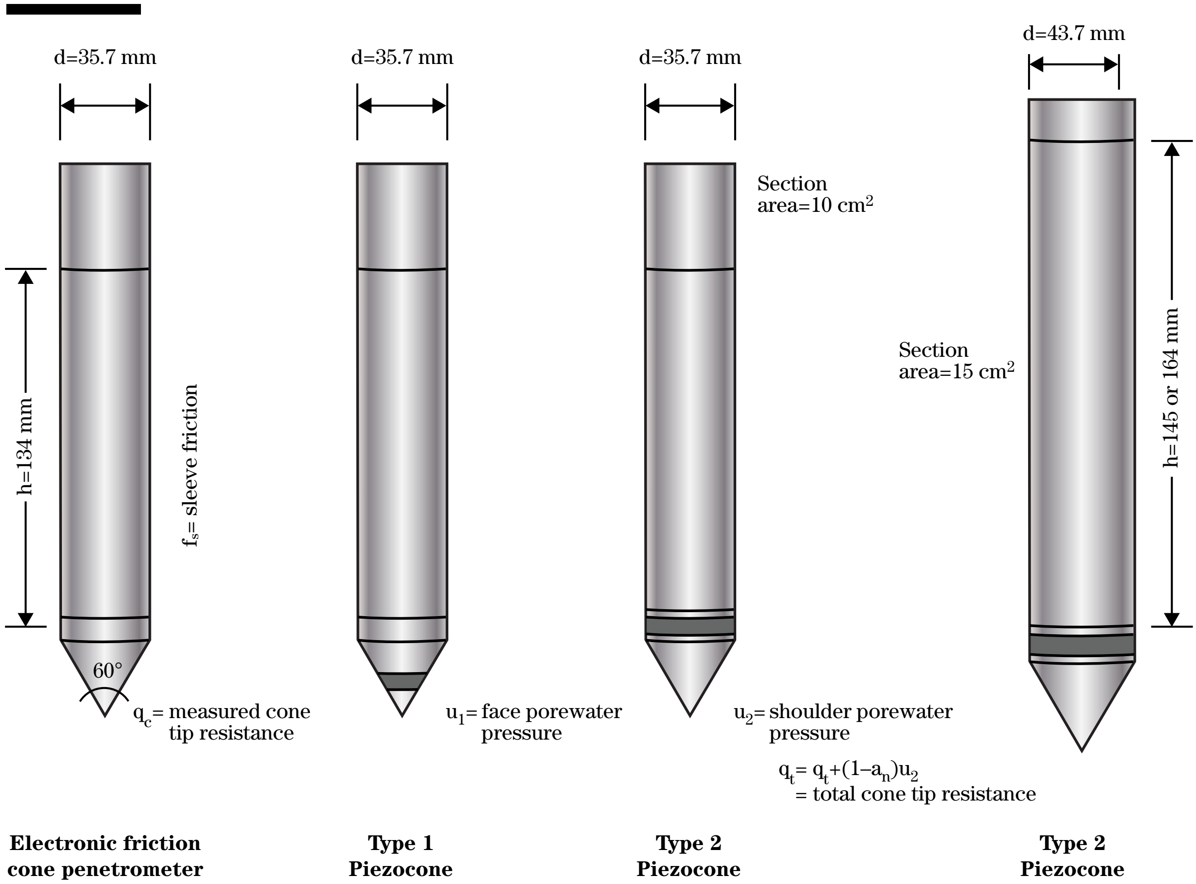
Cone penetrometers without porewater transducers can be used in soils with minor porewater pressure development, such as fill, clean sands, and soils well above the groundwater interface. However, for most soils below the water table, the piezocone penetrometer is recommended. It contains a porous filter element, pressure transducer, and fluid-filled ports connecting the element to the transducer. The filter element is usually positioned either at the apex or midface of the cone tip, or at the shoulder just behind the tip.

For the proper correction of measured cone tip resistance to total resistance, placement at the shoulder is required by national and international standards. Filter elements placed midface of the cone top are useful in fissured earth materials and other materials prone to desaturation.

The element is a fine porous filter made from plastic, ceramic, or sintered steel or bronze (formed by heating metal powders without melting). Typical pore size is between 20 and 200 microns. Different materials have unique properties that affect their suitability, including brittleness and durability, expense, and the ability to be cleaned and reused. Plastic filters are inexpensive, disposable, and can be replaced often to avoid possible clogging problems, particularly in plastic clays. Metal and ceramic filters are reusable and cleaned using an ultrasonic bath. Hydrophilic polypropylene elements placed at the shoulder are most commonly used in practice.

When using the cone to penetrate dense layers, such as cemented siltstone, sandstone, or conglomerate, a polypropylene piezo-filter can become compressed. This may induce high positive pore pressures. Plastic

**Figure 11–5** Dimensions and measurements taken by the standard 10-cm$^2$ and 15-cm$^2$ penetrometers, ASTM D5778



filters do not exhibit this tendency; however, they do become brittle with time and should be replaced periodically (Rogers 2006).

In stiff, overconsolidated clays, such as glacial till, the pore pressure is usually negative, and negative pore pressures may desaturate the cone, resulting in erroneous measurements. The pore pressure gradient around the cone can be high in these soils, resulting in dissipations recorded behind the tip that increase originally, and then decrease to the equilibrium value.

## (b) Hydraulic pushing systems

The hydraulic pushing machine can consist of the new dedicated CPT hydraulic system or a standard drill rig, mounted on a truck, track, trailer, all-terrain vehicle, skid arrangement, or portable unit. A variety of CPT systems are available, from mini units installed in vans used in shallow investigations, to large trucks and tracked vehicles useful for well-cemented or coarse-grained materials.

Standard drill rigs have the ability to drill or bore through hard zones and then continue the soundings to the desired depths, as well as to obtain soil samples. This greatly reduces costs associated with mobilizing a dedicated CPT truck.

Disadvantages of using a standard drill rig can include less thrust capabilities, the need for additional sub-connector pieces to advance and withdraw the rods, and manual controls, which depend on the operator and rarely push at a constant rate. A standard drill rig outfitted with CPT equipment is shown in figures 11–6 and 11–7.

Cone penetration soundings usually require thrust capabilities ranging from 100 to 200 kN, which is equivalent to 11 to 22 tons. After positioning the rig at the desired test location, the rig is usually leveled with hydraulic jacks or "outriggers." Many small lightweight CPT systems in the 18- to 50-kN range (2- to 6- ton) use earth anchors to gain capacity and provide the necessary reaction for the penetrometer, as well as to prevent the rig from moving during thrust, relative to the soil surface.

**Figure 11–6** Drill rig set up to conduct SCPT. Metal plates are struck with a sledge hammer to initiate energy pulse. The seismic cone penetrometer has a geophone incorporated into its design. (*Photo courtesy of Glen Miller, Geologist (retired), NRCS, Stillwater, Oklahoma)*

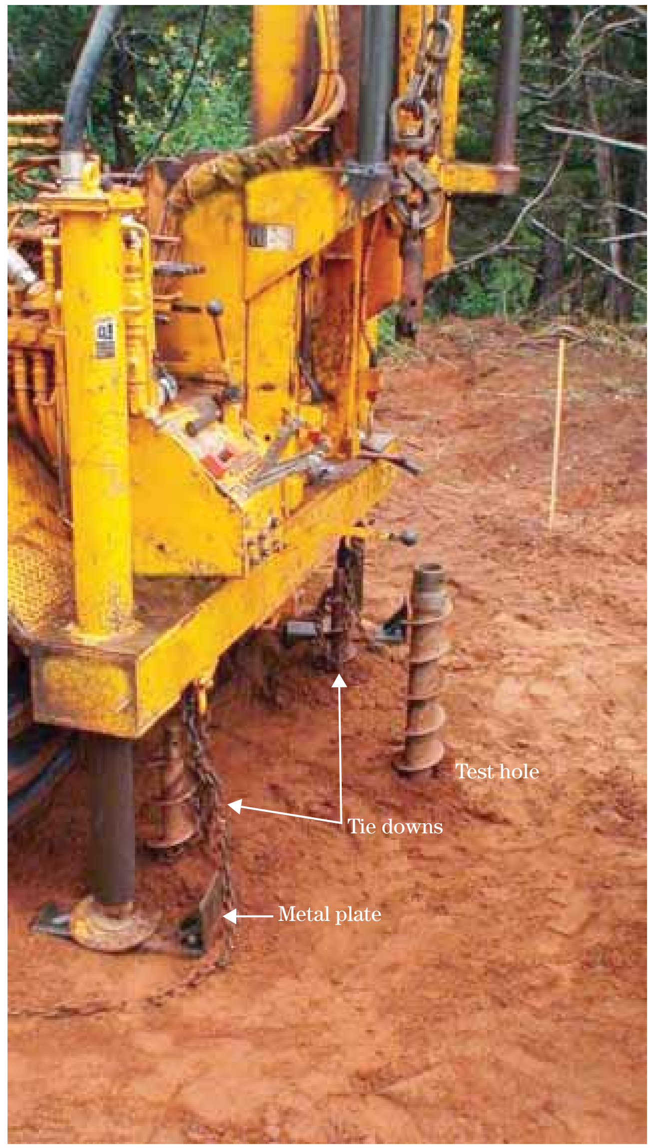


**Figure 11–7** SCPT being conducted through hollow stem augers (*Photo courtesy of Glen Miller, Geologist (retired), NRCS, Stillwater, Oklahoma*)

## (c) Push rods

The push rods are typically 35.7-millimeter diameter, hollow, steel rods in 1-meter lengths with tapered threads. For hard materials, larger diameter cone rods (44 mm) are also available. Steel rods must have enough cross-sectional area to sustain, without buckling, the thrust required to advance the cone. For penetrometers using electrical cables, the cable is prestrung through the rods prior to testing. Hydraulic systems of dedicated CPT trucks are usually outfitted with grips to grasp the rods from the side during pushing and pulling. With standard drill rigs, pushing and pulling of rods is done from the top.

## (d) Friction reducer

Rod friction can be reduced through the use of a friction reducer, which is an enlarged section of rod (e.g., a ring welded to the outside rod) above the penetrometer that opens the hole to a larger diameter, thereby reducing soil contact on all the upper rods.

## (e) Data transmission and cabling

All analog and most digital CPT systems use a cable threaded through the rods that transmits the data uphole. It also provides between 5 to 20 volts of current to the penetrometer. The original analog systems require an external power supply, signal enhancer, and analog-digital converter at the surface.

Some of the newer designs include wireless digital CPT systems. They are useful when standard drill rigs are running the penetration equipment, as the cables can be easily damaged. They are used increasingly in deep-water offshore site investigations. Special receivers are required uphole to capture the signals and decode them for digital output. A variety of wireless technologies are available, including:

- infrared signals conveyed uphole in glass-lined rods
- audio signals
- battery-operated micro chips that store data until the rods are back at the surface

### (f) Depth loggers

Common systems for recording depth include depth wheels, low-voltage or direct current displacement transducers (LVDT and DCDT), gear boxes, optical readers, spooled wire potentiometers, and ultrasonic sensors, which use high-intensity acoustic energy. Spooled wire potentiometers consist of a transducer used to detect and measure the length of a moving object using a flexible cable and spring-loaded spool.

### (g) Data acquisition systems

Data acquisition systems used with electrical CPTs have evolved from simple pen plotters and analog-digital converters to laser printers. Now data are digitized to a computer at intervals that are typically 1 to 2 inches in depth. Fully digital systems include ruggedized notebook computers and microchip technologies built into the cone penetrometer itself.

Older systems can be adapted to almost any type of cone commercially available; however, most new systems have proprietary designs which require that the penetrometer, cable, and data acquisition system be matched.

## 631.1106 Standards

Procedures for calibrating and maintaining cone penetration equipment and for conducting CPTs are well-established. The following procedures are intended to contain the essential requirements for equipment, calibrations, and testing. Current ASTMs that are specific to individual systems are listed in table 11–4.

**Table 11–4** Applicable ASTM standards and standard guides for cone penetration testing

| ASTM | Title |
|---|---|
| D3441 | Standard Test Method for Mechanical Cone Penetration Tests of Soil |
| D5434 | Standard Guide for Field Logging of Subsurface Explorations of Soil and Rock |
| D5753 | Standard Guide for Planning and Conducting Borehole Geophysical Logging |
| D5778 | Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils |
| D6066 | Standard Practice for Determining the Normalized Penetration Resistance of Sands for Evaluation of Liquefaction Potential |
| D6067 | Standard Guide for Using the Electronic Cone Penetrometer for Environmental Site Characterization |

# 631.1107 Field operations—performing the CPT

Before setting up the rig, check for any safety hazards, including overhead utilities or obstructions. Local utility companies must be notified and their subsurface lines located and flagged. Such contact is normally required at least 24 to 48 hours in advance of the investigation. Soundings must not be performed any closer than 25-borehole diameters from any existing uncased or open boreholes.

## (a) Preparation for use of the penetrometer

Modern CPT equipment has the potential for producing results with a high degree of accuracy and repeatability. This accuracy depends on skilled operators and adequate facilities for calibration and maintenance of the equipment. Procedures and requirements for calibrating electronic penetrometers are described in the Annex to ASTM D5778. Simple calibrations and checks are also essential to ensure that everything is functioning properly in the field after connecting the equipment.

Electronic baselines or zero-load readings in both cone and friction sleeve load cells and porewater pressure transducers must be taken before and after each sounding. Baseline readings are a reliable indicator of output stability, temperature-induced apparent loads, soil ingress, internal friction, and threshold sensitivity. Also, they may indicate any unknown conditions that may be loading the system.

Baseline readings of the porewater pressure transducers should be obtained immediately after assembly to prevent evaporation at a temperature close to that of the material to be sounded. The penetrometer tip can hang freely in air or be immersed in a bucket of water. Baseline readings should not be obtained with protective caps or covers in place, as these may induce pressure in the system. It is also recommended to secure a set of baseline readings after the sounding has been completed, and the penetrometer withdrawn to the surface.

## (b) General procedures

For the soundings, the penetrometer thrust system of the CPT truck or drill rig must be set to as near vertical as possible. For penetration in compacted fills or hard soils, it may be necessary to prebore a hole through the upper material, using a diameter slightly larger than the cone. This will prevent damage to the cone. Before beginning the sounding, check individual push rods for straightness. Assemble and tighten push rods by hand, cleaning the threads if necessary to ensure that the shoulders are tightly butted to prevent damage to the rods.

The standard rate of push for CPT soundings is 2 centimeters per second (cm/s), usually applied in 1 meter increments, the length of a standard cone rod. With dedicated CPT rigs, the hydraulic system automatically adjusts the pressures to maintain a constant rate. When using a rotary drill rig, the driller must manually adjust the pressure to maintain the 2 centimeters per second rate. Cone results are generally not sensitive to slight variations in the rate of penetration.

As the rods are pushed, electrical cones produce continuous readings of cone resistance and sleeve friction. Electrical cones produce analog data, but most systems convert it to digital form at selected intervals. Most standards require the interval to be no more than 20 centimeters (~8 in); ASTM D5778 requires intervals not to exceed 5 centimeters (~2 in).

During testing, monitor the tip and sleeve forces continuously for signs of proper operation. As data are recorded, note any unusual occurrences in testing. These can include “crunching” sounds that may indicate gravel and directional drift of the penetrometer as it passes through or alongside obstructions such as boulders, cobbles, soil concretions, or thin rock layers. Inclination is a useful indicator of imminent danger to the system, as damage can be caused if resistant layers or obstructions are penetrated. Generally, a 5-degree change in inclination over 1 meter of penetration can result in rod bending.

As push rods are added, interruptions of short duration can affect initial cone and sleeve readings at the beginning of the next push. During a pause in the penetration, excess pore pressures will begin to dissipate. For that reason, it is important to note and record the depths at which long pauses may have affected initial startup resistances.

At the end of the sounding, obtain a final set of baseline readings with the penetrometer tip hanging freely and check them against the initial readings. Maintain a continuous record of initial and final baselines for the tip and sleeve load cells and the porewater transducers, as they may indicate problems with the equipment.

Inspect penetrometer tips before and after soundings for damage, soil ingress, and wear. If soil ingress is significant, the cone assembly may need to be dismantled, cleaned, and lubricated before the next sounding.

## (c) Procedure for piezocone use

There are no major differences in field test procedures between CPT and CPTu, except those required for the preparation of a porous piezo-element, or filter, used in the latter (Robertson 1986). Before use, filters must be saturated under vacuum in a bath of glycerin, a mix of glycerin plus water, or peanut oil to remove compressible air bubbles which can cause errors in the soundings. In the field, the filter elements must be installed so that a continuity of fluid is maintained from the filter face through the ports in the penetrometer and the cavity housing the pressure transducer.

Caution should be used when interpreting CPT soundings above the water table. Unsaturated soils have negative pore pressures that can potentially distort the readings. They can also cause the development of air bubbles in the filter that can be suctioned off into the surrounding soils. Cohesive soils that are not fully saturated may exert significant skin friction, which can complicate the interpretation. In some geologic conditions, it may be necessary to prebore a pilot hole to the water table to obtain accurate porewater pressure readings in the saturated materials below.

## (d) Hole closure—techniques

The need for grouting or sealing of holes is usually established by individual States, most of which have laws requiring that exploration holes be backfilled, sealed, or grouted after sampling and testing are completed. The same applies to CPT sounding holes. This is of particular importance in specific geologic settings where aquifer(s) need to be protected against cross-contamination or water transmission.

As the CPT cone is pushed into the ground, it is creating a hole that could be as detrimental to groundwater as an open borehole. If the hole stays open after the tool is withdrawn, these cavities can become pathways for contamination of aquifers either by cross-communication between permeable units or by the transport of surface contaminants down the hole. Surface and subsurface contaminants can potentially flow into aquifers that were previously uncontaminated.

Providing a permanent seal in small diameter holes presents a number of challenges compared with large-diameter holes drilled with a conventional drill rig. In larger-diameter holes, successful sealing can be performed using bentonite. In smaller diameter holes, it can be difficult or impossible to verify the seal's effectiveness due to the likelihood of bridging.

Specific geologic conditions may cause the holes to immediately close as the tool is removed. The best examples are relatively clean sands below the water table and very soft, saturated clays.

Borings in relatively clean, saturated sands are well known for unstable sidewalls that collapse during the drilling process. Drilling mud must be used to counteract this instability to keep the hole open. In loose deposits, the vibrations from the cone truck are enough to cause collapse during retraction. At the same time, the hydraulic conductivity in these deposits is likely to be several orders of magnitude above that of the sealing materials. For very soft clays below the water table, the hole may squeeze shut as the tools are being withdrawn. Suction that develops as the penetrometer is pulled from the hole increases this action.

# 631.1108 Field operations—readings and calculations

The two basic measurements taken during the test are tip resistance ($q_c$) and sleeve friction ($f_s$). Both $q_c$ and $f_s$ are determined by dividing the axial force by the surface area of the instrument (tip or sleeve). The axial force is represented by F. $F_c$ is the axial force on the tip of the cone, while $F_s$ is the axial force on the sleeve.

Cone tip resistance ($q_c$) is the measured axial force pushing down on the tip, which is the force ($F_c$) divided by the tip area ($A_c$):

$$q_c = \frac{F_c}{A_c}$$

Sleeve resistance ($f_s$) is the measured axial force pushing down on the sleeve ($F_s$), divided by the sleeve area ($A_s$):

$$f_s = \frac{F_s}{A_s}$$

## (a) Correcting tip and sleeve readings using porewater pressure ($u_2$)

Measured tip resistance ($q_c$) must be adjusted to account for porewater pressures acting on unequal tip areas of the cone. In clean sands and dense, granular soils, they are nearly equivalent. However, in soft to stiff clayey soils, appreciable porewater pressures are generated, and the correction can be from 20 to 70 percent. Total tip resistance ($q_t$) is calculated as:

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

where:
$q_t$ = total tip resistance
$a_n$ = tip net area ratio from triaxial test
$q_c$ = measured tip resistance
$u_2$ = porewater pressure at shoulder

The correction to total cone resistance is particularly important when porewater pressures are generated during penetration; e.g., in saturated clays and silts, as weak soils are the most critical in a geotechnical investigation. The correction is usually not so significant for clean sands, dry soils, or dense to hard earth materials. The correction is due to porewater pressures acting on opposing sides of the face and the joint annulus of the tip (ASTM D5778).

The sleeve friction ($f_s$) is also exposed to pore water pressures as well, which must be corrected. When excess pore pressures are generated, they are normally different at the upper ($u_3$) and lower ($u_2$) ends of the sleeve. The corrected sleeve friction ($f_t$) is given by:

$$f_t = f_s - \left(\frac{u_2 \times A_{sh}}{A_s}\right) - \left(\frac{u_3 \times A_{st}}{A_s}\right)$$

where:
$f_t$ = sleeve friction, corrected
$f_s$ = sleeve friction
$u_2$ = lower end of sleeve
$u_3$ = upper end of sleeve
$A_{sh}$ = bottom end area of sleeve
$A_{st}$ = top end area of sleeve
$A_s$ = area of sleeve

## (b) Field logging

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) standard logging procedures are outlined in NEH631.03. In particular, logs should contain:

- location and characteristics of contacts
- number of outer sounding tubes, as their weight can be an appreciable part of the record
- number of inner rods, to maintain the record of depth of penetration
- depth and length of long pauses in pushing
- initial and final baselines for each sounding
- any unusual condition affecting test procedures or results

# 631.1109 Soil mechanics laboratory use of CPT data

## (a) Soil classification

Where possible, soil classifications are to be based on the Visual-Manual Procedure outlined in ASTM D2488, Standard Practice for Description and Identification of Soils, and the appropriate laboratory test data. The CPT does not classify soils on their grain-size distribution, but provides a guide based on their mechanical characteristics or the soil behavior type. Some overlapping of zones can be expected. The SBT is derived from non-normalized data, which do not include pore pressure as do the newer CPT equipment and interpretation charts.

## (b) Determining extent of soils to be represented by sample testing

One of the most important and beneficial uses of CPT data in the laboratory is to provide a basis for judging whether engineering property test data can be accurately extended to represent soils located some distance from the sampling location. For example, in the slope stability analysis of an embankment, shear strength values determined using samples taken from the centerline of a structure are usually assumed to represent the foundation soils several hundred feet upstream and downstream. CPT data can be used to judge the extent of the area to which these data apply or indicate the need for further sampling and testing.

## (c) Consolidation and settlement testing and analysis

Undisturbed samples are seldom obtained from the center of a particular layer of foundation soil. CPT data provide information for determining more precisely the upper and lower boundaries represented by one or more samples. Engineering properties are not always uniform in earth materials of a given formation or geologic age.

A grouping of several cone tests at the base of an abutment can establish a reasonably accurate estimate of potential differential settlements, which can then be confirmed by sampling and testing.

To compute horizontal strain associated with the design of principal spillway conduits, the lower limit of settlement must be known. Cone penetrometer tests extended to bedrock or to refusal in sands, gravels, or stiff clays provide good information for determining this lower limit. The reliability of samples, often obtained with great difficulty and expense, can then be judged for their potential use in settlement and strain analyses.

In areas where previous work has established a base of test results, analyses, and field measurements, settlement can be estimated using only CPT data if results of direct testing are not available. The general equation for consolidation of a layer ($\Delta h$) is:

$$\Delta h = h \times \Delta p \times m_v$$

**or**

$$\Delta h = h \times \Delta p \times \left( \alpha \times \frac{1}{q_c} \right)$$

where:

$\Delta h$ = change in layer thickness, cm
$h$ = layer thickness, cm
$\Delta p$ = load; increase in vertical strength, kg/cm$^2$
$\alpha$ = variable coefficient based on the state parameters of the soil
$q_c$ = cone point resistance, kgf/cm$^2$
$m_v$ = $\left( \alpha \times \frac{1}{q_c} \right)$; coefficient of mass volume change, cm$^2$/kg

Using settlement plate data supported by laboratory testing, a graph of $q_c$ vs. $\alpha$ is computed for soils found in a given area:

$$\alpha = \frac{h \times \Delta p}{q_c \times \Delta h}$$

For fairly uniform soils and given adequate time, $\Delta h$ from settlement plate records can be accurate for determining the $\alpha$ coefficient. Compute the increase in stress due to the embankment load ($\Delta p$) from field placement records. The graph is less accurate where the basis for computation is only laboratory testing to determine $\Delta h$.

## (d) Shear strength comparisons

Undrained shear strength values ($S_u$ or cohesion, $C_u$) are used in analyses of stability and bearing capacities for clays and clayey silts under short-term loadings. No single value of undrained shear strength of a given material exists, since the undrained response of a soil depends on the direction of loading, strain rate, bondary conditions, stress level, sample disturbance, and other factors.

While there is no single value of $S_u$, a relationship has been established between the undrained shear strength ($S_u$) of a soil and a theoretical net cone resistance. Both theoretical and empirical solutions exist. The theoretical studies result in the following relationship between theoretical cone factor ($N_c$) and in situ total pressure ($\sigma_o$):

$$q_c = \left(N_c \times S_u\right) + \sigma_o$$

Empirical correlations are in a range of 10 to 20, with an average of 15. $S_u$ is expressed as:

$$S_u = \frac{q_t - \sigma_t}{N_{kt}}$$

where:
$q_t$ = total cone resistance
$\sigma_t$ = vertical stress
$N_{kt}$ = empirical cone factor

## (e) Slope stability analysis

Slip surfaces in landslides and other slope failures can be thin—less than 1 inch. CPT soundings are the best tool available to positively identify these low-strength horizons, which are otherwise difficult to sample, test, or measure reliably. In most cases, however, the soundings represent an average value of a zone that can be 8 to 15 inches thick.

In addition, the actual mobilized shear strength along the slip surface is usually considerably lower than the sleeve friction and tip resistance values recorded in the CPT, potentially as low as 20 percent of the estimated value (Rogers 2010, personal communication). Soundings are more definitive for thicker planes of weakness.

CPT results, coupled with results of laboratory shear testing, are useful in analyzing slope stability of foundation soils. Temperature sensors are also useful in assessing the precise position of the zone or zones of saturation, which is of great importance in slope stability and consolidation studies. A temperature shift of about 6 degrees Fahrenheit (3.3 ºC) is common at the groundwater interface, even in perched water tables within landslides.

# 631.1110 Use of CPT data in design

## (a) Foundation

When determining the extent of excavation needed in fine-grained soils, compare results of representative laboratory consolidation and shear tests with CPT data. Tests on undisturbed samples usually represent a small volume of soil. In-place testing with the penetrometer allows the laboratory data to be applied to larger volumes of soil.

The CPT is a good tool for use during construction to determine if foundation excavation is completed and to locate soils of questionable properties not found in the predesign investigations. Construction specifications should allow the designer to use CPT or other in-place tests.

## (b) Sectional embankment or preloading

CPT can determine settlement at various points, where highly compressible soils extend to great depths. This information indicates that preloading the foundation soil or a sectional embankment is needed if settlement, differential settlement, or horizontal strain are potential problems. If preloading or a sectional embankment does not provide a solution to the potential problem, relocation of the structure may be required. Data from CPT can aid in locating soils of acceptable properties. Sampling and testing can then confirm the decision of structure location.

Data from CPT at locations of stilling basins and risers can confirm the results of laboratory tests on samples which are in many cases obtained only on the centerline of the structure.

## (c) Channels

Channel projects usually involve stratified soils and encompass long reaches. Use of the friction sleeve cone is accurate enough to classify the soils vertically and horizontally so that sampling may be more representative, and the investigation will also be faster and more economical. However, negative pore water pressures in banks of influent streams cause an apparent cohesion that could skew results.

## (d) Liquefaction potential

CPT offers several capabilities in the evaluation of seismic ground hazards. The sounding can be used to identify loose, weak sands and silty sands below the groundwater interface that are susceptible to liquefaction. CPT data can also be used to determine the threshold for triggering liquefaction. Care should be taken to identify layers or zones of potential concern. Samples should be taken for fine-content testing to aid in the analysis.

CPT soundings can also be used to provide an assessment of the amount of resistance available to counter the shearing of the soil during ground shaking. The penetrometer can also be fitted with geophones to allow for the determination of downhole shear wave velocity profiles.

Liquefaction potential has traditionally been determined by the use of the Standard Penetration Test (SPT). Today, liquefaction potential is increasingly estimated based directly on the CPT (e.g., Youd et al. 2001; Robertson 2010, personal communication) because the CPT provides a continuous profile that is more reliable.

## 631.1111 SPT

Use of the SPT is presented in NEH631.04. The test provides a measure of earth material strength and also provides a representative sample of the horizon tested.

### SPT advantages and disadvantages over CPT

Caution must be used in sampling geologic contacts and interpreting materials interfaces; as with the CPT there is an increase in the resistance to penetration as the drive sampler barrel approaches a stiffness boundary.

A major disadvantage of the SPT method is the small diameter of the cutting shoe. The equipment cannot recover clasts over 1.375 inches in diameter, which often leads to erroneous interpretations about bedrock contacts or drilling refusal.

SPT and CPT procedures work best when used together, not one exclusive of the other. The best correlations can be made when CPT soundings are verified with a SPT hole nearby (2 feet is a good distance). Use of the CPT allows detailed examinations of site stratigraphy. Individual beds and stringers can be traced across a sizable area in a minimal amount of time. In addition, the cone is able to delineate discrete, low-strength horizons that can be missed in a SPT sampler.

Robertson, Campanella, and Wightman (1983) summarized correlations between CPT cone penetration resistance and the SPT N value (blow count) and found that a relationship applies with an average energy ratio of about 60 percent; i.e., $N_{60}$.

The $(q_c/p_a)/N_{60}$ ratio correlates to the mean particle size of the soil ($D_{50}$), where $p_a$ is the atmospheric pressure in the same units as $q_c$ (fig. 11–8). Table 11–5 relates this ratio to the soil behavior types (SBT). Values of $q_c$ are made dimensionless when dividing by the atmospheric pressure ($p_a$) in the same units as $q_c$. These ratios are a reasonable estimate, but discontinuous changes in the predicted SPT $N_{60}$ values may occur. Note for sandy soils that the measured tip resistance ($q_c$) = the total tip resistance ($q_t$).

**Figure 11–8** CPT–SPT correlations with mean grain size (Robertson, Campanella, and Wightman 1983)

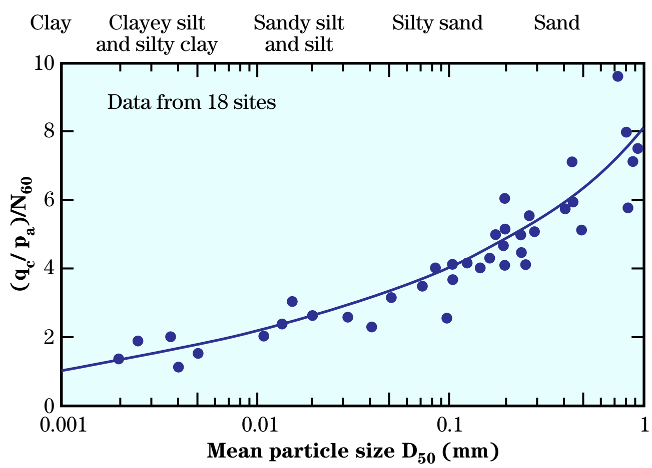



**Table 11–5** Soil type correlating between CPT and SPT (Robertson 1986)

| Zone | Soil behavior type * | $\frac{(q_s/p_a)}{N_{60}}$ |
|---|---|---|
| 1 | Sensitive fine grained | 2.0 |
| 2 | Organic soils—clay | 1.0 |
| 3 | Clays: clay to silty clay | 1.5 |
| 4 | Silt mixtures: clayey silt and silty clay | 2.0 |
| 5 | Sand mixtures: silty sand to sandy silt | 3.0 |
| 6 | Sands: clean sands to silty sands | 5.0 |
| 7 | Dense sand to gravelly sand | 6.0 |
| 8 | Very stiff sand to clayey sand | 5.0 |
| 9 | Very stiff fine-grained | 1.0 |

* Suggested $(q_c/p_a)/N_{60}$ ratios

## 631.1112 Glossary

| | |
|---|---|
| $A_c$ | Projected area of cone |
| $a_n$ | Tip net area ratio from triaxial test |
| $A_s$ | Area of sleeve |
| $b_n$ | Sleeve net ratio from triaxial test on the equipment itself, used to calibrate new equipment |
| $f_s$ | Sleeve friction measured |
| $f_t$ | Total sleeve friction, calculated |
| F | Total axial force acting on the instrument |
| $F_c$ | Total force acting on the tip of the cone, $f_s/A_c$ |
| $F_s$ | Total force acting on friction sleeve, $f_s/A_s$ |
| $N_c$ | Theoretical cone resistance factor |
| $N_{kt}$ | Empirically derived cone resistance factor |
| $p_a$ | Atmospheric pressure |
| $R_f$ | Friction ratio, $f_s/q_t$ |
| $q_c$ | Measured tip resistance |
| $q_t$ | Total tip resistance |
| $u_m$ | Measured penetration porewater pressure |
| u | Penetration pore water pressure |
| $u_1$ | Porewater pressure at face |
| $u_2$ | Porewater pressure at shoulder |
| CPT | Cone Penetrometer Test, can be performed with mechanical and electrical equipment |
| CPTu | Piezocone Penetration Test, can only be performed with electrical equipment |
| CPTù | Piezocone with dissipation |
| SCPTu | Seismic Piezocone Penetration Test, equipment includes imbedded geophones that measure shear wave velocity |
| RCPTu | Resistivity Piezocone Penetration Test |
| $S_u = C_u$ | Undrained shear strength |
| $S_t$ | Soil sensitivity, the ratio of undisturbed, undrained shear strength to totally remolded, undrained shear strength |
| $\tau_f$ | Shear strength, kgf/cm$^2$ |
| $\sigma_o$ | Total in situ pressure |

## 631.1113 References

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**Figure 11A–1** CPT log showing soil classification and soil behavior type, tip ($q_c$), sleeve ($f_s$), pore pressure ($u_2$), and friction ratio ($R_f$). Log clearly shows the varying soil conditions found when pushing CPT in Salina County, Kansas. See figure 11–2 for soil behavior types

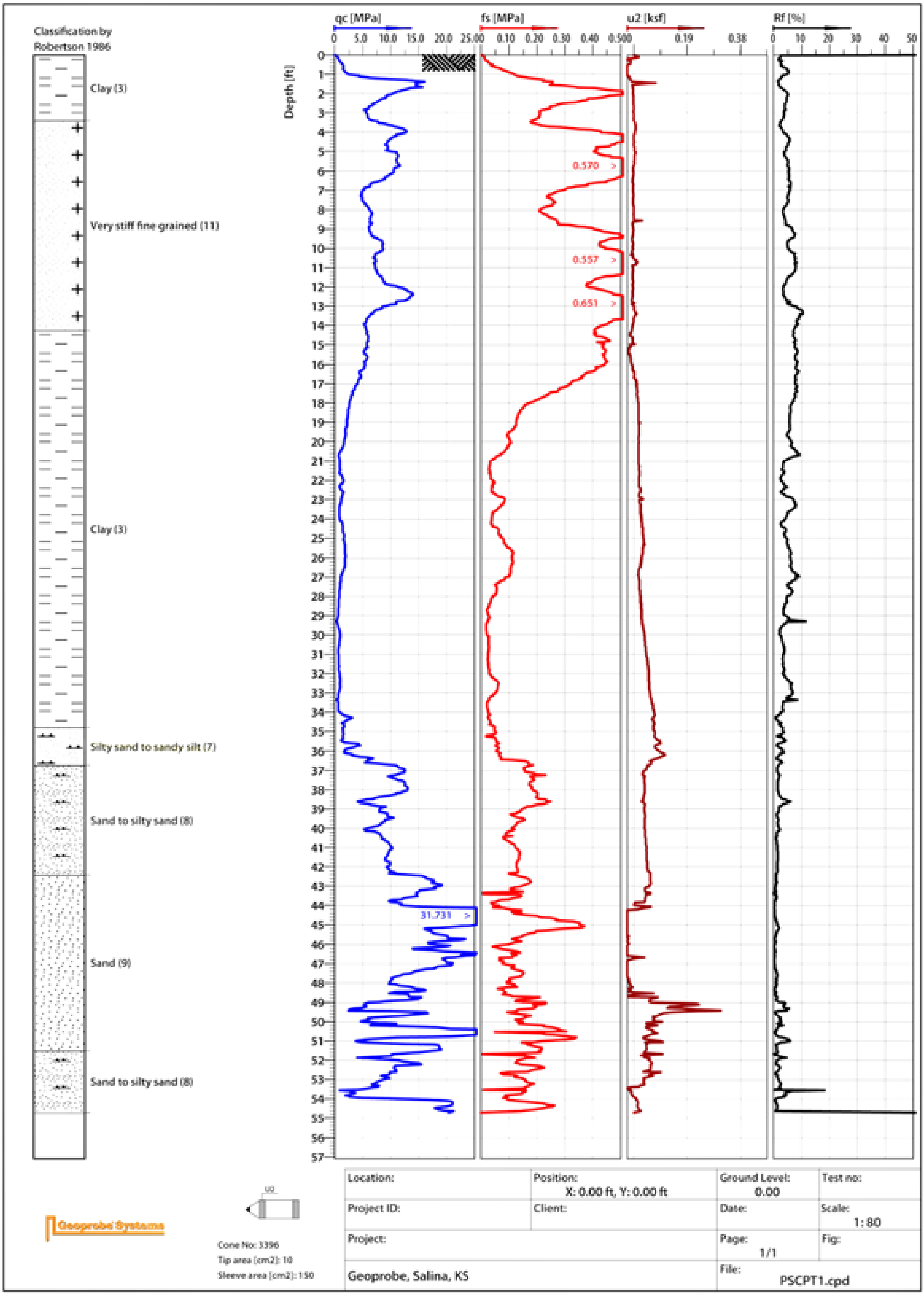

**Figure 11A–2** CPT log showing soil classification, tip ($q_c$), sleeve ($f_s$), pore pressure ($u_2$), and friction ratio ($R_f$). Log clearly shows the change from clay to sand in both tip pressure and pore pressure. Note the steady increase in pore pressure beginning at 36 feet, indicating the probe had penetrated the water table.

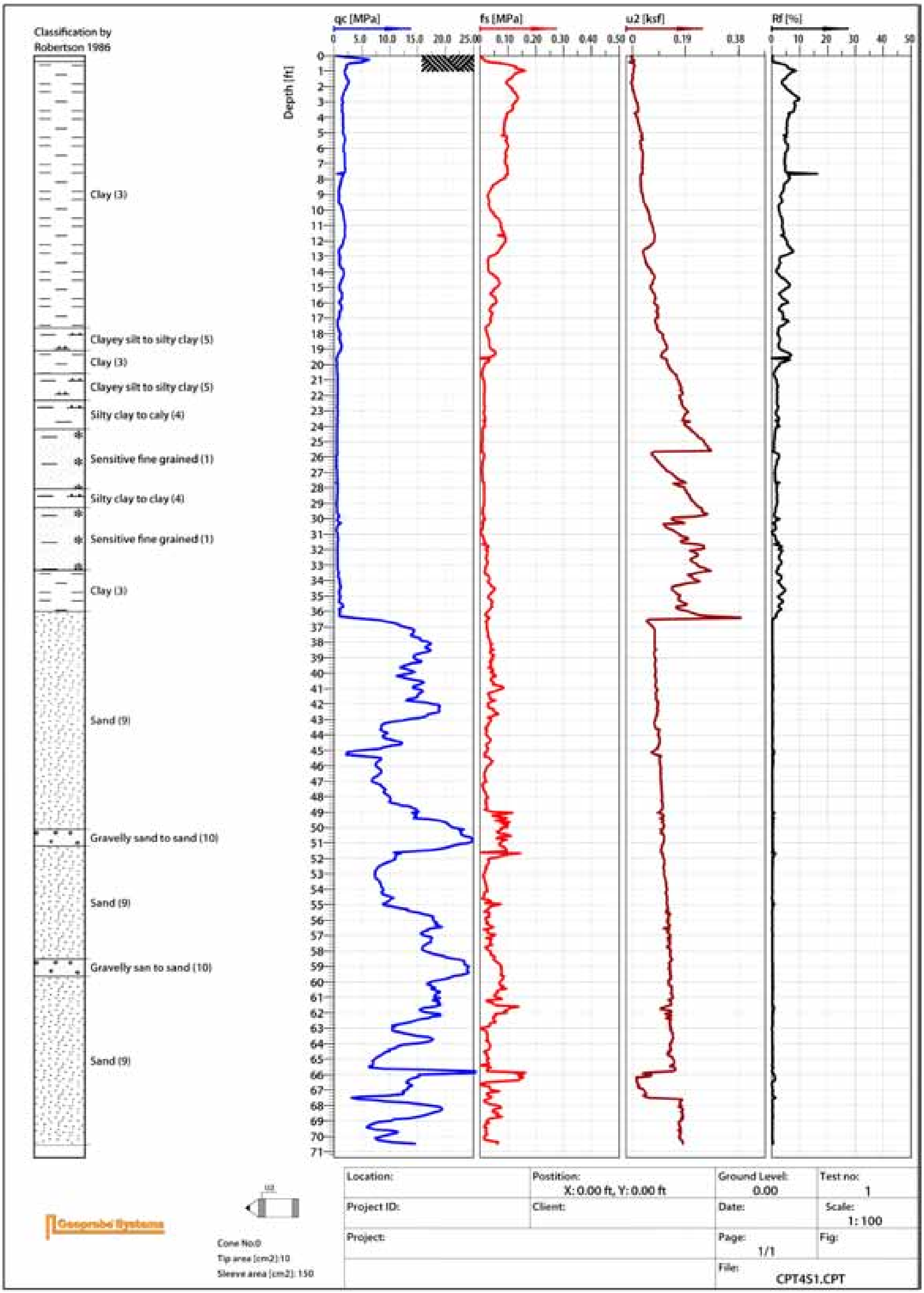

**Figure 11A–3** Plot of CPT Data Record, Monroe County, Iowa

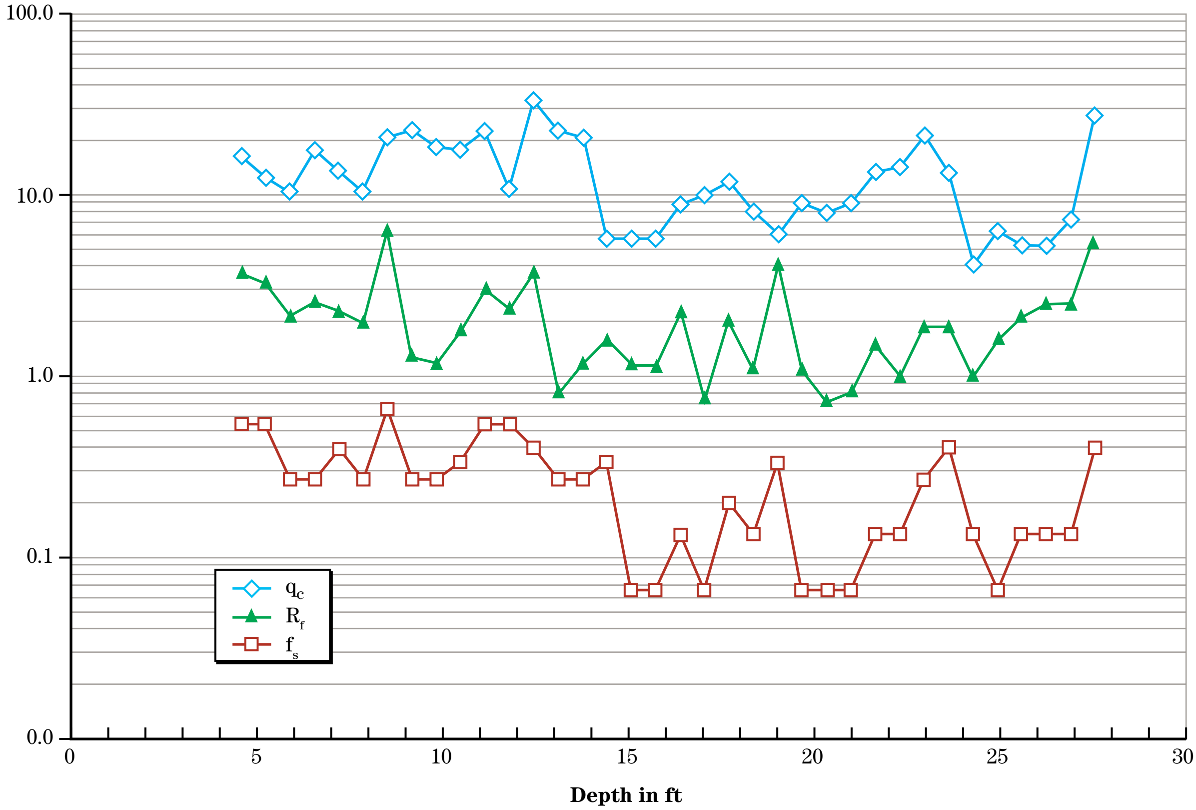

**Table 11A–1** CPT data record, Monroe Co., Iowa

| **Dutch Cone**<br>**Soap Creek 4–86**<br>**DG=$P_2$–$P_1$** | | **Monroe Co., IA**<br>$q_c = 0.14 \times (\#\ \text{rods}) + 2 \times P_1$ | | | **10/5/2005**<br>$f_s = 0.133 \times DG$ | | **TH–2**<br>$R_f = \frac{f_s}{q_c} \times 100$<br>**($q_c$ = previous reading)** | **W.L.=12.2** |
|---|---|---|---|---|---|---|---|---|
| **Depth (meters)** | **Depth (feet)** | **# rods** | **$P_1$** | **$P_2$** | **DG** | **$q_c$** | **$f_s$** | **$R_f$** |
| 0.2 | 0.66 | | | | | | | |
| 0.4 | 1.31 | | | | | | | |
| 0.6 | 1.97 | | | | | | | |
| 0.8 | 2.62 | | | | | | | |
| 1 | 3.28 | | | | | | | |
| 1.2 | 3.94 | 2 | 7 | 8 | 1 | 14.3 | 0.1 | #DIV/0! |
| 1.4 | 4.59 | 2 | 8 | 12 | 4 | 16.3 | 0.5 | 3.7 |
| 1.6 | 5.25 | 3 | 6 | 10 | 4 | 12.4 | 0.5 | 3.3 |
| 1.8 | 5.90 | 3 | 5 | 7 | 2 | 10.4 | 0.3 | 2.1 |
| 2 | 6.56 | 3 | 8.5 | 10.5 | 2 | 17.4 | 0.3 | 2.6 |
| 2.2 | 7.22 | 3 | 6.5 | 9.5 | 3 | 13.4 | 0.4 | 2.3 |
| 2.4 | 7.87 | 3 | 5 | 7 | 2 | 10.4 | 0.3 | 2.0 |
| 2.6 | 8.53 | 4 | 10 | 15 | 5 | 20.6 | 0.7 | 6.4 |
| 2.8 | 9.18 | 4 | 11 | 13 | 2 | 22.6 | 0.3 | 1.3 |
| 3 | 9.84 | 4 | 9 | 11 | 2 | 18.6 | 0.3 | 1.2 |
| 3.2 | 10.50 | 4 | 8.5 | 11 | 2.5 | 17.6 | 0.3 | 1.8 |
| 3.4 | 11.15 | 4 | 11 | 15 | 4 | 22.6 | 0.5 | 3.0 |
| 3.6 | 11.81 | 5 | 11 | 15 | 4 | 10.7 | 0.5 | 2.4 |
| 3.8 | 12.46 | 5 | 16 | 19 | 3 | 32.7 | 0.4 | 3.7 |
| 4 | 13.12 | 5 | 11 | 13 | 2 | 22.7 | 0.3 | 0.8 |
| 4.2 | 13.78 | 5 | 10 | 12 | 2 | 20.7 | 0.3 | 1.2 |
| 4.4 | 14.43 | 5 | 2.5 | 5 | 2.5 | 5.7 | 0.3 | 1.6 |
| 4.6 | 15.09 | 6 | 2.5 | 3 | 0.5 | 5.8 | 0.1 | 1.2 |
| 4.8 | 15.74 | 6 | 2.5 | 3 | 0.5 | 5.8 | 0.1 | 1.1 |
| 5 | 16.40 | 6 | 4 | 5 | 1 | 8.8 | 0.1 | 2.3 |
| 5.2 | 17.06 | 6 | 4.5 | 5 | 0.5 | 9.8 | 0.1 | 0.8 |
| 5.4 | 17.71 | 6 | 5.5 | 7 | 1.5 | 11.8 | 0.2 | 2.0 |
| 5.6 | 18.37 | 7 | 3.5 | 4.5 | 1 | 8.0 | 0.1 | 1.1 |
| 5.8 | 19.02 | 7 | 2.5 | 5 | 2.5 | 6.0 | 0.3 | 4.2 |
| 6 | 19.68 | 7 | 4 | 4.5 | 0.5 | 9.0 | 0.1 | 1.1 |
| 6.2 | 20.34 | 7 | 3.5 | 4 | 0.5 | 8.0 | 0.1 | 0.7 |
| 6.4 | 20.99 | 7 | 4 | 4.5 | 0.5 | 9.0 | 0.1 | 0.8 |
| 6.6 | 21.65 | 8 | 6 | 7 | 1 | 13.1 | 0.1 | 1.5 |

**Table 11A–1** CPT data record, Monroe Co., Iowa—continued

| **Dutch Cone**<br>**Soap Creek 4–86**<br>**DG=$P_2$–$P_1$** | | $q_c = 0.14 \times (\#\ \text{rods}) + 2 \times P_1$ | **Monroe Co., IA** | | **10/5/2005**<br>$f_s = 0.133 \times DG$ | | **TH–2**<br>$R_f = \frac{f_s}{q_c} \times 100$<br>**($q_c$ = previous reading)** | **W.L.=12.2** |
|---|---|---|---|---|---|---|---|---|
| **Depth (meters)** | **Depth (feet)** | **# rods** | **$P_1$** | **$P_2$** | **DG** | **$q_c$** | **$f_s$** | **$R_f$** |
| 6.8 | 22.30 | 8 | 6.5 | 7.5 | 1 | 14.1 | 0.1 | 1.0 |
| 7 | 22.96 | 8 | 10 | 12 | 2 | 21.1 | 0.3 | 1.9 |
| 7.2 | 23.62 | 8 | 6 | 9 | 3 | 13.1 | 0.4 | 1.9 |
| 7.4 | 24.27 | 8 | 1.5 | 2.5 | 1 | 4.1 | 0.1 | 1.0 |
| 7.6 | 24.93 | 9 | 2.5 | 3 | 0.5 | 6.3 | 0.1 | 1.6 |
| 7.8 | 25.58 | 9 | 2 | 3 | 1 | 5.3 | 0.1 | 2.1 |
| 8 | 26.24 | 9 | 2 | 3 | 1 | 5.3 | 0.1 | 2.5 |
| 8.2 | 26.90 | 9 | 3 | 4 | 1 | 7.3 | 0.1 | 2.5 |
| 8.4 | 27.55 | 9 | 13 | 16 | 3 | 27.3 | 0.4 | 5.5 |