27

In Situ Subsurface Characterization

J. David Frost
Georgia Institute of Technology

Susan E. Burns
Georgia Institute of Technology

27.1 Introduction

The *in situ* **subsurface** characterization section of a civil engineering handbook published 20 years ago would have been dominated by details of the standard penetration test with perhaps no more than a passing reference to some other test methods. As a result of significant technological advances in the past two decades and, perhaps equally important, increased recognition that there is a direct relationship between the efficiency of a design and the quality of the parameters on which this design is based, discussion of a much broader range of test methods is now appropriate in a text such as this. **Invasive** and **noninvasive** test methods using a variety of penetrometers and wave propagation techniques (e.g., cone **penetration testing**, seismic reflection/refraction testing, dilatometer testing, and pressuremeter testing) are now routinely used in many instances in preference to, or at least as a complement to, the standard penetration test. A listing of the more common techniques is given in Table 27.1.

27.2 Subsurface Characterization Methodology

The process of characterizing a site begins long before the first boring or sounding is advanced. In most cases, there will be information available either at the immediate site or at least in the general vicinity such that some initial impressions can be synthesized with respect to the subsurface conditions and the types of potential problems which may be encountered during the proposed development at the site. Example sources and types of information which may be available are summarized in Table 27.2.

When this available data has been synthesized, the engineer can then develop a site investigation strategy to supplement/complement the existing information and help achieve the objectives of the exploration program, including:

- Determine the subsurface stratigraphy (geologic profile), including the interface between fill and natural materials and the depth to bearing strata (e.g., bedrock) if appropriate.
- Investigate the groundwater conditions, including the location of water-bearing seams as well as perched aquifer and permanent groundwater table elevations.

TABLE 27.1 Summary of Common *In Situ* Subsurface Characterization Techniques

Test	Invasive/ Noninvasive	Sample Recovered	Usage
Standard penetration test	Invasive	Yes	Extensive
Cone penetration test	Invasive	No	Extensive
Pressuremeter test	Invasive	No	Moderate
Dilatometer	Invasive	No	Moderate
Vane shear test	Invasive	No	Moderate
Becker density test	Invasive	Yes	Limited
Borehole seismic test	Invasive	No	Extensive
Surface seismic test	Noninvasive	No	Extensive

TABLE 27.2 Sources and Types of Background Information

Data Source	Information Available
Topographic maps	Maps published by the U.S. Geological Survey showing site terrain, dams, surface water conditions, rock quarries
Previous geologic studies	Soil types, current and previous river and lake locations, floodplains, groundwater conditions, rock profiles
Soil survey data	Maps published by the Department of Agriculture profiling the upper 6 to 10 feet of soil
Previous engineering reports	Site geological description, record of fills or cuts, groundwater information, floodplains, wetlands, previous construction activity
Aerial photogrammetry	Macroscopic identification of topography, surface water drainage/erosion patterns, vegetation
State/municipal well logs	Groundwater table information, pumping rates, water table drawdown
Seismic potential	Maps published by the U.S. Geological Survey delineating seismicity zones in the U.S.
Personal reconnaissance	Identification of geological features through the examination of road cuts, vegetation, slopes, rivers, previously constructed buildings

- Obtain samples of subsurface materials for additional laboratory testing as appropriate.
- Install any instrumentation as required to permit additional assessment of the subsurface environment at subsequent time intervals (e.g., piezometers, inclinometers, thermistors).

27.3 Subsurface Characterization Techniques

As noted above, the range of test methods available today for subsurface characterization programs has increased significantly over the past few decades. For discussion purposes, they are considered herein under the following broad categories:

- Test pits
- Conventional drilling and sampling
- Penetration testing
- **Geophysical testing**
- Other testing techniques

Additional details of these categories are given below.

Test Pits

Test pits are a valuable technique for investigating near-surface conditions under a variety of scenarios. Typical depths of 15 to 20 feet are readily excavated with backhoe equipment of the type generally available on most construction sites. Excavations to greater depths are possible with long-boom equipment or if a multiple-layer excavation is made. The method becomes less efficient with deeper test pits since the area of the excavation typically increases for deeper holes as the sides are sloped to facilitate excavation and personnel access and safety. Among the advantages of test pits are that the engineer can clearly document and photograph the subsurface stratigraphy, and the recovery of bulk samples for laboratory compaction and other tests requiring large samples is easy. Near-surface groundwater and cohesionless soils can combine to make excavation difficult as soil caving undermines the edges of the test pit. Although, unfortunately, less frequently used nowadays than the authors consider appropriate, block sampling techniques are easily conducted in the base or side of a test pit.

Conventional Drilling and Sampling

Depending on the anticipated subsurface conditions and the specific objectives of the investigation program, a number of conventional drilling and sampling techniques are available. An example field borehole log is shown in Fig. 27.1. Typical boring techniques used include auger drilling, rotary drilling, cable tool drilling, and percussion drilling. Factors ranging from the anticipated stratigraphy (sequence and soil type) to depth requirements can influence the method chosen. A summary of the main advantages and disadvantages for the various methods is given in Table 27.3.

Samples of soil and rock for subsequent analysis and testing can be obtained using a variety of techniques. These may range from chunk samples (taken from flights of augers) to split spoon samples (disturbed samples), which are typically obtained by driving a split barrel sampler as in the standard penetration test [ASTM D1586], to thin-walled tube samples (**undisturbed samples**), which can be obtained using one of a variety of mechanical or hydraulic insertion devices [ASTM D1587]. A summary of the factors pertinent to the selection of a specific sampling technique is listed in Table 27.4.

Penetration Testing

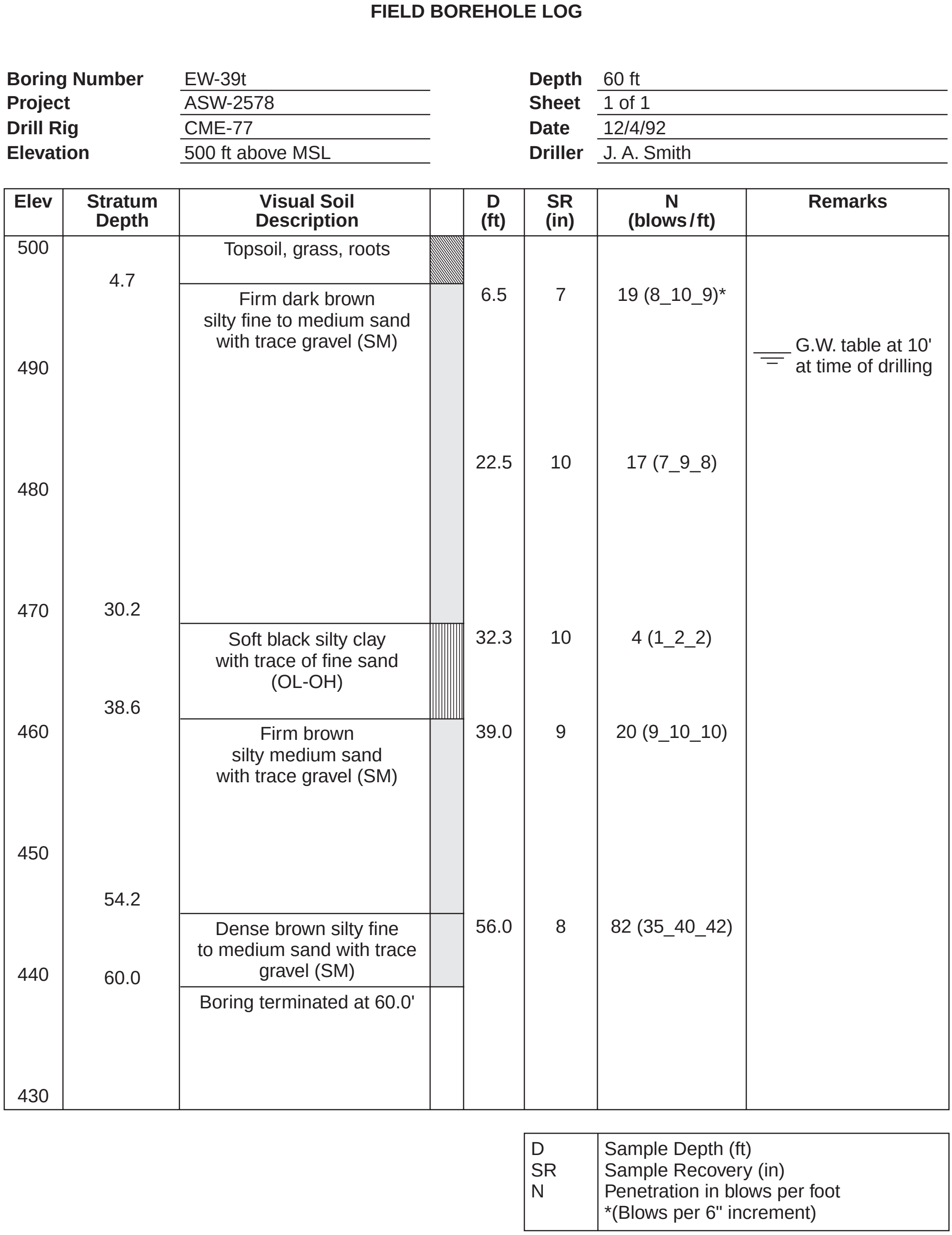
The term *penetration testing* is being used herein to describe a variety of test procedures which involve the performance of a controlled application and recording of loads and/or deformations as a tool is being advanced into the subsurface. For the purposes of this text, this includes pressuremeter tests [ASTM D4719] performed in predrilled holes (although obviously this is strictly not a penetration-type test as defined above). In some cases, the loads and/or deformations are recorded continuously as the device is being inserted into the ground, while in other cases measurements are made when the insertion process is halted at predetermined intervals. An assessment of *in situ* testing is given in Table 27.5. Brief descriptions of the most common methods follow.

Standard Penetration Testing

Standard penetration testing refers to a test procedure wherein a split tube sampler is driven into the ground with a known force and the number of blows required to drive the sampler 12 inches is recorded as an N value [de Mello, 1971]. The standard test procedure [ASTM D1586] refers to sampler devices which have an outside diameter of 5.1 cm, an inside diameter of 3.5 cm, and a length somewhere in the range of 50 to 80 cm to retain the soil sample. The sampler is driven into the ground with a drive weight of 63.5 kg dropping 76 cm. A variety of different hammer types are available. These range from donut and safety hammers, which are manually operated through the use of a rope and cathead, to automatic trip hammers. There is little question that this is still probably the most widely used penetration test device in the U.S. although there is clearly more widespread recognition of the many limitations of the test device resulting from equipment and operator error sources. The principal advantages and disadvantages of standard penetration testing are summarized in Table 27.6.

Cone Penetration Testing

Cone penetration testing refers to a test procedure wherein a conical-shaped probe is pushed into the ground and the penetration resistance is recorded [Robertson and Campanella, 1983]. The standard test procedure [ASTM D3441] refers to test devices which have a cone with a 60° point angle and a base



FIELD BOREHOLE LOG

Boring Number	EW-39t	**Depth**	60 ft
Project	ASW-2578	**Sheet**	1 of 1
Drill Rig	CME-77	**Date**	12/4/92
Elevation	500 ft above MSL	**Driller**	J. A. Smith

Elev	Stratum Depth	Visual Soil Description		D (ft)	SR (in)	N (blows / ft)	Remarks
500		Topsoil, grass, roots	▨				
	4.7	Firm dark brown silty fine to medium sand with trace gravel (SM)		6.5	7	19 (8_10_9)*	
490							G.W. table at 10' at time of drilling
				22.5	10	17 (7_9_8)	
480							
470	30.2						
		Soft black silty clay with trace of fine sand (OL-OH)	▥	32.3	10	4 (1_2_2)	
	38.6						
460		Firm brown silty medium sand with trace gravel (SM)		39.0	9	20 (9_10_10)	
450							
	54.2						
		Dense brown silty fine to medium sand with trace gravel (SM)		56.0	8	82 (35_40_42)	
440	60.0						
		Boring terminated at 60.0'					
430							

D	Sample Depth (ft)
SR	Sample Recovery (in)
N	Penetration in blows per foot *(Blows per 6" increment)

FIGURE 27.1 Typical field boring log.

diameter of 3.57 cm that results in a projected cross-sectional area of 10 cm^2. While original cones operated with an incremental mechanical system, most new cones are electronic and are pushed continuously at a rate of 2 cm/sec. Other frequent additions to a penetrometer include a friction sleeve with an area of 150 cm^2 and a porous element which permits the pore water pressure to be recorded by a pressure transducer. A typical cone penetration test system along with details of an electronic piezo-friction cone are illustrated in Fig. 27.2. Simultaneous continuous measurements of tip resistance, q_c, side friction, f_s, and pore pressure, u, are recorded. Appropriate corrections are required to account for

TABLE 27.3 Comparison of Various Drilling Methods

Drilling Method		Advantages	Disadvantages
Auger drilling	Hollow stem	• Rapid • Inexpensive • Visual recognition of changes in strata • Hole easily cased to prevent caving • Soil/water samples easily recovered, although disturbed • No drilling fluid required	• Depth limited to approximately 80–100 ft • Cannot drill through rock • Can have heave in sands • Limited casing diameter
	Solid stem	• Rapid • Inexpensive • Small borehole required	• Sampling difficulty • Borehole collapse on removal
Rotary drilling	Direct	• Rapid • Used in soil or rock • Casing not required • Wells easily constructed • Soil disturbance below borehole minimal • Easily advances borehole through dense layers	• Drilling fluid required • No water table information during drilling • Difficult to identify particular strata • Sampling not possible during boring • Slow in coarse gravels
	Air	• Rapid • Used in soil or rock • Capable of deep drilling • No water-based drilling fluid required	• Casing required in soft heaving soils • Relatively expensive
Cable tool		• Inexpensive • Small quantities of drilling fluid required • Used in soil or rock • Water levels easily determined	• Minimum casing diameter 4 in. • Steel casing required • Slow • Screen required to take water sample • Depth limited to approximately 50–60 ft • Difficult to detect thin layers
Percussion drilling (Becker density test)		• Measure penetration resistance of gravelly soils • Relatively operator independent • Estimate pile drivability • Continuous profiling • Designed for gravels and cobbles	• Equipment strongly influences test results • Based on empirical correlations

TABLE 27.4 Selection of Sampling Technique

Sample Type	Sample Quality	Suitability for Testing
Block sample	Excellent	Classification, water content, density, consolidation, shear strength
Thin-walled tube, piston	Very good	Classification, water content, density, consolidation, shear strength
Thin-walled tube	Good	Classification, water content, density, consolidation, shear strength
Split spoon	Poor	Classification, water content
Auger/wash cuttings	Very poor	Soil identification

unequal end areas behind the tip of the penetrometer. An example cone sounding record is shown in Fig. 27.3. The principal advantages and disadvantages of cone penetration testing are summarized in Table 27.7. Cone penetrometers are being used for an increasing number of applications as new sensors are being developed and incorporated into penetration devices for a variety of geotechnical and geo-environmental applications, as summarized in Table 27.8.

TABLE 27.5 Assessment of *In Situ* Testing

Advantages	Disadvantages
Rapid	No sample recovered (except SPT)
Inexpensive	Indirect measurement related through calibration
Difficult deposits can be tested	Complex data reduction
In situ stress, pore fluid, temperature conditions	Relies heavily on empirical correlations
Real-time measurements	Unknown boundary conditions
Reproducible results	Unknown drainage conditions
Large volume of soil tested	Strain-rate effects
Continuous or semicontinuous profiling	Nonuniform strains applied
	Specialized equipment and skilled operators often required

TABLE 27.6 Assessment of Standard Penetration Testing

Advantages	Disadvantages
Commonly available	Based on empirical correlations
Applicable to most soils	Significant operator/equipment influences (See Navfac DM7.1)
Sample (disturbed) recovered	Not useful in gravels, cobbles
Rapid/inexpensive	Not useful in sensitive clays

Dilatometer Testing

The flat plate dilatometer test [Marchetti, 1980; Schmertmann, 1986] was originally introduced to provide an easy method for determining the horizontal soil pressures acting on laterally loaded piles. The present design of the dilatometer blade consists of a flat blade 1.5 cm thick by 9.6 cm wide with a 6.0 cm diameter membrane on one face, as shown in Fig. 27.4. The test is performed by advancing the blade by quasi-static push at a rate of 2 cm/s. At regular intervals, typically every 20 cm, two or three pressure readings are obtained. The A pressure reading is a membrane liftoff pressure and is obtained just as the membrane begins to move. The B pressure reading is the pressure required to cause the center of the membrane to move 1.1 mm into the soil mass. If desired, a C pressure reading may be obtained by controlling the rate of deflation of the membrane and finding the pressure at which the membrane once again comes in contact with its seat. The A and B pressure readings, corrected for membrane stiffness to P_1 and P_0, respectively, are used to define a number of dilatometer indices:

$$\text{Dilatometer index, } E_D = 34.7(P_1 - P_0)$$

$$\text{Horizontal stress index, } K_D = (P_1 - U_0)/(\sigma'_{v0})$$

$$\text{Material index, } I_D = (P_1 - P_0)/(P_0 - U_0)$$

The C pressure reading, corrected for membrane stiffness, is thought to provide an upper bound to the induced pore pressures.

Using these dilatometer indices and numerous correlations which have been developed, a large number of soil parameters can be estimated. The principal advantages and disadvantages of dilatometer testing are summarized in Table 27.9.

Pressuremeter Testing

The pressuremeter test [Baguelin et al., 1978] typically consists of placing an inflatable cylindrical probe in a predrilled borehole and recording the changes in pressure and volume as the probe is inflated. The standard test procedure (ASTM D4719) uses probes with typical diameters ranging between 4.4 and

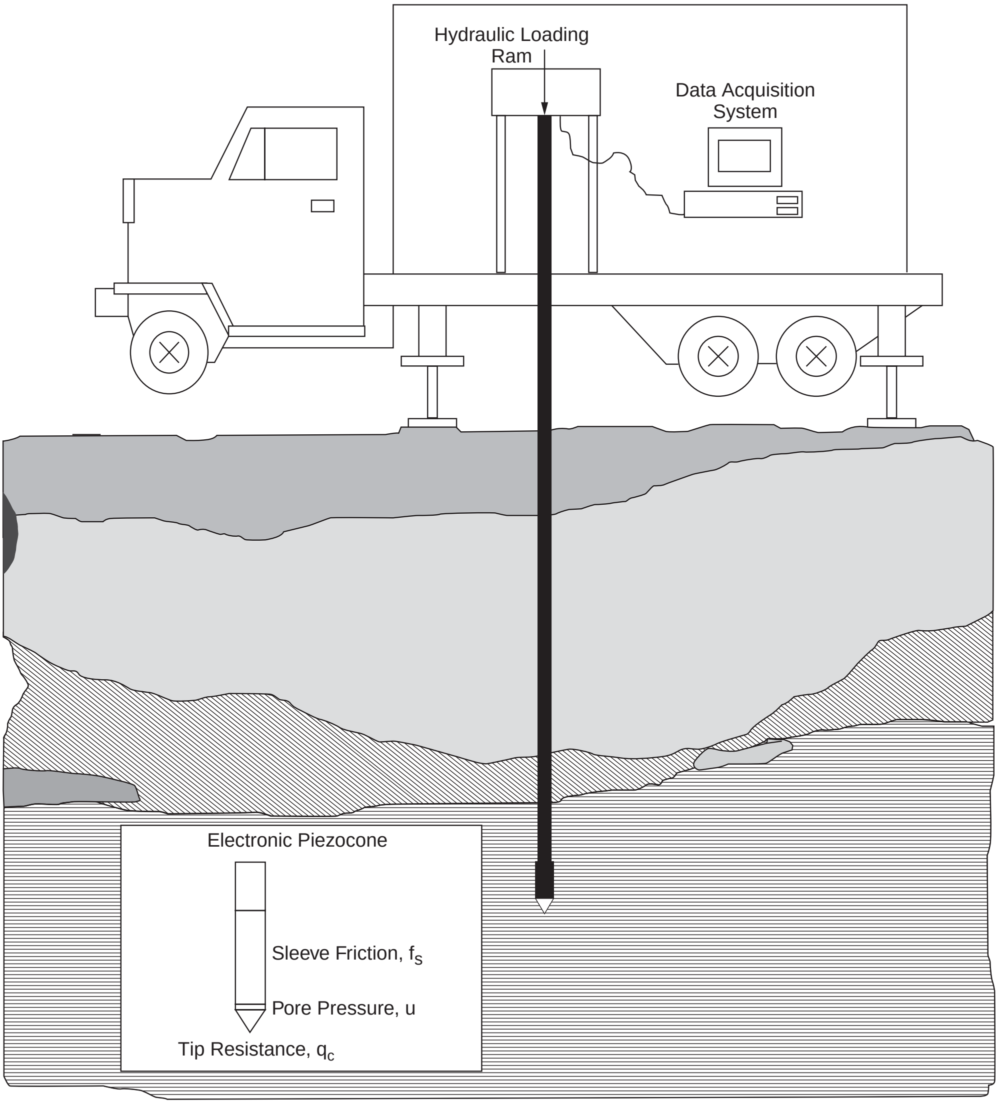


FIGURE 27.2 Cone penetration test system.

7.4 cm while the length of the inflatable portion of the probe on which the soil response is based varies between about 30 and 60 cm depending on whether the unit is a single-cell type or has guard cells at either end of the measuring cell. The probe can be expanded using equal pressure increments or equal volume increments. A schematic of a typical test arrangement is shown in Fig. 27.5. Pressuremeter soundings consist of tests performed at 1 m intervals, although clearly this is a function of the site geology and the purpose of the investigation. The test results, appropriately corrected for membrane stiffness and hydrostatic pressure between the control unit and the probe, are plotted as shown in Fig. 27.6, from which the pressuremeter modulus, E_{PM}, and the limit pressure, P_L, are determined. Using these pressuremeter indices and numerous correlations which have been developed, a large number of soil parameters can be estimated. The principal advantages and disadvantages of pressuremeter testing are summarized in Table 27.10.

One of the key factors which affects the results of the pressuremeter test is the amount of stress relief which occurs before the probe is expanded. To minimize this problem, guidelines for borehole sizes and

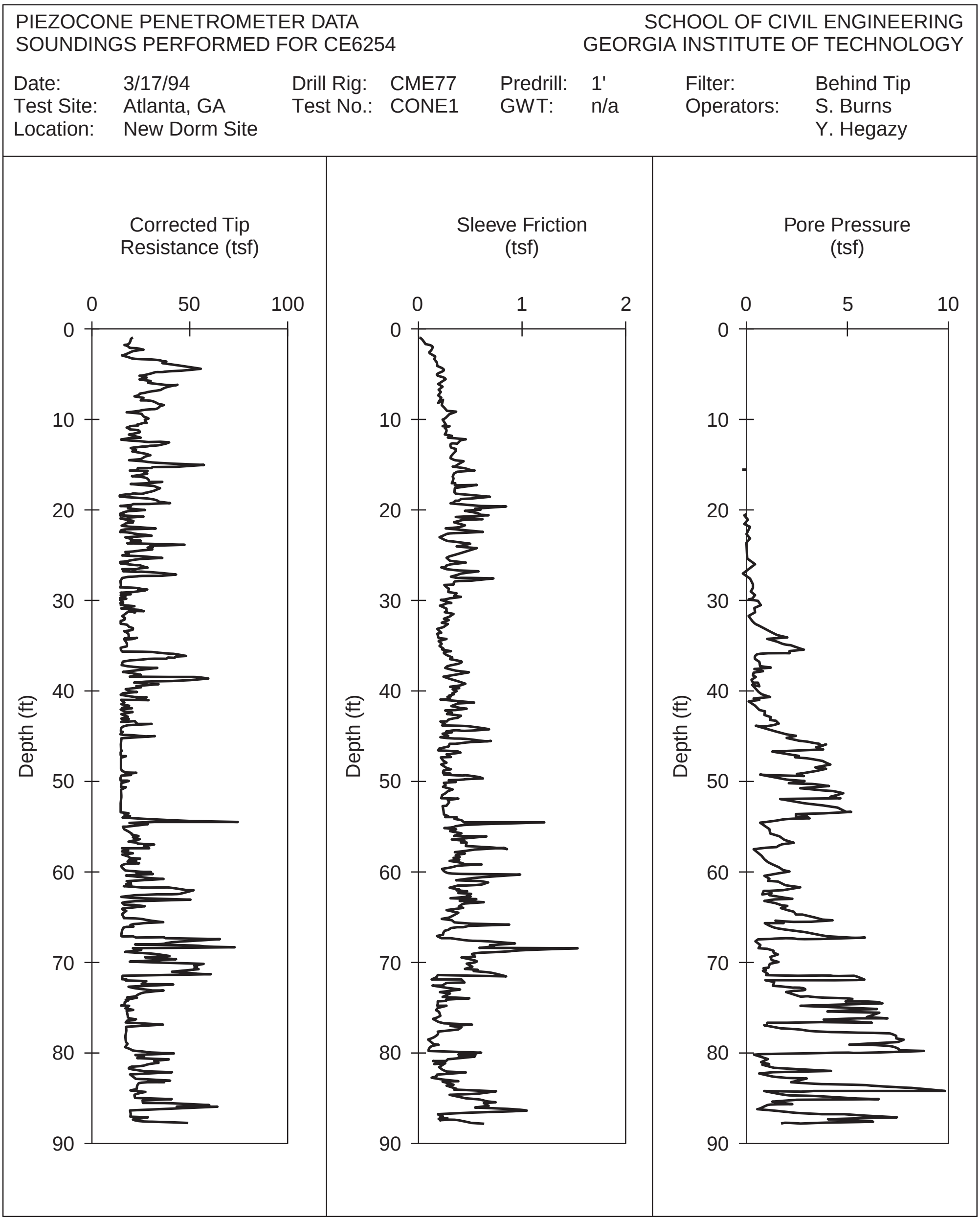


FIGURE 27.3 Typical cone penetrometer record.

the test sequence are given in ASTM D4719 for probes requiring a predrilled borehole. Alternatively, self-boring devices can be used to reduce the impact of stress relief.

Vane Shear Test

The vane shear test consists of placing a four-bladed vane in the undisturbed soil at the bottom of a boring and determining the torsional force required to cause a cylindrical surface to be sheared by the vane [Becker et al., 1987]. The test is applicable for cohesive soils. The standard test procedure [ASTM D2573] uses vanes with typical diameters ranging between 3.8 and 9.2 cm and lengths of 7.6 to 18.4 cm, as shown in Fig. 27.7. Selection of the vane size depends on the soil type with larger vanes used in softer

TABLE 27.7 Assessment of Cone Penetration Testing

Advantages	Disadvantages
Rapid/inexpensive	No sample recovered
Reproducible results	Penetration depth limited to 150–200 ft
Continuous tip resistance, sleeve friction, and pore pressure (piezocone) profile	Normally cannot push through gravel
Accurate, detailed subsurface stratigraphy/identification of problem soils	Requires special equipment and skilled operators
Real-time measurements	Most analysis based on correlations
Pore pressure dissipation tests allow prediction of permeability and C_h	
Models available to predict strength, stress history, compressibility	

TABLE 27.8 Specialized Cone Penetrometers

Sensor	Application
Accelerometer	Measurement of seismic wave velocity
Nuclear moisture content sensors	Measurement of soil moisture content
Resistivity electrodes	Identification of pore characteristics and fluids
Laser-induced fluorescence	Hydrocarbon detection
Temperature	Measurement of cone body temperature
Hydrocarbon sensors	Detection of BTEX chemicals in pore fluid and vadose zone

clays so as to provide measured torque values of a reasonable magnitude. The torque is applied at a relatively slow rate of the order of 0.1°/s which results in times to failure of 2 to 10 minutes depending on soil type. The shear strength of the soil is calculated as the product of the torque applied and a constant depending on the geometry of the vane. The principal advantages and disadvantages of vane shear testing are summarized in Table 27.11.

Geophysical Testing

Geophysical testing techniques [Woods, 1978] for investigating subsurface conditions have become a frequently used tool by engineers. They offer a number of advantages over other investigation techniques, including the noninvasive nature of the methods and the volume of soil for which properties are determined. The most common methods are seismic reflection and seismic refraction. The basis of these methods is that the time for seismic waves to travel between a source and receiver can be used to interpret information about the material through which it travels. Depending on the arrangement of the source and receivers, the subsurface environment can thus be characterized. In general, the methods require a subsurface profile where the layer stiffnesses and hence wave velocities increase with depth. Advantages and disadvantages of geophysical test methods are given in Table 27.12.

Seismic Reflection

Seismic reflection is used to describe methods where the time for the reflection of a seismic wave induced at the surface is recorded. A typical test configuration is shown in Fig. 27.8. This method involves study of complete wave trains from multiple receivers to characterize the subsurface; thus, interpretation of the test results can be subjective.

Seismic Refraction

Seismic refraction is used to describe methods where the time for seismic waves which are refracted when they encounter a stiffer material in the subsurface are recorded. A typical test configuration is shown in Fig. 27.9. Unlike reflection methods, refraction methods only rely on the time for first arrivals; thus, interpretation of the results can be more straightforward.

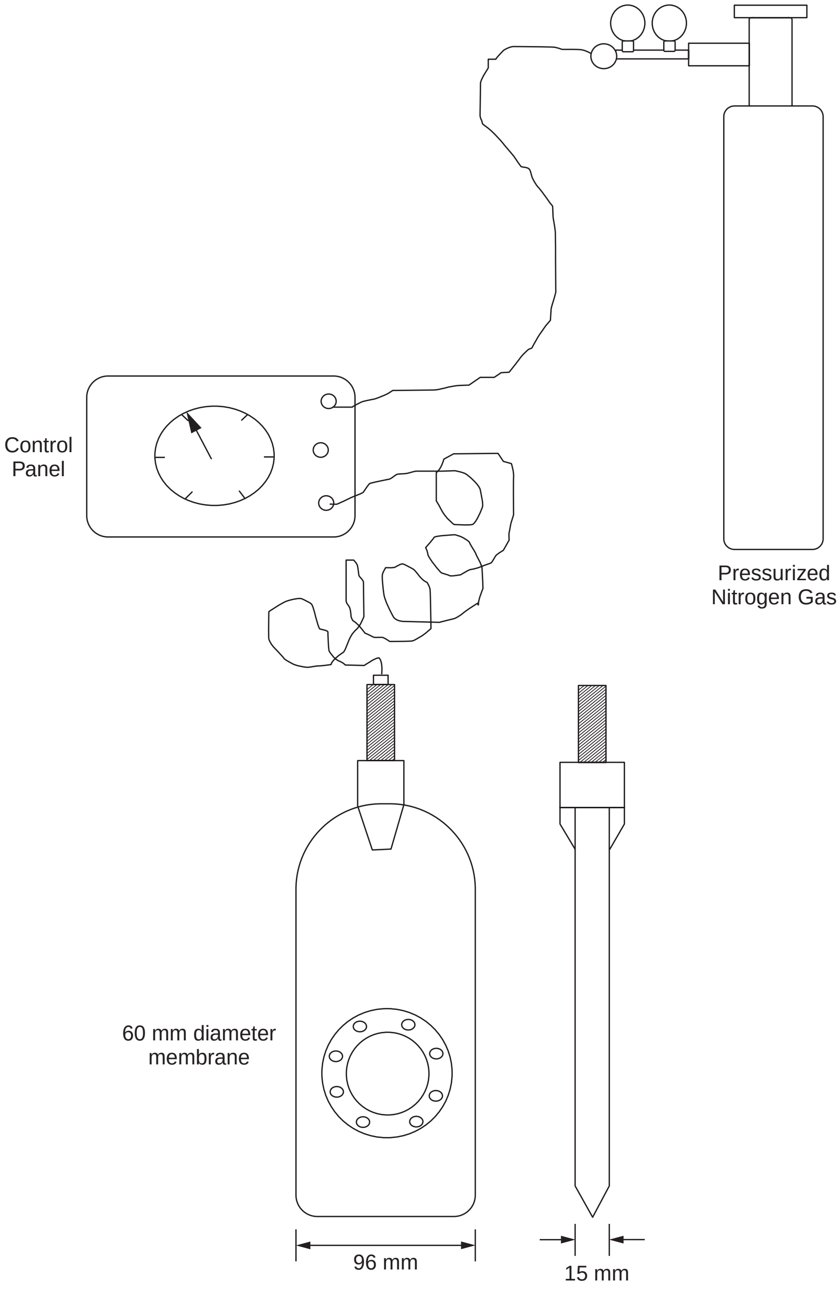


FIGURE 27.4 Dilatometer test system.

TABLE 27.9 Assessment of Dilatometer Testing

Advantages	Disadvantages
Rapid/inexpensive	Not applicable in gravels
Does not require skilled operators	No sample recovered
Semicontinuous profile	Based on empirical correlations
Estimates of horizontal stress and OCR	
Rapid data reduction	

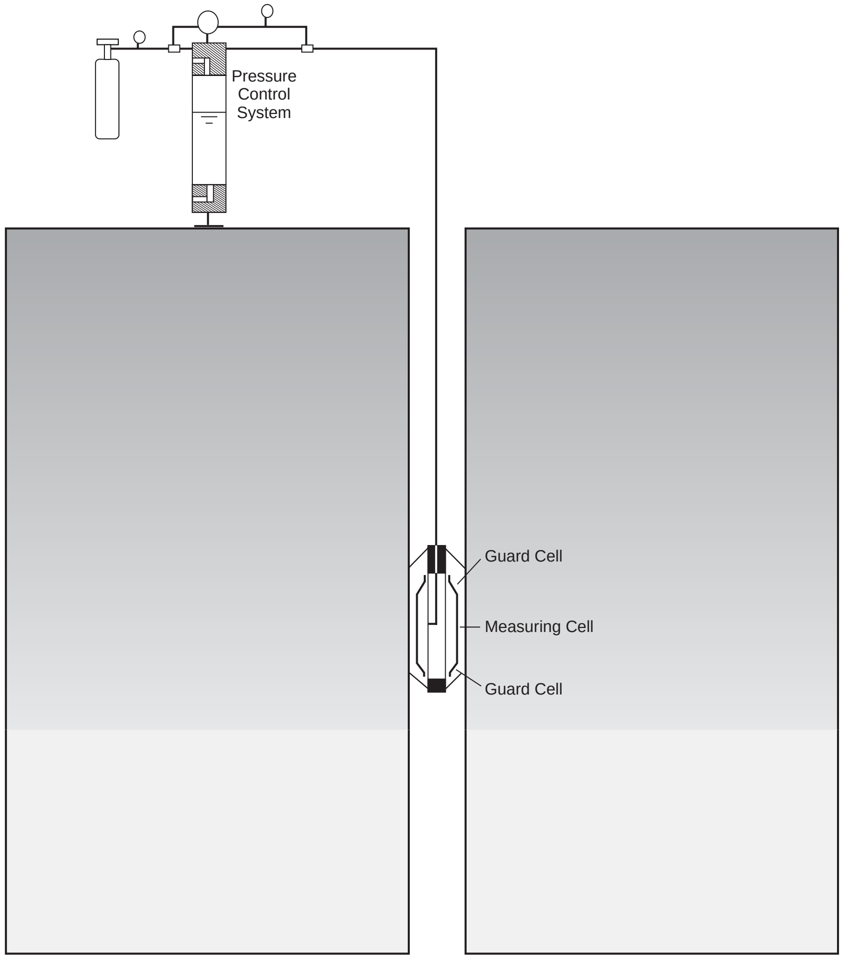


FIGURE 27.5 Pressuremeter test system.

Crosshole Testing

Crosshole seismic testing differs from the methods described above in that the source and receiver are located at the same depth in adjacent boreholes and the time for seismic waves to travel between these instruments is recorded. The standard test procedure for crosshole testing [ASTM D4428] involves drilling a minimum of three boreholes in line spaced about 3 m apart. A PVC casing is then grouted in place to ensure a good couple between the source/receiver and the PVC casing and between the PVC casing and the surrounding soil. A typical configuration is shown in Fig. 27.10.

Other Testing Techniques

While the specific test methods described above represent those that are most frequently used, there are a large number of other devices and methods that are available and should be considered by the engineer designing a site investigation program. A number of these methods are used extensively in geo-environmental site characterization programs while others are still in development or are available only for use on a limited basis. Nevertheless, since the efficiency and quality of any foundation design is directly dependent on the quality of the subsurface information available, the engineer should be aware of all possible investigation tools available and select those which can best suit the project at hand. Recognition

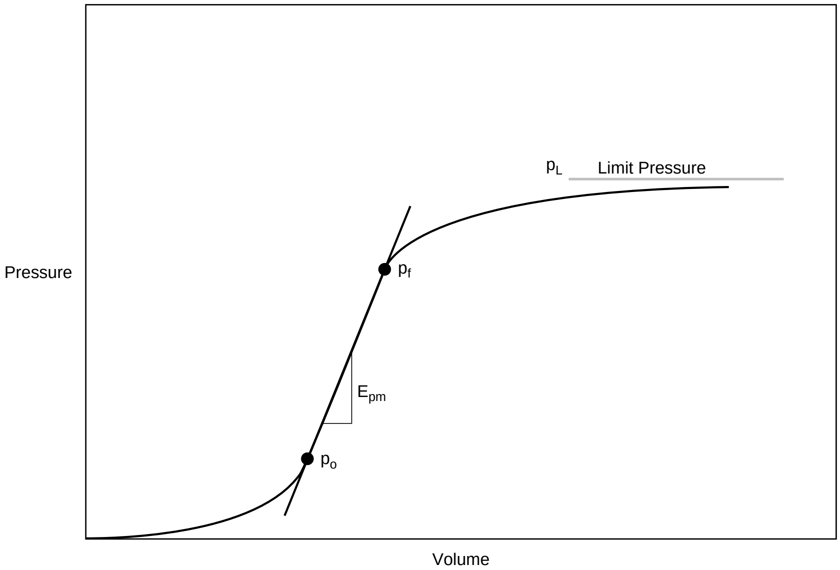


FIGURE 27.6 Typical pressuremeter test result.

TABLE 27.10 Assessment of Pressuremeter Testing

Advantages	Disadvantages
Applicable in most soils	Expensive
In situ measurements of horizontal stresses, deformability, strength	Specialized equipment and skilled operators required
Prediction of modulus	Delicate equipment
	Independent soil characterization required
	Prebored hole may be required

of the simple fact that the expenditure of an additional few thousand dollars at the site investigation stage could result in the savings of many thousands or even millions of dollars as a result of an inefficient design or, worse, a failed foundation system, is important. Accordingly, Table 27.13 contains a listing of several other testing techniques which should be considered.

27.4 Shipping and Storage of Samples

Use of the best available techniques for drilling and sampling can be negated if appropriate procedures are not used for shipping and storing samples. Accordingly, an integral part of the planning of any site investigation program should be the identification of procedures required for shipping samples to a laboratory and for their subsequent storage prior to testing. Typical details of procedures and containers appropriate for maintaining subsurface samples in a condition as close as possible to their undisturbed state are available [for example, ASTM D3213, ASTM D4220, ASTM D5079].

Defining Terms

Geophysical testing — Test procedures which involve the application and recording of the travel of relatively low frequency, high amplitude waves in the subsurface.

Invasive — Test procedure which involves physical insertion of a test instrument into the subsurface.

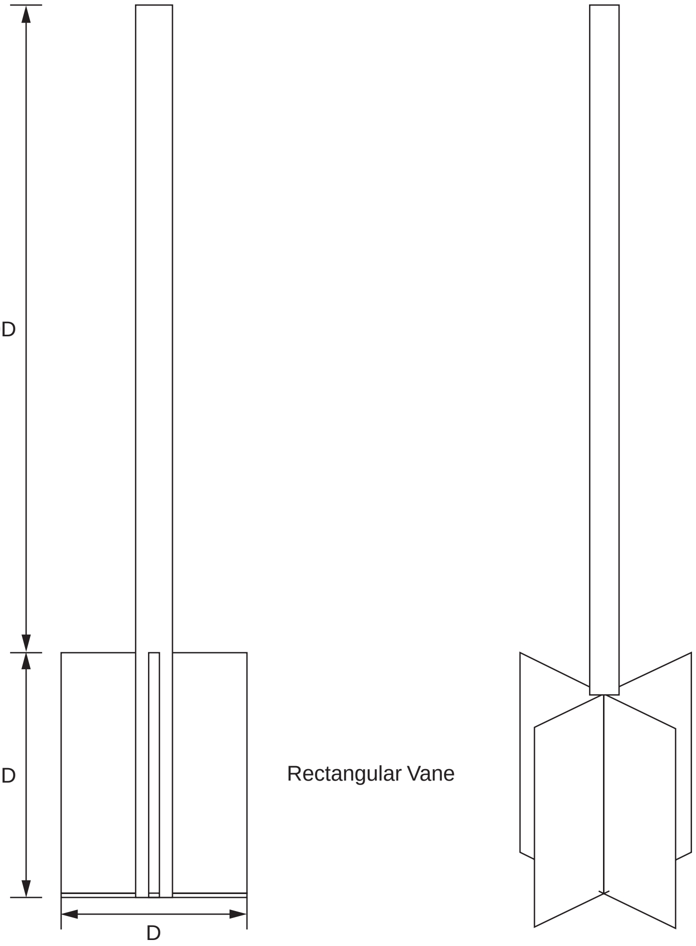


FIGURE 27.7 Vane shear test system.

TABLE 27.11 Assessment of Vane Shear Testing

Advantages	Disadvantages
Rapid/inexpensive	Only applicable in soft clays
Applicable to sensitive clays	Point measurement
Theoretical basis	Generally only undrained shear strength measurements
Measurement of shear strength, remolded shear strength, and sensitivity	No sample recovered
	Prebored hole may be required
	Independent soil characterization required

Noninvasive — Test procedure which does not involve physical insertion of a test instrument into the subsurface.

Penetration testing — Test procedures which involve the performance of a controlled application and recording of loads and/or deformations as a device is being advanced into the subsurface.

Subsurface — Matrix of soil, rock, groundwater, and pores from which earth structures will be made and on which buildings will be supported.

Undisturbed sampling — Retrieval of samples from subsurface for subsequent laboratory evaluation and testing with minimum of disturbance.

TABLE 27.12 Assessment of Geophysical Testing

Method	Advantages	Disadvantages
Downhole	Only one borehole required Relatively inexpensive Measurement of seismic soil properties	Attenuation with depth Invasive No sample recovered Limited by depth of borehole
Crosshole	Minimum of two boreholes required No attenuation with depth Measurement of seismic soil properties	Expensive Invasive Possible refraction interference No sample recovered Limited by depth of borehole
Surface	Noninvasive Inexpensive Measurement of seismic soil properties No boreholes required Environmental applications due to limited contaminant exposure	Complex data analysis Special equipment and skilled operators required No sample recovered Attenuation with depth Refraction method applicable only when velocities increase with depth Possible refraction interference

TABLE 27.13 Alternative Testing Techniques

Test	Usage	Reference
Iowa stepped blade	Lateral stress measurement	Handy et al., 1982
Borehole shear test	Shear strength measurement	Handy et al., 1967
Screwplate	*In situ* determination of modulus	Schmertmann, 1970
Plate load test	Incremental loading of a plate model of a foundation to predict ultimate bearing capacity	Marsland, 1972
Field direct shear	Strength of fissured soils	Marsland, 1971
Field hydraulic conductivity test	*In situ* measurement of hydraulic conductivity	Daniel, 1989

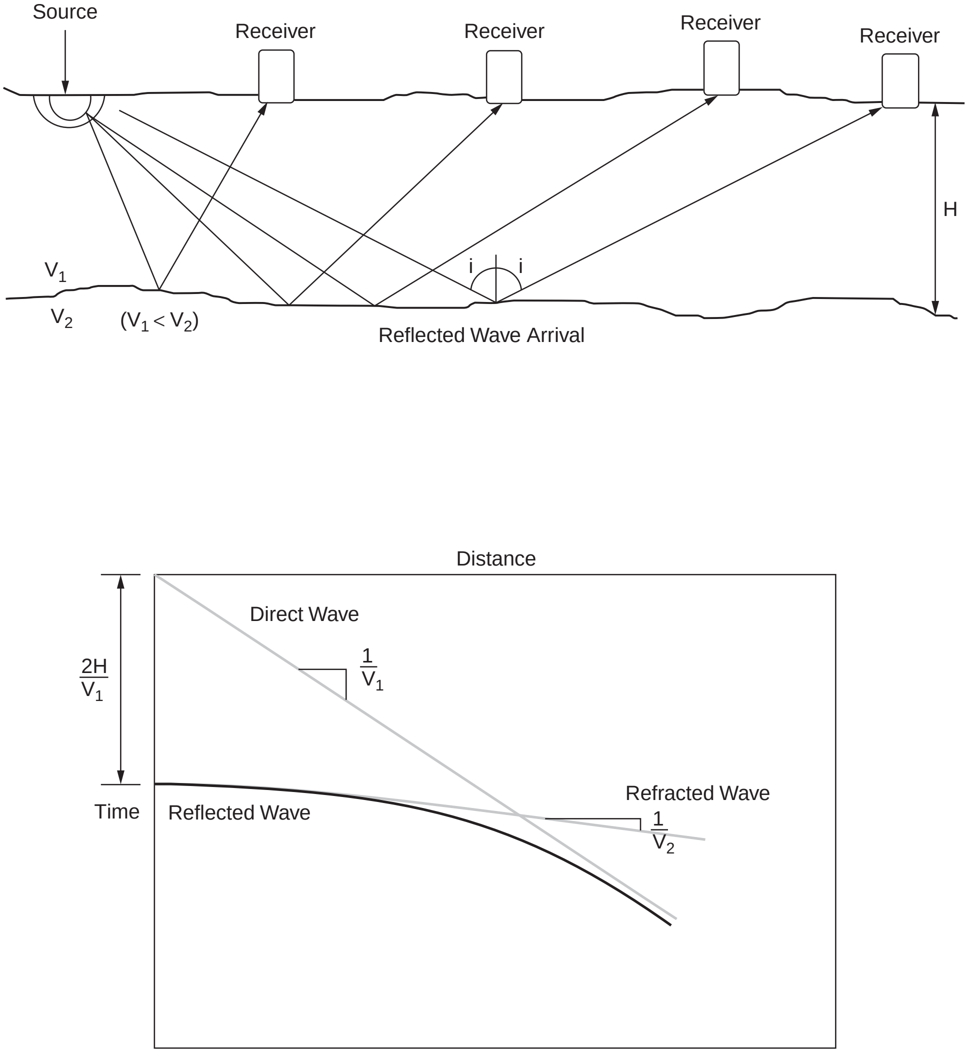


FIGURE 27.8 Seismic reflection test configuration.

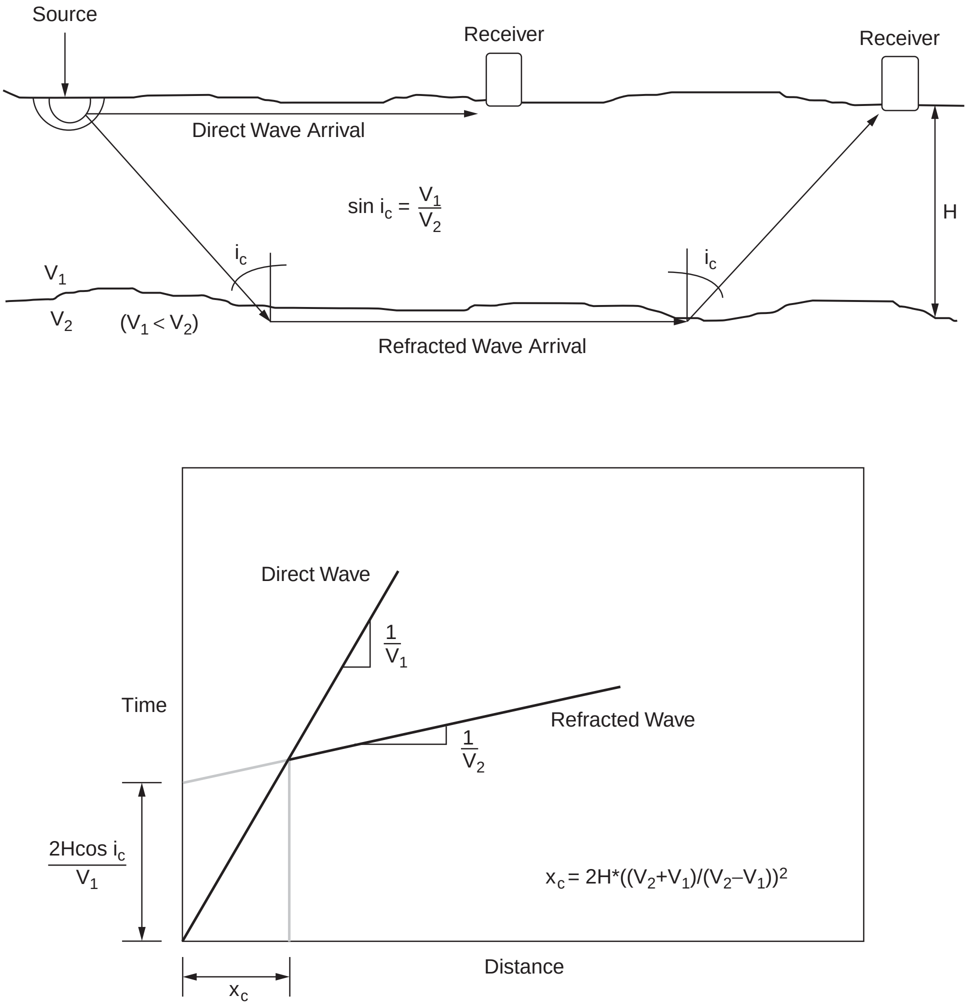


FIGURE 27.9 Seismic refraction test configuration.

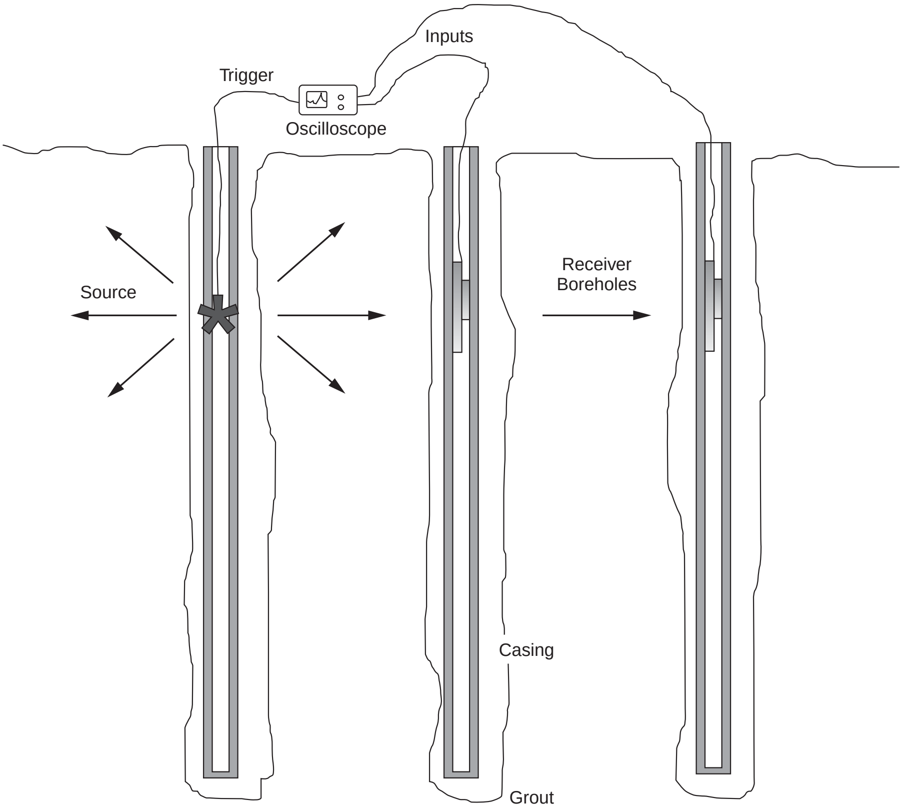


FIGURE 27.10 Crosshole seismic test configuration.

References

ASTM 1194, Standard Test Method for Bearing Capacity of Soil for Static Load and Spread Footings, Vol. 04.08.

ASTM D1586, Standard Test Method for Penetration Test and Split Barrel Sampling of Soils, Vol. 04.08.

ASTM D1587, Standard Practice for Thin-Walled Sampling of Soils, Vol. 04.08.

ASTM D2573, Standard Test Method for Field Vane Shear Test in Cohesive Soil, Vol. 04.08.

ASTM D3213, Standard Practices for Handling, Storing and Preparing Soft Undisturbed Marine Soil, Vol. 04.08.

ASTM D3441, Standard Test Method for Deep, Quasi-Static, Cone and Friction Cone Penetration Tests of Soil, Vol. 04.08.

ASTM D4220, Standard Practices for Preserving and Transporting Soil Samples, Vol. 04.08.

ASTM D4428, Standard Test Methods for Crosshole Seismic Testing, Vol. 04.08.

ASTM D4719, Standard Test Method for Pressuremeter Testing in Soils, Vol. 04.08.

ASTM D5079, Standard Practice for Preserving and Transporting Rock Samples, Vol. 04.08.

Baguelin, F., Jezequel, J. F., and Shields, D. H.1978. The pressuremeter and foundation engineering. *Trans. Tech.*, 617 pp.

Becker, D. E., Crooks, J. H. A., and Been, K. 1987. Interpretation of the field vane test in terms of *in situ* and yield stresses. In *ASTM Symp. Lab. Field Vane Shear Strength Test.* Tampa.

Daniel, D. E. 1989. *In situ* hydraulic conductivity tests for compacted clay. *J. Geotech. Eng., ASCE.* 115(9): 1205–1226.

de Mello, V. F. B. 1971. The standard penetration test. In *Pro. 4th Pan Am Conf. Soil Mech. Found. Eng.*, Puerto Rico. 1:1–86.

Demartinecourt, J. P., and Bauer, G. E. 1983. The modified borehole shear device. *Geotech. Test. J., ASTM.* 6(1):24–29.

Handy, R. L., and Fox, N. S. 1967. A soil borehole direct shear test device. *Highway Res. News* 27:42–51.

Handy, R. L., Remmes, B., Moldt, S., Lutenegger, A. J., and Trott, G. 1982. *In situ* stress determination by Iowa stepped blade. *J. Geotech. Eng., ASCE.* 108(GT11):1405–1422.

Harder, L. F., and Seed, H. B. 1986. *Determination of Penetration Resistance for Coarse Grained Soils Using the Becker Hammer Drill,* Report No. UCB/EERC-86-06, University of California, Berkeley.

Janbu, N., and Senneset, K. 1973. Field compressometer — Principles and applications. *Proc. 8th Int. Conf. Soil Mech. Found. Eng.* Moscow, 1.1:191–198.

Marchetti, S. 1980. *In situ* tests by flat dilatometer. *J. Geotech. Eng., ASCE.* 106(GT3):299–321.

Marsland, A. 1971. Large *in situ* tests to measure the properties of stiff fissured clays. *Proc. Aust. — N. Z. Conf. Geomech.,* Melbourne, 1:180–189.

Marsland, A. 1972. Clays subjected to *in situ* plate tests. *Ground Eng.* 5, 5(6):24–31.

Robertson, P.K., and Campanella, R. G. 1983. Interpretation of cone penetration tests. Part I: Sand, Part II: Clay. *Can. Geotech. J.* 20(4):718–745.

Schmertmann, J. H. 1970. Suggested Method for Screwplate Load Test. *Am. Soc. Test. Mater., Spec. Tech. Publ. 479*: 81–85.

Schmertmann, J. H. 1986. Suggested method for performing flat dilatometer test. ASTM *Geotech. Test. J., ASTM.* 9(2):93–101.

Woods, R. D. 1978. Measurement of dynamic soil properties. *Proc. ASCE Spec. Conf. Earthquake Eng. Soil Dynamics,* Pasadena, 1:91–178.

For Further Information

There is a very extensive bibliography describing the numerous test devices and methods introduced in this chapter. There have been a number of important conferences, symposia, and workshops over the past two decades. The interested reader is encouraged to review the proceedings of such meetings for additional information. The principal proceedings include the following:

- Proceedings of ASCE Specialty Conference on *In Situ* Measurement of Soil Properties, Raleigh, USA, 1975.
- Proceedings of ASCE Specialty Session on Cone Penetration Testing and Experience, St. Louis, USA, 1981.
- Proceedings of First European Symposium on Penetration Testing, ESOPT I, Stockholm, Sweden, 1974.
- Proceedings of Second European Symposium on Penetration Testing, ESOPT II, Amsterdam, Holland, 1982.
- Proceedings of ASCE Specialty Conference on Use of *In Situ* Tests in Geotechnical Engineering, (IN SITU '86), Blacksburg, USA, 1986.
- Proceedings of First International Symposium on Penetration Testing, (ISOPT I), Orlando, USA, 1988.

In addition to the above proceedings, a number of substantive reports have been written by various researchers/practitioners about specific test devices. Some of the more notable ones include the following:

- Mitchell, J. K., Guzikowski, F., and Villet, W. C. B., *The Measurement of Soil Properties* In Situ, Geotechnical Engineering Report # LBL-636, University of California, Berkeley, 1978.
- Robertson, P. K., and Campanella, R. G., *Guidelines for Geotechnical Design Using CPT and CPTU,* Soil Mechanics Report # 120, University of British Columbia, 1989.
- Miran, J., and Briaud, J. L., *The Cone Penetrometer Test,* Geotechnical Report, Texas A&M University, 1990.
- Davidson, J. L., Bloomquist, D. G., and Basnett, C. R., *Dilatometer Guidelines and the Effects of Dynamic Insertion,* Report # FL/DOT/MO/345-89, University of Florida, 1988.
- Whittle, A. J., Aubeny, C. P., Rafalovich, A., Ladd, C. C., and Baligh, M. M., *Prediction and Interpretation of* In Situ *Penetration Tests in Cohesive Soils,* Report # R91-01, Massachusetts Institute of Technology, 1991.
- Schmertmann, J. H., *Guidelines for Using the Marchetti DMT for Geotechnical Design,* Volumes 3 and 4, Report # FHWA-PA-024+84-24 and Report # FHWA-PA-025+84-24, NTIS, 1988.
- Kulhawy, F. H., and Mayne, P.W., *Manual on Estimating Soil Properties for Foundation Design,* Report # EPRI EL-6800, Electric Power Research Institute, 1990.