GEOTECHNICAL POLICIES AND PROCEDURES MANUAL

CHAPTER 7

IN SITU TESTING

TABLE OF CONTENTS

1. PURPOSE

The testing described in this Chapter allows the Geotechnical Engineer to determine various soil and rock parameters under natural in-place conditions. This type of testing is useful for projects, where obtaining representative samples suitable for laboratory testing is difficult, such as those involving soft clays, loose sands and/or soils below the water table. Some benefits of in situ testing include avoidance of soil disturbance (and changes in stress) and large scale testing when size requirements exceed common sample dimensions. The discussion for each test includes a brief description of the test method, the equipment and the uses of the data. Diagrams, photographs, and example test results are included in the: AASHTO Manual on Subsurface Investigations; and FHWA Manual on Subsurface Investigations (NHI Course No. 132031).

Some in situ tests are performed in conventional drilled borings, whereas other more specialized tests require a separate borehole or different insertion equipment.

2. INTRODUCTION

Common in situ tests are performed in conventional drilled borings, whereas specialized tests require a separate borehole or different insertion equipment. Field in situ borehole tests can be grouped into three categories:

- ➢ Correlation Tests
  - o Standard Penetration Test (SPT)
  - o Dynamic Penetration Test (DPT)
- ➢ Strength and Deformation Tests
  - o Penetrometers, such as Cone Penetrometer Test (CPT) and Piezocone Penetrometer Test (PQS)
  - o Pressuremeters (PMT), such as Menard, Self-Boring, and Dilatometer
  - o Stress or Shear Devices, such as Vane Shear and Borehole Shear Tests
- ➢ Permeability Tests
  - o Pump Tests and Slug Tests
  - o Water Pressure Tests
  - o Hydraulic Conductivity Tests
  - o Percolation Tests

3. CORRELATION TESTS

Data obtained through these tests may be correlated to a number of different design parameters, such as, relative density, angle of internal friction, and shear strength.

3.1 Standard Penetration Test (SPT)

This test is probably the most widely used field test in the United States. It has the advantages of simplicity, the availability of a wide variety of correlations for its data, and that a sample is typically obtained with each test.

The test involves advancing a standard split-barrel sampler a total of 18 inches into the bottom of a borehole by dropping a 140-pound hammer from a height of 30 inches. The number of blows required to advance the sampler for each of three 6-inch increments is recorded. The sum of the number of blows for the second and third increments is the Standard Penetration Value, or more commonly, N-value (blows per foot). Standard Penetration Tests are performed in accordance with ASTM D 1586.

SPT values are sensitive to materials encountered and variations in individual drilling practices and equipment used, such as the type of hammer (hammer efficiency), diameter and length of drill rods, presence of a liner in the sampler, and diameter of the drill hole. Correction values are used to standardize the test results. Studies have indicated that SPT results are more reliable in sands than clays. Although this technique is extensively used in subsurface exploration, depending on the application, the test results should be augmented by other field and laboratory tests, particularly when dealing testing clays.

Depending on the type of project, N-values can be correlated to a number of different design parameters including relative density, angle of internal friction, and shear strength. There are several methods available that use corrected N-values in the design of driven piles, embankments, spread footings, and drilled shafts. For foundation design and liquefaction studies, N-values are typically corrected for overburden pressure. This correction normalizes the N-value to an effective overburden pressure of one tsf. Testing conditions and data should be accurately recorded during exploration operations so the appropriate correction values can be applied.

Noting the type of hammer used during the investigation is required on the boring logs, since this affects the actual input driving energy (hammer efficiency correction) transferred to the sampler. Because the rope and cathead method is not as consistent, only hammers using an automatic drop system are allowed on Department projects. The required method to measure the energy transfer from the hammer to the sampler using a dynamic Pile Driving Analyzer (PDA) is detailed in ASTM D 4945, which is the testing standard used in conjunction with pile driving. Since there is a wide variability in the performance of various SPT hammers, calibrations of all hammers used on Department projects are required. Calibration factors for the hammers, along with correction factors for nonstandard sized samplers, are required to be included in the boring log key in the Geotechnical Report. The procedure used to determine the hammer efficiency and resistance to pile driving is governed by stress wave propagation. By measuring the hammer’s force and velocity during a test, the transmitted energy can be determined. Once the transmitted energy ($E_{measured}$) is known, the N-values can be modified to the standard N_{60} equation.

3.2 Dynamic Cone Penetrometer Test (DCP)

This Manual test consists of manually driving a cone shaped probe by dropping a 15-pound hammer 20 inches. The blow count results provide an indication of the uniformity or consistency of soils. Since no samples are recovered, dynamic cone penetrometer tests should only be used as a supplement to profile interpretations determined from standard borehole sampling techniques.

As the cone is driven into the soil, the number of blows required to advance the cone through a 6-inch increment is recorded. A single DCP test consists of two 6-inch increments. Tests can be performed continuously to the depth desired with an expendable cone, which is left in the ground upon drill rod withdrawal, or at specified intervals by using a retractable cone and advancing the hole by auger or other means between tests. Experience has shown that the DCP can be used effectively up to depths of 15 to 20 feet. It is extremely important to provide the full 20-inch hammer drop, per each blow, but care must be taken not to strike the weight against the handle on the upward motion. Doing so would cause the instrument to withdraw and results would be in question. If a test is performed at the bottom of an open boring, the blow counts in granular soils tend to be larger for the second 6-inch increment than for the first. In cohesive soils, the blow counts from the two increments tend to be about the same.

While correlations between DCP blow counts and engineering properties of the soil exist, they are not as widely adopted as SPT values. A relationship has been developed where the blows required to drive the embedded DCP cone a distance of 1-3/4 inches yields roughly the same density/consistency values as SPT N-values. DCP results have also been correlated to California Bearing Ratio (CBR) values for use in pavement design.

4. STRENGTH AND DEFORMATION TESTS

In situ tests for measuring strength and deformation properties include cone penetrometer, piezocone penetrometer, pressuremeter, dilatometer, vane shear, and borehole shear devices. These tests provide different methods to measure strength parameters.

4.1 Cone Penetrometer Test (CPT) and Piezocone Penetrometer Test (PQS)

The Cone Penetrometer Test (CPT) is a specialized quasi-static penetration profiling test performed independently of drilled borings. A disadvantage of this device is that no samples are obtained, so there is no positive identification of soil types. This method should only be used to supplement sampled borings, not to replace them.

A cylindrical rod with a conical point is pushed through the soil at a constant rate and the penetration resistance is measured. A series of tests performed at varying depths at one location is called a sounding. Several types of penetrometers are in use, including mechanical (mantle) cone, mechanical friction-cone, electric cone, electric friction-cone, and piezocone penetrometers. Although many different cone configurations have been used, the current standard was developed through work performed in the Netherlands, so it is sometimes referred to as the Dutch cone.

Cone penetrometers measure the resistance to penetration at the tip of the penetrometer, or the end-bearing component of resistance. Friction-cone penetrometers are equipped with a friction sleeve, which provides the added capability of measuring the side friction component of resistance. Mechanical penetrometers have telescoping tips allowing measurements to be taken incrementally, generally at intervals of 8 inches or less. Electric (or electronic) penetrometers use electric force transducers to obtain continuous measurements with depth. Piezocone penetrometers are electric penetrometers, which are also capable of measuring pore water pressures during penetration. Cones can also be equipped with time-domain sensors that allow the cone to measure shear wave velocity.

For all types of penetrometers, cones with a 60-degree tip angle and a projected end area of 1.55 square inches are standard. The outside diameter of the friction sleeve is the same as the base of the cone. Penetration rates are maintained between 0.4 to 0.8 inches per second. Tests are conducted in accordance with ASTM D 3441 (mechanical cones) and ASTM D 5778 (piezocones).

The penetrometer data is plotted showing the end-bearing resistance, the friction resistance and the friction ratio (friction resistance divided by end bearing resistance) as functions of depth. Pore pressures, if measured, can also be plotted with depth. The results are presented in tabular form, indicating the interpreted results of the raw data.

There are published correlations relating CPT data to soil type and several engineering properties. CPT data can be used in some design methods for spread footings and piles. The penetrometer can be used in sands or clays, but not in rock, dense sands, or soils containing appreciable amounts of gravel.

The piezocone penetrometer can measure the dissipation rate of excessive pore water pressure. This type of measurement, is useful in characterization, subsurface materials, such as fibrous peat or muck that are very sensitive to sampling techniques. The cone should be equipped with a pressure transducer that is capable of measuring the induced water pressure. To perform this measurement, the cone is advanced into the ground at the standard rate. Pore water pressures are measured immediately and at several time intervals thereafter. The recorded data is used to develop a plot of a pore pressure versus log-time graph. This graph can be used to directly calculate the rate of pore water pressure dissipation, which directly relates to the rate of soil settlement.

4.2 Pressuremeter Test (PMT)

The pressuremeter measures stress/strain properties of soils by inflating a probe placed at the desired depth in the borehole. The PMT provides much more direct measurements of soil compressibility and lateral stresses than do the SPT or CPT. Test results are interpreted based on semiempirical correlations from past tests and observation. In situ horizontal stresses, shear strength, bearing capacities, and settlement can be estimated using these correlations. The pressuremeter test is a delicate tool, and the test is very sensitive to borehole disturbance. The data may be difficult to interpret for some soils, but it provides the advantage that due to the large size of the pressuremeter cell it is less likely to be adversely affected by gravel in the soil. The test has the advantage of less likely to be adversely affected by gravels in soils due to the large size of the pressuremeter cell. This test requires a high level of technical expertise to perform, and is time consuming. Typically, 6 to 8 tests are conducted per day.

The Menard type pressuremeter requires predrilling of the borehole. The self-boring type pressuremeter advances the hole itself, which reduces soil disturbance. The Menard probe contains three flexible rubber membranes. The middle membrane provides measurements, while the outer two cells, the “guard cells,” protect the measuring cell from end effects. When in place, the guard cell membranes are inflated by pressurized gas, while the middle membrane is inflated with water by means of pressurized gas. The pressure in all cells is incrementally increased or decreased by the same amount. The measured volume change in the middle membrane is plotted against applied pressure. Tests are completed in accordance with ASTM D 4719.

4.3 Dilatometer Test (DMT)

The dilatometer is a 3.75-inch wide and 0.55-inch thick stainless steel blade with a thin 2.4-inch diameter expandable metal membrane on one side. While the membrane is flush with the blade surface, the blade is advanced into the soil. Rods carry pneumatic and electrical lines from the membrane to the surface. Tests are typically conducted at 8-inch intervals. Pressurized gas is used to expand the membrane. Both the pressure required to begin membrane movement and that required to expand the membrane 0.04 inches into the soil are measured. Additionally, upon venting, the pressure corresponding to the return of the membrane to its original position, which correlates to the pore water pressure in the soil, may be recorded. Each test typically requires 1 to 2 minutes to complete for each interval.

The dilatometer test uses pressure readings from the inserted flat plate to determine stratigraphy and obtain estimates of at-rest lateral stresses, elastic modulus, and shear strength of sands (and to a lesser degree, silts and clays). The dilatometer test is not widely used, and the analysis and design methods based on DMT results are not yet as thoroughly developed as other techniques. However, the test provides consistent results when repeated, is useable in soils ranging from soft to moderately stiff; and provides several direct measurements of stress-strain properties. The plate can be difficult to advance into dense and hard materials. Calibration is needed to correlate to local geologic environments. Because of its relatively low cost, versatility, and compatibility with the CPT, its use may increase in the future.

Through developed correlations, information can be deduced regarding material type, pore water pressure, in situ horizontal and vertical stresses, void ratio or relative density, modulus, shear strength parameters, and consolidation parameters. Compared to the pressuremeter, the dilatometer has the advantage of reduced soil disturbance during penetration. The DMT and CPT are complementary tests where the DMT is used to assess compressibility and in situ stresses and the CPT is used to evaluate soil strength.

4.4 Field Vane Test

This test consists of advancing a four-bladed vane into cohesive soil or organic deposits to the desired depth and applying a measured torque at a constant rate until the material fails in shear along a cylindrical surface. The torque measured at failure provides the undrained shear strength of the soil. A second test run immediately after the soil has failed at the same depth provides the remolded strength of the soil and, thus, information on soil sensitivity. Tests are performed in accordance with ASTM D 2573.

This method is primarily intended for soft clays, and should not be used in stiff or hard soils. Vane diameters vary depending on the consistency of the soil, with larger vanes used in softer materials. Test results can be affected by the presence of gravel, roots, or sand layers. Shear strength may be overestimated in highly plastic clays, and a correction factor should be applied. Vane shear test results may be invalid for varved clays, fibrous peats, and other deposits with a high degree of anisotropy. The Geotechnical Engineer should consider the potential for shear strength anisotropy when using the test results, since the test forces a shear failure along a surface that does not represent the actual case in most geotechnical applications.

4.5 Borehole Shear Tests (BST)

Borehole shear strength tests are performed in an uncased borehole. The apparatus is positioned within the material of interest and then expanded to apply horizontal pressure against the sides of the hole. The main components of the borehole shear device are: the shear head, the pulling assembly, and the console (which contains the bottled gas and pressure gauge. The pulling assembly is hand operated by turning a worm gear to provide a uniform rate of strain, which is monitored by a strain gauge. The shear strength is determined by measuring the resistance while pulling up on the shear device. The test is repeated at increasing horizontal pressures to develop a plot of maximum shear stress to normal stress. The Mohr envelope is plotted, and shear strength parameters Φ and c are determined.

This test is dependent on achieving “drained” conditions, and is more reliable on sand and silt soils. Tests on clay soils are possible if sufficiently long consolidation times are allowed and strain rates are applied.

5. PERMEABLILITY TESTS

Hydraulic conductivity, also referred to as permeability, is the measure of the rate of flow of water through soils, usually measured when the soil is saturated. The hydraulic conductivity value is corrected for the hydraulic boundary conditions, such as the hydraulic gradient. In situ hydraulic conductivity tests results are more representative of the actual soil property than test results obtained in the laboratory, since they are performed on the entire hydraulic system, with all its variables including joints, sand seams, and small fissures. Laboratory tests are performed on a small sample that may not be truly representative of field conditions. Several methods to perform in situ hydraulic conductivity tests have been developed with the most commonly used being the pumping test and the slug test.

5.1 Pumping Test

The pumping test requires one test well to pump water and one to four adjacent observation wells to monitor the changes in water levels as the pumping test is performed. Frequently, existing wells of opportunity (preexisting wells) are used for this test, but their depths and efficiency should be determined to properly use the results of the test. Often, there will be other wells within the vicinity that are not part of the test program. In this case, the influence of these wells, if they are operated during the test, must be taken into account.

Pumping continues until a steady-state water level is obtained in the observation wells. The hydraulic conductivity, (*k),* is then computed based on the flow rate from the pumped well, the steady-state water level (total head) in the observation wells, and the configuration of the test hole relative to the observation wells, according to the principles of groundwater flow. (refer to ASTM D 4050)) Pumping tests are typically used in large-scale investigations to more accurately measure the permeability of an area for the design of dewatering systems.

5.2 Slug Test

The slug test, although less representative of the larger area typically represented by a pumping test, is quicker to perform and much less expensive because observation wells are not required. It consists of affecting a rapid change in the water level within a well by quickly injecting or removing a known volume of water or a solid object known as a slug. The natural flow of groundwater out of or into the well is then observed until equilibrium in the water level is obtained. The flow rate to equilibrium is used to compute *k* (refer to ASTM D 4044).

5.3 Water Pressure Tests (Packer Tests)

This test is performed in a borehole by placing packers above and below the soil/rock zone to be tested. The time rate of water flow into the isolated test zone, at a constant pressure, is recorded for 5 to 30 minutes. This procedure is repeated at higher pressure with care not to cause hydraulic fracturing. The coefficient of permeability that is calculated provides a gross indication of the overall mass permeability (refer to FHWA, “Rock Slopes: Design, Excavation, Stabilization”).

5.4 Hydraulic Conductivity Tests

There are several methods of determining the hydraulic conductivity of water bearing materials. The tests may be performed with packers in place to isolate a specific zone; however, the test is not run with the borehole sealed or under pressure. One method is to remove water from the material being tested (Rising Water Level Method). Another method is to add water to the borehole (Falling Water Level Method and Constant Water Level Method). (refer to AASHTO, “Manual on Subsurface Investigations”).

5.5 Infiltration Tests

The movement of water from the surface into the soil or rock is called infiltration. Two types of infiltrometer systems are available: sprinkler type and flooding type. Sprinkler types attempt to simulate rainfall, while the flooding type is applicable for simulating runoff conditions. These methods measure the vertical flow of water, expressed in inches per hour. Applications for these tests include the design of subdrainage and dry well systems. The most common application is the falling head test, performed by filling (flooding) a test pit hole in concentric rings and monitoring the rate the water level drops (refer to ASTM D 4043).

6. SPECIALIZED TESTS

Specialized tests are those that are not commonly used, but may have application on unique or complex projects. These tests are listed for reference, along with brief descriptions. If these tests are to be used, the Geotechnical Engineer should perform research on test details and applicability.

6.1 Bearing Capacity Plate Test (PLT)

This test is performed to determine field bearing capacities on circular plates that are subsequently used to estimate bearing capacity of shallow spread footings. The loads are applied to the bearing plates by either jacking against a dead load or against a reaction beam attached to several piles. The bearing plates vary in diameter from 12 to 30 inches, are made of steel or concrete, and are placed at the proposed footing embedment level (refer to test method ASTM D 1194).

6.2 In Situ Direct Shear Tests On Rock Discontinuities

This test is used to measure the peak and residual direct shear strength along an in situ rock discontinuity as a function of the stress normal to the sheared plane. Because of the complicated nature of the test, it is typically restricted to slope, tunnel, dam, or bridge foundation projects, where a failure along a particular discontinuity can have a significant impact. In general, the in situ test is performed on a larger specimen than the one used in a laboratory testing and is, therefore, more representative of actual conditions such as surface irregularities along the discontinuity.

The test requires several pieces of equipment that typically Consultants specializing in rock mechanics would have on hand. The equipment includes rock saws, drills, hammers and chisels, formwork, and materials for reinforced concrete encapsulation for preparing the test specimen; jacks or rams and a reaction system for applying normal loads; a pump and hydraulic ram, and a reaction system for applying the shear force; and appropriate load cells and gauges for measuring the applied shear and normal forces and shear displacements.

The test includes a consolidation stage during which the pore pressures within the rock and any infilling material adjacent to the shear plane are allowed to dissipate under full normal stress before shearing is initiated. During the test, corrections to the normal load may be necessary to hold the normal load constant. As in the more traditional soil shear strength testing, once the peak shear strength is obtained additional readings can be taken to determine the residual shear strength along the discontinuity (refer to ASTM D 4554).

6.3 Other Tests

- Large Penetration Test (LPT) – This test is a modification of the Standard Penetration Test, which uses a larger diameter sampler for use in gravelly soils.
- Becker Penetration Test (BPT) – This test is used to investigate coarse-grained materials (gravel, cobbles) by using an instrumented steel pipe pile.
- Iowa Stepped Blade Test (ISB) – This test attempts to directly measure the in situ lateral stress state (K_o) in soils.
- Total Stress Cells – (TSC) – This test attempts to directly measure the in situ lateral stress state (K_o) in soils.
- Push-in Spade Cells – This test attempts to directly measure the in situ lateral stress state (K_o) in soils.
- Hydraulic Fracturing Test (HF) - This test attempts to directly measure the in situ lateral stress state (K_o) in rock formations.

7. FIGURES

7-1: Specifications and Standards

SUBJECT	ASTM	AASHTO
Dilatometer	-	-
Chloride Content - Soil (Retaining Wall Backfill)	-	-
Chloride Ion In Water	D 512	-
Electrical Conductivity and Resistivity of Water	D 1125	-
Bearing Capacity of Soil for Static Load on Spread Footings	D 1194	-
pH of Water	D 1293	-
Penetration Test and Split Barrel Sampling of Soils	D 1583	-
Field Vane Shear Test in Cohesive Soil	D1586	T 223
Mechanical Cone Penetration Tests of Soil	D 3441	-
Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques	D 4043	-
Instantaneous Change in Head (Slug Test), for determining Hydraulic Properties of Aquifers	D 4044	-
Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems	D 4050	-
Sulfate Ion in Brackish Water, Seawater, and Brines	D 4130	-
In Situ Determination of Direct Shear Strength of Rock Discontinuities	D 4554	-
Pressuremeter Testing in Soils	D 4719	-
Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)	D 4750	-
High Strain Dynamic Testing of Piles	D 4945	-
Preserving and Transporting Rock Core Samples	D 5079	-
Electronic Friction Cone and Piezocone Penetration Testing of Soils	D 5778	-
Hydraulic Conductivity of Porous Materials Using Two Stages of Infiltration from a Borehole	D 6391	-
Flat Plate Dilatometer	D 6635	-
pH of Soil for Use in Corrosion Testing	G 51	T 289
Soil Resistivity (ASTM – Field Procedure Using the Wenner Four-Electrode Method and AASHTO – Laboratory Procedure)	G 57	T 288

8. REFERENCES

AASHTO, “Manual on Subsurface Investigations,” 1988

ASCE, “Use of In-Situ Tests in Geotechnical Engineering,” ASCE Special Technical Publication No. 6, 1986

Department of the Navy, “Soils Mechanics Design Manual 7.1,” NAVFAC DM-7.1, Naval Facilities Engineering Command, 1986

FHWA, “Cone Penetrometer Test,” FHWA- SA-91-043, 1991

FHWA, “Determination of Horizontal Stress in Soils,” FHWA- RD-81-118, 1981

FHWA, “Evaluation of Self-boring Pressuremeter Tests in Boston Blue Clay,” Interim Report, FHWA- RD-80-052, 1980

FHWA, “Evaluation of Soil and Rock Properties,” Geotechnical Engineering Circular No. 5, FHWA-IF-02-034, 2002

FHWA, “Flat Dilatometer Test,” FHWA- SA-91-044, 1991

FHWA, “Geotechnical Engineering Notebook,” (sections added when needed)

FHWA, “Ground Anchors and Anchors Systems,” Geotechnical Engineering Circular, No. 4, FHWA IF-99-015, 1999

FHWA, “Pressuremeter Test for Highway Applications,” FHWA-IP-89-008, 1989

FHWA, “Rock Slopes: Design, Excavation, Stabilization,” 1989

FHWA, “Sensing Systems for Measuring Mechanical Properties in Ground Masses,” Vols. 1 to 5, FHWA-RD-81-109 through FHWA-RD-81-113, 1981

FHWA, “Soils and Foundations Workshop Reference Manual,” NHI Course No. 132012, FHWA NHI-00-045, August 2000

FHWA, “Subsurface Investigations – Geotechnical Site Characterization,” Reference Manual for NHI Course No. 132031, FHWA-NHI-01-031, 2002

NCHRP, “Treatment of Problem Foundations for Highway Embankments,” Synthesis 147, 1989

TRB, “Landslides: Investigation and Mitigation,” Special Report 247, 1996