Geotechnical Engineering

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§ 1.1 SOIL PROPERTIES AND LABORATORY TESTING

§ 1.1.1 Introduction

The materials that form the earth’s surface can be arbitrarily divided into rock and soil. The term “rock” typically defines large-sized solid particles formed by minerals strongly bonded to one another. “Soils” are a system of small-sized particles that are weakly bonded together. This particulate system is formed by minerals and, in some cases, organic materials. These particles or grains are derived from rocks subjected to mechanical or chemical processes.

§ 1.1.2 Soil Classification

Gradation and Plasticity

The mechanical properties of the soil, such as its compressibility, strength, permeability, and so forth, depend on the properties of the different particles that comprise it. One of the most important properties of these particles is their size. Soil particle sizes can vary from a fraction of a micron (1 micron = $10^{-6}$ m) to a few centimeters.

Relatively simple laboratory tests can be performed on soil samples to obtain the particle size distribution of the soil mass. The particle size distribution, or percentile distribution, in weight, of particles with similar diameters can be determined following standard procedures recommended by ASTM International (ASTM), listed below:

- “Standard Test Method for Particle-Size Analysis of Soils,” ASTM D422-63
- “Standard Test Methods for Amount of Material in Soils Finer than No. 200 Sieve,” ASTM D1140-00

The gradation test is used for soils containing primarily coarser grains (i.e., particle sizes larger than 0.075 mm). This test, often referred to as Sieve Analysis, uses a series of sieves to separate the soil into groups of particles of similar sizes. A graduated scale then weighs the amount of soil with similar sizes.

Sedimentation analysis estimates the particle size distribution when the particle size is too small for using sieves. This test method mixes fine soils with water and uses a hydrometer to estimate the particle size distribution of the solids in suspension.

Although fine-grained soils can be classified in terms of their grain size, their mechanical properties are best defined by their plasticity. Plasticity measures the tendency of soil to act like a fluid or solid when it is mixed with water. The Plasticity Index can be correlated to the actual mineralogy of the soil and its mechanical properties. The most common way to measure plasticity is through Atterberg Limit tests:

In geotechnical practice, gradation and plasticity tests are typically performed in representative soil samples. When test results are not available, experienced engineers can estimate their classification by visual inspection of the soil samples.

Soil particle distribution, in conjunction with the soil’s plasticity, is used to classify the soil into groups that share similar properties and uses in civil engineering practice. Different classification systems exist in the industry. The Unified Soil Classification System is widely utilized in most geotechnical work and has been adopted by the United States Bureau of Reclamation and Corps of Engineers. The AASHTO classification, proposed by the Highway Research Board’s Committee on Classification of Materials for Subgrades and Granular Type Roads, is widely utilized to relate the different groups of soils with their suitability as roadway subgrade materials. Even though significant differences exist among the classification systems, they all classify soil into four groups: clay, silt, sand, and gravel.

Soil Volume and Density Relationships
Soil is a three-phase material, typically formed by a system of grains (solids), air (gases), and water (fluids). The relative amount of solid, gas, and fluid per unit volume define, among other things, the density of the soil. The soil density is an indirect measurement of the tightness of the solid structure: the tighter the solid particle arrangement, the less compressible is the soil and the higher strength the soil exhibits.

Different tests conducted in the laboratory environment determine the volume-weight relationship between the different phases of soil. These tests include:

- “Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density,” ASTM D4254-00

§ 1.1.3 Flow of Water
The voids encountered between the soil particles form pathways or channels for water to flow through the soil mass. The size of these channels determines the “permeability” of the soil—the ability of fluids to flow through the soil. “Permeability” may be measured in the laboratory environment via the following tests:

§ 1.1.4 Concept of Stresses

The stresses applied to soils are carried in part by the solid particles and in part by the fluids (water) in the soil skeleton void space. "Effective stresses" are the stresses carried by the soil skeleton and transmitted across the soil particles through the points of contact of the soil grains. The "pore water pressure" is the pressure within the fluid. The magnitude of the effective stress influences the compressibility and strength of the soil.

§ 1.1.5 Soil Compressibility

The deformation of soils is time-dependent and can occur almost instantaneously or over long periods of time after the application of a load. When the soil is compressed, the applied pressure is initially transferred to the water trapped in the void space. Because water is practically incompressible, no initial volume change is apparent. Over time, as the water is squeezed out of the soil, the stresses applied to the fluids are transferred to the compressible soil skeleton. The rate of settlement depends on the amount of time it takes for the fluids to be squeezed out of the soils (i.e., the permeability). For soils with high permeability, such as sands or gravels, where the fluids flow at high rates, settlements and soil deformations occur almost immediately. For soils with low permeability, such as clays and silts, where the fluids flow at slow rates, settlement occurs very slowly over long periods of time.

After the water has been squeezed out of the soil mass and the excess pressure in the water has dissipated, the total applied pressure is carried by the soil skeleton, increasing the effective stress in the soil.

Water is almost incompressible. For this reason, the amount of settlements or soil deformations depends largely on the compressibility of the soil skeleton. Field and lab tests can assess the compressibility of the soil skeleton. Since the compressibility of the soil depends on its density, it is necessary to obtain undisturbed samples to test in the laboratory. Because it is very difficult to obtain undisturbed samples of granular soils (such as sands and gravels), the compressibility of these type of soils is usually determined using tests performed in the field. Laboratory tests are typically performed in fine-grained soils. The most common laboratory test utilized to measure soil compressibility is:


§ 1.1.6 Strength

The maximum pressure that a soil can sustain is related to its so-called soil strength. The frictional resistance of the soil grains and cohesive forces
provide the strength of a soil. In other words, the soil strength is provided in part by the grain-to-grain frictional resistance (at the points of contact), which depends on the grains’ type, shape, and size, and by cohesive resistance, which depends primarily on cementation and capillarity stresses.

Cohesive forces tend not to be significant in coarse-grained soils, such as sands and gravels. Thus, they are typically referred to as “cohesion-less soils.” Therefore, the inter-particle friction primarily provides the strength of cohesion-less soils.

Cohesive forces are significant in fine-grained soils. Thus, plastic silts and clays are typically referred to as “cohesive soils.” Cohesive forces tend to vanish with time as capillarity forces decrease. When the water is allowed to flow, pore water pressure dissipates. For this reason, strength of the soil is also time-dependent. Lab tests can determine soil strength via the following standard test procedures:

- “Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils,” ASTM D2850-03a

§ 1.2  SUBSURFACE EXPLORATION AND TESTING

The geotechnical engineer uses various exploration methods and techniques to obtain necessary soil information, including soil borings, cone penetrometer testing, in-situ testing, and test pits or trenches. Typically, the geotechnical engineer dictates the exploration plan, including sampling, testing, and the number of test locations, based on the proposed construction and the anticipated soil conditions.

§ 1.2.1 Soil Borings

 Soil borings are commonly used for subsurface exploration. Soil borings are small diameter holes drilled vertically into the ground. Borehole diameters may vary but are typically three to six inches in diameter. The geotechnical engineer determines the sampling interval for the borings. Borings are accomplished using a machine mounted to a truck, skid, all-terrain-vehicle, or barge, depending on the site conditions. Where site conditions present challenging conditions, such as low overhead or steep slope, the geotechnical engineer may resort to performing borings by manual auger.
Sampling
The two most common ways to obtain samples are by driven split-barrel (also known as split-spoon) and pushed Shelby tube methods.

- ASTM D1586-11: “Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils”
- ASTM D1587-08: “Standard Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes”

The split-spoon sampling method may be used on any type of soil. In general, the split-spoon sample is driven into the soil 18 inches using a 140-pound hammer dropping 30 inches in free fall. The energy required to drive the sampler is measured by how many hammer blows per each six-inch increment. The last foot of blows are added together to provide a “blow count,” or “N-value,” which is used to determine the in-situ relative density of the soil. The blow count is not typically used to classify strength in cohesive soils. The samples obtained from the split-spoon sampler should be considered disturbed soils and are typically used for visual classification and laboratory classification testing, such as moisture content and Atterberg limit testing.

Shelby tube sampling is used for obtaining cohesive soil samples with minimal disruption of the sample. The Shelby tube consists of a steel tube, typically two to three inches in diameter, which is pushed into the cohesive soil, retracted after a period of time, and returned to the soil laboratory, where the samples are extruded for further testing. The Shelby tube sampler provides a less-disturbed sample than the split-spoon method. If the goal is the least-disturbed samples, then an Osterberg piston sampler is the preferred equipment as it uses fluid pressure.

Boring Advancement
The industry has developed many methods for advancing the boreholes. The method selected should take into account the anticipated soil conditions, the depth of the borings, and local practice. Borings performed for geotechnical purposes are most commonly advanced using solid stem, hollow stem, or rotary drilling methods.

The solid stem auger method advances no casing; it typically limits the boring depth to areas of relatively stiff cohesive soils and granular soils above the water table.

The hollow stem auger method consists of an outer auger with a plug in the base. To sample the soil, the plug is removed and replaced by the sampler. For this method, the auger serves as casing against squeezing or sloughing soils. If this method is used in granular soils below the water table, the soils at the base of the auger may loosen and create a blow-in, which in turn produces a lower N-value (an artificially lower strength).

Rotary drilling methods are commonly used for deep soil borings. This method uses smooth-sided casing and drilling mud to maintain an open
borehole. Casing is either used as surface casing or continuously, depending on the soil conditions. The drilling mud is used to help maintain an open borehole.

Rock coring is necessary for sites where the rock properties will be used for design or excavation purposes. Core barrels are typically 5 to 10 feet in length and range from 1 7/8 inch to 3 7/8 inches in diameter. The barrel is connected to either a diamond- or carbide-tipped drill bit.

Groundwater readings should be recorded when encountered during drilling and after boring completion. After completion of the drilling, sampling, and groundwater readings, the boreholes are typically backfilled using soil cuttings from the boreholes, bentonite chips, and a cementitious grout. It is important to backfill borings properly as improper backfilling may provide a path for groundwater flow or may leave surface voids as the backfill material settles.

**Cone Penetrometer Testing**

Cone Penetrometer Testing (CPT) has become a popular testing method over the last two decades. In the cone penetrometer test, a drill rig pushes a cone tip with a friction sleeve into the ground. The CPT measures the tip resistance and friction resistance, respectively, as well as pore water pressures. One of the primary advantages of the CPT is a near-constant readout that provides a continuous soil profile. Soil sampling is not performed in CPT boreholes.

**§ 1.2.2 In-Situ Testing**

In-situ tests are performed in the soil boring, typically by lowering apparatus down into the borehole. One of the main benefits of in-situ testing is the ability to test soil in a minimally disturbed state. In-situ testing is often combined with Vane Shear Testing (VST), which consists of a four-bladed vane that is pushed into soft to medium-stiff cohesive soils. As the vane rotates in the cohesive soils, it measures the resistance and provides the unconfined compressive strength.

- ASTM D2573-08: Standard Test Method for Field Vane Shear Test in Cohesive Soil

Pressuremeter testing (PMT) consists of an expandable cylindrical probe that is inserted into the borehole and expanded radially against the walls of the borehole. The stress-strain curves are measured to provide soil stress-strain and strength characteristics of the soil tested.


**§ 1.2.3 Test Pits and Trenches**

Test pits or trenches are very useful tools for observing bedding planes, subsurface obstructions, and existing structures, such as adjacent building
footings. Test pits are also very helpful for observing fill conditions at previously developed sites. Common obstructions in fill soils in urban environments include construction debris and abandoned foundations from previous structures at the site. The depth and lateral limits of the obstructions should be determined by the test pits. Test pits are typically used in combination with soil borings and not as the only source of geotechnical information. In-place density testing can be performed in the base of the excavation, and bag or bulk sampling can also be obtained from the excavated material.

§ 1.3 GROUND IMPROVEMENT

Buildings, roads, and other constructed facilities are often proposed for sites that have poor ground conditions. Development on such sites is increasing due to the unavailability of sites with good ground support conditions. Previous solutions included the use of deep foundations or conventional removal and replacement techniques. Ground improvement techniques are now available to allow these new structures to be built directly on the improved ground.

§ 1.3.1 Dynamic Compaction

Introduction
Dynamic compaction is an improvement technique that can treat the ground to depths up to 30 feet. Dynamic compaction is defined as the densification of the ground by repeatedly dropping a heavy weight onto the surface. Other terms such as heavy tamping, pounding, and dynamic consolidation have been used for dynamic compaction. Dynamic compaction is typically performed with weights ranging from 6 to 30 tons. The weights are lifted and dropped at free-fall from heights ranging from 30 to 75 feet. Figure 1.1 illustrates the dynamic compaction process. This process temporarily leaves craters across the surface at the weight impact points as shown in figure 1.2.

Dynamic compaction restructures the soil grains into a denser state at lower moisture content and/or collapses voids within the ground mass. But dynamic compaction is distinct from conventional fill compaction in the following ways:

- During conventional compaction, soil is placed in multiple thin loose lifts of 12 inches or less and then compacted layer by layer from the bottom up. In dynamic compaction, the deposits are compacted in-situ in one lift thickness from the ground surface down to some predetermined depth.
- Conventional compaction equipment can generally densify materials to a depth of about 2 to 4 feet, whereas dynamic compaction can improve the ground to depths of 15 to 30 feet.
The conventional method restricts compaction to particles under six inches, whereas dynamic compaction can be used on larger particles, such as broken concrete and boulders.

Dynamic compaction is effective both above and below the groundwater table. However, the working surface needs to be maintained about five to six feet above the water table. Conventional compaction must be performed completely above the water table.

(A) Advantages of Dynamic Compaction

- Simple equipment
- Serves as both an exploration and improvement technique
- Degree of compaction can be observed in the field as the work progresses
- Applies to a wide variety of material types
- Minimizes differential settlement by providing more uniform bearing conditions
- Materials below the water table can be densified
- Can be performed in wet weather and with limited frost penetration
- Generally less expensive than other ground improvement techniques
(B) Disadvantages of Dynamic Compaction

- Generates off-site vibrations
- Causes several inches of lateral ground movement, which may impact buried utility lines
- Ground surface must be five to six feet above the water table for this method to be effective
- Very loose deposits, such as recent landfills, require addition of imported granular material to provide a working platform for crane, limit penetration of weight, and provide confinement of weak deposits

Soil Types

Dynamic compaction can be used on a wide variety of materials ranging from naturally occurring soils to heterogeneous fill deposits. This partial list identifies materials where dynamic compaction has been utilized:

- Natural, loose gravel, sand, and silt
- Landfill material
- Building rubble and construction debris
- Mine spoil
- Partially saturated clay soils above the water table
- Collapsible soils such as loess
- Near surface karst or sinkhole formation
- Loose liquefiable sand and silt
- Special waste

Dynamic compaction is performed on materials at their prevailing moisture content. During dynamic compaction, the energy imparted into the ground increases the pore water pressure between the soil particles. The material must be permeable enough for the pore pressure to dissipate quickly, thereby permitting the soil particles to move into a denser state of packing and increase the density of the deposit—meaning materials with a higher permeability and better drainage features are the most favorable candidates for dynamic compaction. Consequently, low permeability materials are not favorable for dynamic compaction. Following this reasoning, soils are typically grouped into the following three major categories as shown in figure 1.3.

(A) Most Favorable Soil Deposits—Zone 1

Dynamic compaction is most effective on materials with a low degree of saturation and high permeability—pervious granular deposits such as natural sand and gravel, building rubble, slag, and decomposed refuse deposits. Above the water table, these materials move into a denser state of packing during densification. Below the water table, the permeability of these deposits