Lab Testing for Soils and Rock

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CHAPTER 7.0

LABORATORY TESTING FOR SOILS

7.1 GENERAL

Laboratory testing of soils is a fundamental element of geotechnical engineering. The complexity of testing required for a particular project may range from a simple moisture content determination to specialized strength and stiffness testing. Since testing can be expensive and time consuming, the geotechnical engineer should recognize the project's issues ahead of time so as to optimize the testing program, particularly strength and consolidation testing.

Before describing the various soil test methods, soil behavioral under load will be examined and common soil mechanics terms introduced. The following discussion includes only basic concepts of soil behavior. However, the engineer must grasp these concepts in order to select the appropriate tests to model the in-situ conditions. The terms and symbols shown will be used in all the remaining modules of the course. Basic soil mechanics textbooks should be consulted for further explanation of these and other terms.

7.1.1 Weight-Volume Concepts

A sample of soil is usually composed of soil grains, water and air. The soil grains are irregularly shaped solids which are in contact with other adjacent soil grains. The weight and volume of a soil sample depends on the specific gravity of the soil grains (solids), the size of the space between soil grains (voids and pores) and the amount of void space filled with water. Common terms associated with weight-volume relationships are shown in Table 7-1. Of particular note is the void ratio (e) which is a general indicator of the relative strength and compressibility of a soil sample, i.e., low void ratios generally indicate strong soils of low compressibility, while high void ratios are often indicative of weak & highly compressible soils. Selected weight-volume (unit weight) relations are presented in Table 7-2.

TABLE 7-1.
TERMS IN WEIGHT-VOLUME RELATIONS (After Cheney and Chassie, 1993)

Property	Symbol	Units[1]	How obtained (AASHTO/ASTM)	Direct Applications
Moisture Content	w	D	By measurement (T 265/ D 4959)	Classification and in weight-volume relations
Specific Gravity	G_s	D	By measurement (T 100/D 854)	Volume computations
Unit weight	(	FL^{-3}	By measurement or from weight-volume relations	Classification and for pressure computations
Porosity	n	D	From weight-volume relations	Defines relative volume of solids to total volume of soil
Void Ratio	e	D	From weight-volume relations	Defines relative volume of voids to volume of solids

[1] F = Force or weight; L = Length; D = Dimensionless. Although by definition, moisture content is a dimensionless fraction (ratio of weight of water to weight of solids), it is commonly reported in percent by multiplying the fraction by 100.

TABLE 7-2.

UNIT WEIGHT-VOLUME RELATIONSHIPS

Case	***Relationship***	***Applicable Geomaterials***
Soil Identities:	1. $G_s w = S e$ 2. Total Unit Weight: $\gamma_T = \frac{(1+w)}{(1+e)} G_s \gamma_w$	All types of soils & rocks
Limiting Unit Weight	Solid phase only: w = e = 0: $\gamma_{rock} = G_s \gamma_w$	Maximum expected value for solid silica is 27 kN/m^3
Dry Unit Weight	For w = 0 (all air in void space): $\gamma_d = G_s \gamma_w/(1+e)$	Use for clean sands and dry soils above groundwater table
Moist Unit Weight (Total Unit Weight)	Variable amounts of air & water: $\gamma_t = G_s \gamma_w (1+w)/(1+e)$ with $e = G_s w/S$	Partially-saturated soils above water table; depends on degree of saturation (S, as decimal).
Saturated Unit Weight	Set S = 1 (all voids with water): $\gamma_{sat} = \gamma_w (G_s+e)/(1+e)$	All soils below water table; Saturated clays & silts above water table with full capillarity.
Hierarchy:	γ_d # γ_t # $\gamma_{sat} < \gamma_{rock}$	Check on relative values

Note: γ_w = 9.8 kN/m^3 (62.4 pcf) for fresh water

7.1.2 Load-Deformation Process in Soils

When a load is applied to a soil sample, the deformation which occurs will depend on the grain-to-grain contact (intergranular) forces and the amount of water in the voids. If no porewater exists, the sample deformation will be due to sliding between soil grains and deformation of the individual soil grains. The rearrangement of soil grains due to sliding accounts for most of the deformation. Adequate deformation is required to increase the grain contact areas to take the applied load. As the amount of pore water in the void increases, the pressure it exerts on soil grains will increase and reduce the intergranular contact forces. In fact, tiny clay particles may be forced completely apart by water in the pore space.

Deformation of a saturated soil is more complicated than that of dry soil as water molecules, which fill the voids, must be squeezed out of the sample before readjustment of soil grains can occur. The more permeable a soil is, the faster the deformation under load will occur. However, when the load on a saturated soil is quickly increased, the increase is carried entirely by the pore water until drainage begins. Then more and more load is gradually transferred to the soil grains until the excess pore pressure has dissipated and the soil grains readjust to a denser configuration. This process is called *consolidation* and results in a higher unit weight and a decreased void ratio.

7.1.3 Principle of Effective Stress

The consolidation process demonstrates the very important principle of effective stress, which will be used in all the remaining modules of this course. Under an applied load, the total stress in a saturated soil sample is composed of the intergranular stress and porewater pressure (neutral stress). As the porewater has zero shear strength and is considered incompressible, only the intergranular stress is effective in resisting shear or limiting compression of the soil sample. Therefore, the intergranular contact stress is called the *effective stress*. Simply stated, this fundamental principle states that *the effective stress (σ') on any plane within a soil mass is the net difference between the total stress (σ) and porewater pressure (u).*

When pore water drains from soil during consolidation, the area of contact between soil grains increases, which increases the level of effective stress and therefore the soil's shear strength. In practice, staged construction of embankments is used to permit increase of effective stress in the foundation soil before subsequent fill load is added. In such operations the effective stress increase is frequently monitored with piezometers to ensure the next stage of embankment can be safely placed.

Soil deposits below the water table will be considered saturated and the ambient pore pressure at any depth may be computed by multiplying the unit weight of water (γ_w) by the height of water above that depth. For partially saturated soil, the effective stress will be influenced by the soil structure and degree of saturation (Bishop, *et. al.*, 1960). In many cases involving silts & clays, the continuous void spaces that exist in the soil behave as capillary tubes of variable cross-section. Due to capillarity, water may rise above the static groundwater table (*phreatic surface*) as a negative porewater pressure and the soils may be nearly or fully saturated.

7.1.4 Overburden Stress

The purpose of laboratory testing is to simulate in-situ soil loading under controlled boundary conditions. Soils existing at a depth below the ground surface are affected by the weight of the soil above that depth. The influence of this weight, known generally as the *overburden stress*, causes a state of stress to exist which is unique at that depth for that soil. When a soil sample is removed from the ground, that state of stress is relieved as all confinement of the sample has been removed. In testing, it is important to reestablish the in-situ stress conditions and to study changes in soil properties when additional stresses representing the expected design loading are applied. In this regard, the effective stress (grain-to-grain contact) is the controlling factor in shear, state of stress, consolidation, stiffness, and flow. Therefore, the designer should try to re-establish the effective stress condition during most testing.

The test confining stresses are estimated from the total, hydrostatic, and effective overburden stresses. The engineer's first task is determining these stress and pressure variations with depth. This involves determining the total unit weights (density) for each soil layer in the subsurface profile, and determining the depth of the water table. Unit weight may be accurately determined from density tests on undisturbed samples or estimated from in-situ test measurements. The water table is routinely recorded on the boring logs, or can be measured in open standpipes, piezometers, and dissipation tests during CPTs and DMTs.
The total vertical (overburden) stress (σ_{vo}) at any depth (z) may be found as the accumulation of total unit weights (γ_t) of the soil strata above that depth:

$$\sigma_{vo} = \int \gamma_t \, dz \approx \Sigma(\gamma_t) z \qquad (7\text{-}1)$$

For soils above the phreatic surface, the applicable value of total unit weight may be dry, moist, or saturated depending upon the soil type and degree of capillarity (see Table 7-2). For soil elements situated below the groundwater table, the saturated unit weight is normally adopted.

The hydrostatic pressure depends upon the degree of saturation and level of the phreatic surface and is determined as follow:

Soil elements above water table: $u_o = 0$ (Completely dry) (7-2a)

$u_o = \gamma_w(z - z_w)$ (Full capillarity) (7-2b)

Soil elements below water table: $u_o = \gamma_w(z - z_w)$ (7-2c)

where z = depth of soil element, z_w = depth to groundwater table. Another case involves partial saturation with intermediate values between (7-2a and 7-2b) which literally vary daily with the weather and can be obtained via tensiometer measurements in the field. Usual practical calculations adopt (7-2a) for many soils, yet the negative capillary values from (7-2b) often apply to saturated clay & silt deposits.

The effective vertical stress is obtained as the difference between (7-1) and (7-2):

$$\sigma_{vo}' = \sigma_{vo} - u_o \quad (7\text{-}3)$$

A plot of effective overburden profile with depth is called a σ_v' diagram and is extensively used in all aspects of foundation testing and analysis (see Holtz & Kovacs, 1981; Lambe & Whitman, 1979).

7.1.5 Selection and Assignment of Tests

Certain considerations regarding laboratory testing, such as when, how much, and what type, can only be decided by an experienced geotechnical engineer. The following minimal criteria should be considered while determining the scope of the laboratory testing program:

- Project type (bridge, embankment, rehabilitation, buildings, etc.)
- Size of the project
- Loads to be imposed on the foundation soils
- Types of loads (i.e., static, dynamic, etc.)
- Critical tolerances for the project (e.g., settlement limitations)
- Vertical and horizontal variations in the soil profile as determined from boring logs and visual identification of soil types in the laboratory
- Known or suspected peculiarities of soils at the project location (i.e., swelling soils, collapsible soils, organics, etc.)
- Presence of visually observed intrusions, slickensides, fissures, concretions, etc.

The selection of tests should be considered preliminary until the geotechnical engineer is satisfied that the test results are sufficient to develop reliable soil profiles and provide the soil parameters needed for design.

Following this subsection are brief discussions of frequently used soil properties and tests. These discussions assume that the reader will have access to the latest volumes of AASHTO and ASTM standards containing details of test procedures and will study them in connection with this presentation. Table 7-3 presents a summary list of AASHTO and ASTM tests frequently used for laboratory testing of soils.

TABLE 7-3.

AASHTO AND ASTM STANDARDS FOR FREQUENTLY-USED LABORATORY TESTING OF SOILS

Test Category	Name of Test	Test Designation	
		AASHTO	**ASTM**
Visual Identification	Practice for Description and Identification of Soils (Visual-Manual Procedure)	-	D 2488
	Practice for Description of Frozen Soils (Visual-Manual Procedure)	-	D 4083
Index Properties	Test Method for Determination of Water (Moisture) Content of Soil by Direct Heating Method	T 265	D 4959
	Test Method for Specific Gravity of Soils	T 100	D 854
	Method for Particle-Size Analysis of Soils	T 88	D 422
	Test Method for Amount of Material in Soils Finer than the No. 200 (75-μm) Sieve		D 1140
	Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils	T 89 T 90	D 4318
	Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (600 kN-m/m^3)	T 99	D 698
	Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (2,700 kN-m/m^3)	T 180	D 1557
Corrosivity	Test Method for pH of Peat Materials	-	D 2976
	Test Method for pH of Soils	-	D 4972
	Test Method for pH of Soil for Use in Corrosion Testing	T 289	G 51
	Test Method for Sulfate Content	T 290	D 4230
	Test Method For Resistivity	T 288	D 1125 G 57
	Test Method for Chloride Content	T 291	D 512
	Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils	T 194	D 2974
	Test Method for Classification of Soils for Engineering Purposes	M 145	D 2487 D 3282