ADVANCED SOIL MECHANICS

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PREFACE

This textbook is intended for use in an introductory graduate level course, and the general sequence followed is similar to that used in classrooms in various universities. The book has been developed primarily from class notes that I prepared for teaching initially at South Dakota State University and later at The University of Texas at El Paso.

The first chapter is on *Soil Aggregate* and is a general review of most of the materials to which students are introduced in the first course in soil mechanics offered at the undergraduate level. The remaining six chapters, dealing with permeability and seepage, stress distribution in a soil mass due to various types of loading conditions, development of pore water pressure due to undrained loading conditions, consolidation, methods of calculation of settlement of soils, and shear strength of soils, are presented in such a manner that readers who are unfamiliar with the subject will not face any serious problems in understanding. The basic concepts are presented in the earlier sections of each chapter and are then followed by more advanced topics.

The text has been extensively illustrated for better understanding. During the past ten to fifteen years, several new studies have been published in the geotechnical journals around the world. I have made an effort to include the important findings of most of these works as seem pertinent to the materials covered in this text.

A number of example problems are given in each chapter as well as a fairly large number of representative problems for solution by the students at the end of each chapter.

An extensive list of references is given at the end of each chapter which can be used by readers for in-depth review and/or research work.

Dual units—conventional English and SI—have been used throughout.

I am indebted to my wife, Janice, for her help in typing the manuscript. She also helped in preparing most of the figures and tables. Thanks are also due to Sands H. Figuers, graduate student at The University of Texas at El Paso, for his help in several stages during the preparation of the manuscript.

Braja M. Das

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5 Consolidation

7 Shear Strength of Soils

CHAPTER
ONE
SOIL AGGREGATE

1.1 INTRODUCTION

Soils are aggregates of mineral particles, and together with air and/or water in the void spaces they form three-phase systems. A large portion of the earth's surface is covered by soils, and they are widely used as construction and foundation materials. Soil mechanics is the branch of engineering that deals with the engineering properties of soil and its behavior under stresses and strains.

This chapter is primarily designed to be a review of fundamentals to which the reader will already have been exposed in some detail. It is divided into eight major parts: weight-volume relations for the three-phase systems, grain-size distribution of soil particles, clay minerals, consistency, classification systems, compaction, volume change of soils, and the effective stress concept.

1.2 WEIGHT-VOLUME RELATIONSHIPS

1.2.1 Basic Definitions

Figure 1.1*a* shows a soil mass that has a total volume V and a total weight W. To develop the weight-volume relationships, the three phases of the soil mass, i.e., soil solids, air, and water, have been separated in Fig. 1.1*b*. Note that

$$W = W_s + W_w \tag{1.1}$$

and, also,

$$V = V_s + V_w + V_a \tag{1.2}$$

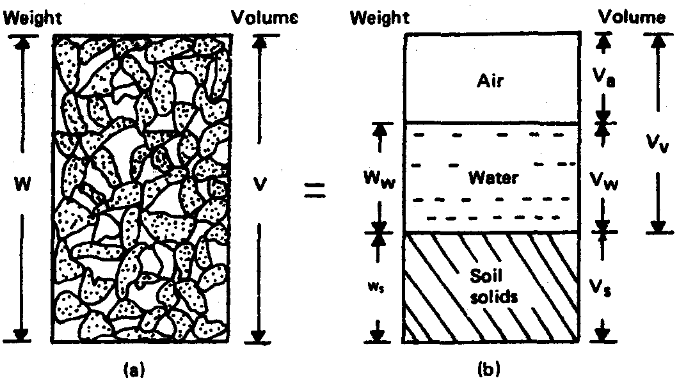

Fig. 1.1 Weight–volume relationships for soil aggregate.

$$V_v = V_w + V_a \tag{1.3}$$

where W_s = weight of soil solids
W_w = weight of water
V_s = volume of the soil solids
V_w = volume of water
V_a = volume of air

The weight of air is assumed to be zero. The volume relations commonly used in soil mechanics are void ratio, porosity, and degree of saturation.

Void ratio e is defined as the ratio of the volume of voids to the volume of solids:

$$e = \frac{V_v}{V_s} \tag{1.4}$$

Porosity n is defined as the ratio of the volume of voids to the total volume:

$$n = \frac{V_v}{V} \tag{1.5}$$

Also, $V = V_s + V_v$

and so

$$n = \frac{V_v}{V_s + V_v} = \frac{V_v/V_s}{V_s/V_s + V_v/V_s} = \frac{e}{1+e} \tag{1.6}$$

Degree of saturation S_r is the ratio of the volume of water to the volume of voids and is generally expressed as a percentage:

$$S_r\,(\%) = \frac{V_w}{V_v} \times 100 \tag{1.7}$$

The weight relations used are moisture content and unit weight. *Moisture content*

w is defined as the ratio of the weight of water to the weight of soil solids, generally expressed as a percentage:

$$w\,(\%) = \frac{W_w}{W_s} \times 100 \tag{1.8}$$

Unit weight γ is the ratio of the total weight to the total volume of the soil aggregate:

$$\gamma = \frac{W}{V} \tag{1.9}$$

This is sometimes referred to as moist unit weight since it includes the weight of water and the soil solids. If the entire void space is filled with water (i.e., $V_a = 0$), it is a saturated soil; Eq. (1.9) will then give use the saturated unit weight γ_{sat}.

The dry unit weight γ_d is defined as the ratio of the weight of soil solids to the total volume:

$$\gamma_d = \frac{W_s}{V} \tag{1.10}$$

Useful weight-volume relations can be developed by considering a soil mass in which the volume of soil solids is unity, as shown in Fig. 1.2. Since $V_s = 1$, from the definition of void ratio given in Eq. (1.4) the volume of voids is equal to the void ratio e. The weight of soil solids can be given by

$$W_s = G_s \gamma_w V_s = G_s \gamma_w \qquad (\text{since } V_s = 1)$$

where G_s is the specific gravity of soil solids, and γ_w is the unit weight of water ($62.4\ \text{lb/ft}^3$, or $9.81\ \text{kN/m}^3$).

From Eq. (1.8), the weight of water is $W_w = wW_s = wG_s\gamma_w$. So the moist unit weight is

$$\gamma = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v} = \frac{G_s\gamma_w + wG_s\gamma_w}{1 + e} = \frac{G_s\gamma_w(1 + w)}{1 + e} \tag{1.11}$$

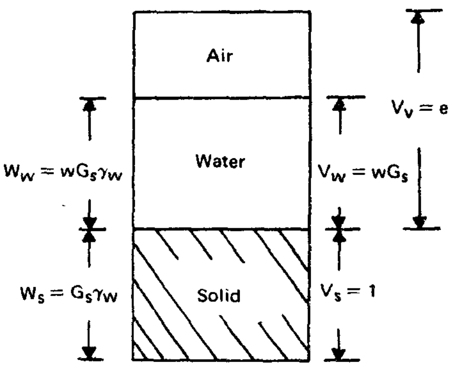

Fig. 1.2 Weight-volume relation for $V_s = 1$.

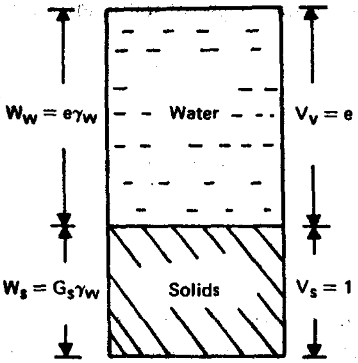

Fig. 1.3 Weight–volume relation for saturated soil with $V_s = 1$.

The dry unit weight can also be determined from Fig. 1.2 as

$$\gamma_d = \frac{W_s}{V} = \frac{G_s\gamma_w}{1+e} \tag{1.12}$$

The degree of saturation can be given by

$$S_r = \frac{V_w}{V_v} = \frac{W_w/\gamma_w}{V_v} = \frac{wG_s\gamma_w/\gamma_w}{e} = \frac{wG_s}{e} \tag{1.13}$$

For saturated soils, $S_r = 1$. So, from Eq. (1.13),

$$e = wG_s \tag{1.14}$$

By referring to Fig. 1.3, the relation for the unit weight of a saturated soil can be obtained as

$$\gamma_{sat} = \frac{W}{V} = \frac{W_s + W_w}{V} = \frac{G_s\gamma_w + e\gamma_w}{1+e} \tag{1.15}$$

Basic relations for unit weight such as Eqs. (1.11), (1.12), and (1.15) in terms of porosity n can also be derived by considering a soil mass that has a total volume of unity as shown in Fig. 1.4. In this case (for $V = 1$), from Eq. (1.5), $V_v = n$. So, $V_s = V - V_v = 1 - n$.

The weight of soil solids is equal to $(1-n)G_s\gamma_w$, and the weight of water $W_w = wW_s = w(1-n)G_s\gamma_w$. Thus the moist unit weight is

$$\gamma = \frac{W}{V} = \frac{W_s + W_w}{V} = \frac{(1-n)G_s\gamma_w + w(1-n)G_s\gamma_w}{1}$$

$$= G_s\gamma_w(1-n)(1+w) \tag{1.16}$$

The dry unit weight is

$$\gamma_d = \frac{W_s}{V} = (1-n)G_s\gamma_w \tag{1.17}$$

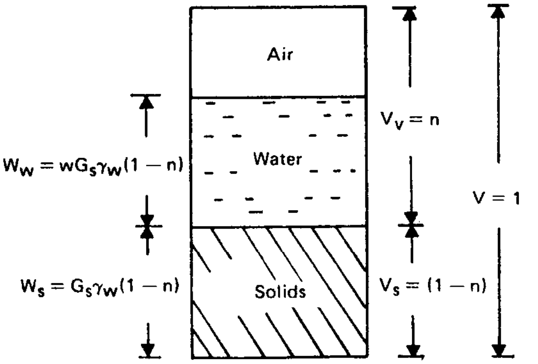

Fig. 1.4 Weight-volume relationship with $V = 1$.

If the soil is saturated (Fig. 1.5),

$$\gamma_{sat} = \frac{W_s + W_w}{V} = (1-n)G_s\gamma_w + n\gamma_w = [G_s - n(G_s - 1)]\gamma_w \tag{1.18}$$

Several other functional relationships are given in Table 1.1.

Example 1.1 For a soil in natural state, given $e = 0.8$, $w = 24\%$, and $G_s = 2.68$.
(*a*) Determine the moist unit weight, dry unit weight, and degree of saturation.
(*b*) If the soil is made completely saturated by adding water, what would its moisture content be at that time? Also find the saturated unit weight.

SOLUTION *Part (a):* From Eq. (1.11), the moist unit weight is

$$\gamma = \frac{G_s\gamma_w(1+w)}{1+e}$$

Since $\gamma_w = 9.81\ \text{kN/m}^3$,

$$\gamma = \frac{(2.68)(9.81)(1+0.24)}{1+0.8} = \mathit{18.11\ kN/m^3}$$

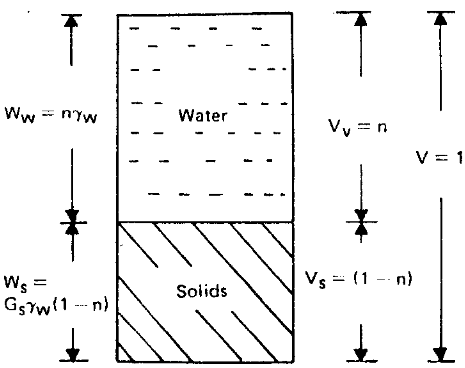

Fig. 1.5 Weight-volume relationship for saturated soil with $V = 1$.

Table 1.1 Functional relationships of various soil properties for saturated soils

Jumikis, A. R., *Soil Mechanics*, 1962, pp. 90–91, D. Van Nostrand Company, Inc., Princeton, New Jersey

Quantities γ_w and:	Sought quantities					
	Specific gravity G_s	Dry unit weight γ_d	Saturated unit weight γ_{sat}	Saturated moisture content, %	Porosity n	Void ratio e
$G_s; \gamma_d$			$\left(1 - \frac{1}{G_s}\right)\gamma_d + \gamma_w$	$\left(\frac{1}{\gamma_d} - \frac{1}{G_s\gamma_w}\right)\gamma_w$	$1 - \frac{\gamma_d}{G_s\gamma_w}$	$\frac{G_s\gamma_w}{\gamma_d} - 1$
$G_s; \gamma_{sat}$		$\frac{\gamma_{sat} - \gamma_w}{G_s - 1} G_s$		$\frac{G_s\gamma_w - \gamma_{sat}}{(\gamma_{sat} - \gamma_w) G_s}$	$\frac{G_s\gamma_w - \gamma_{sat}}{(G_s - 1)\gamma_w}$	$\frac{G_s\gamma_w - \gamma_{sat}}{\gamma_{sat} - \gamma_w}$
$G_s; w$		$\frac{G_s}{1 + wG_s}\gamma_w$	$\frac{1 + w}{1 + wG_s} G_s\gamma_w$		$\frac{wG_s}{1 + wG_s}$	wG_s
$G_s; n$		$G_s(1 - n)\gamma_w$	$[G_s - n(G_s - 1)]\gamma_w$	$\frac{n}{G_s(1 - n)}$		$\frac{n}{1 - n}$
$G_s; e$		$\frac{G_s}{1 + e}\gamma_w$	$\frac{G_s + e}{1 + e}\gamma_w$	$\frac{e}{G_s}$	$\frac{e}{1 + e}$	
$\gamma_d; \gamma_{sat}$	$\frac{\gamma_d}{\gamma_w + \gamma_d - \gamma_{sat}}$			$\frac{\gamma_{sat}}{\gamma_d} - 1$	$\frac{\gamma_{sat} - \gamma_d}{\gamma_w}$	$\frac{\gamma_{sat} - \gamma_d}{\gamma_w + \gamma_d - \gamma_{sat}}$
$\gamma_d; w$	$\frac{\gamma_d}{\gamma_w - w\gamma_d}$		$(1 + w)\gamma_d$		$w\frac{\gamma_d}{\gamma_w}$	$\frac{w\gamma_d}{\gamma_w - w\gamma_d}$

$\gamma_d; n$	$\frac{\gamma_d}{(1-n)\gamma_w}$		$\gamma_d + n\gamma_w$	$\frac{n\gamma_w}{\gamma_d}$		$\frac{n}{1-n}$
$\gamma_d; e$	$(1+e)\frac{\gamma_d}{\gamma_w}$		$\frac{e\gamma_w}{1+e} + \gamma_d$	$\frac{e}{1+e}\frac{\gamma_w}{\gamma_d}$	$\frac{e}{1+e}$	
$\gamma_{sat}; w$	$\frac{\gamma_{sat}}{\gamma_w - w(\gamma_{sat} - \gamma_w)}$	$\frac{\gamma_{sat}}{1+w}$			$\frac{w\gamma_{sat}}{(1+w)\gamma_w}$	$\frac{w\gamma_{sat}}{\gamma_w - w(\gamma_{sat} - \gamma_w)}$
$\gamma_{sat}; n$	$\frac{\gamma_{sat} - n\gamma_w}{(1-n)\gamma}$	$\gamma_{sat} - n\gamma_w$		$\frac{n\gamma_w}{\gamma_{sat} - n\gamma_w}$		$\frac{n}{1-n}$
$\gamma_{sat}; e$	$(1+e)\frac{\gamma_{sat}}{\gamma_w} - e$	$\gamma_{sat} - \frac{e}{1+e}\gamma_w$		$\frac{e\gamma_w}{\gamma_{sat} + e(\gamma_{sat} - \gamma_w)}$	$\frac{e}{1+e}$	
$w; n$	$\frac{n}{(1-n)w}$	$\frac{n}{w}\gamma_w$	$n\frac{1+w}{w}\gamma_w$			$\frac{n}{1-n}$
$w; e$	$\frac{e}{w}$	$\frac{e}{(1-e)w}\gamma_w$	$\frac{e}{w}\frac{1+w}{1+e}\gamma_w$		$\frac{e}{1+e}$	

From Eq. (1.12), the dry unit weight is

$$\gamma_d = \frac{G_s \gamma_w}{1+e} = \frac{(2.68)(9.81)}{1+0.8} = 14.61\ kN/m^3$$

From Eq. (1.13), the degree of saturation is

$$S_r(\%) = \frac{wG_s}{e} \times 100 = \frac{(0.24)(2.68)}{0.8} \times 100 = 80.4\%$$

Part (b): From Eq. (1.14), for saturated soils, $e = wG_s$, or

$$w\ (\%) = \frac{e}{G_s} \times 100 = \frac{0.8}{2.68} \times 100 = 29.85\%$$

From Eq. (1.15), the saturated unit weight is

$$\gamma_{sat} = \frac{G_s \gamma_w + e\gamma_w}{1+e} = \frac{9.81\,(2.68+0.8)}{1+0.8} = 18.97\,kN/m^3$$

1.2.2 General Range of Void Ratio and Dry Unit Weight Encountered in Granular Soils

For granular soils (sand and gravel), the range of void ratio generally encountered can be visualized by considering an ideal situation in which particles are spheres of equal size. The loosest and the densest possible arrangements that we can obtain from these equal spheres are, respectively, the simple cubic and the pyramidal type of packing as shown in Fig. 1.6. The void ratio corresponding to the simple cubic type of arrangement is 0.91; that for the pyramidal type of arrangement is 0.34. In the case of natural granular soils, particles are neither of equal size nor perfect spheres. The small-sized particles may occupy void spaces between the larger ones, which will tend to reduce the void ratio of natural soils as compared to that for equal spheres. On the other hand, the irregularity in the shape of the particles generally tends to increase the void ratio of soil as compared to ideal spheres. As a result of these two factors, the void ratios encountered in real soils are approximately in the same range as those obtained in the case of equal spheres.

Table 1.2 gives some typical values of void ratios and dry unit weights encountered in granular soils.

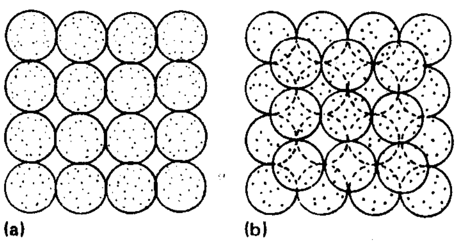

Fig. 1.6 Simple cubic (*a*) and pyramidal (*b*) types of arrangement of equal spheres.