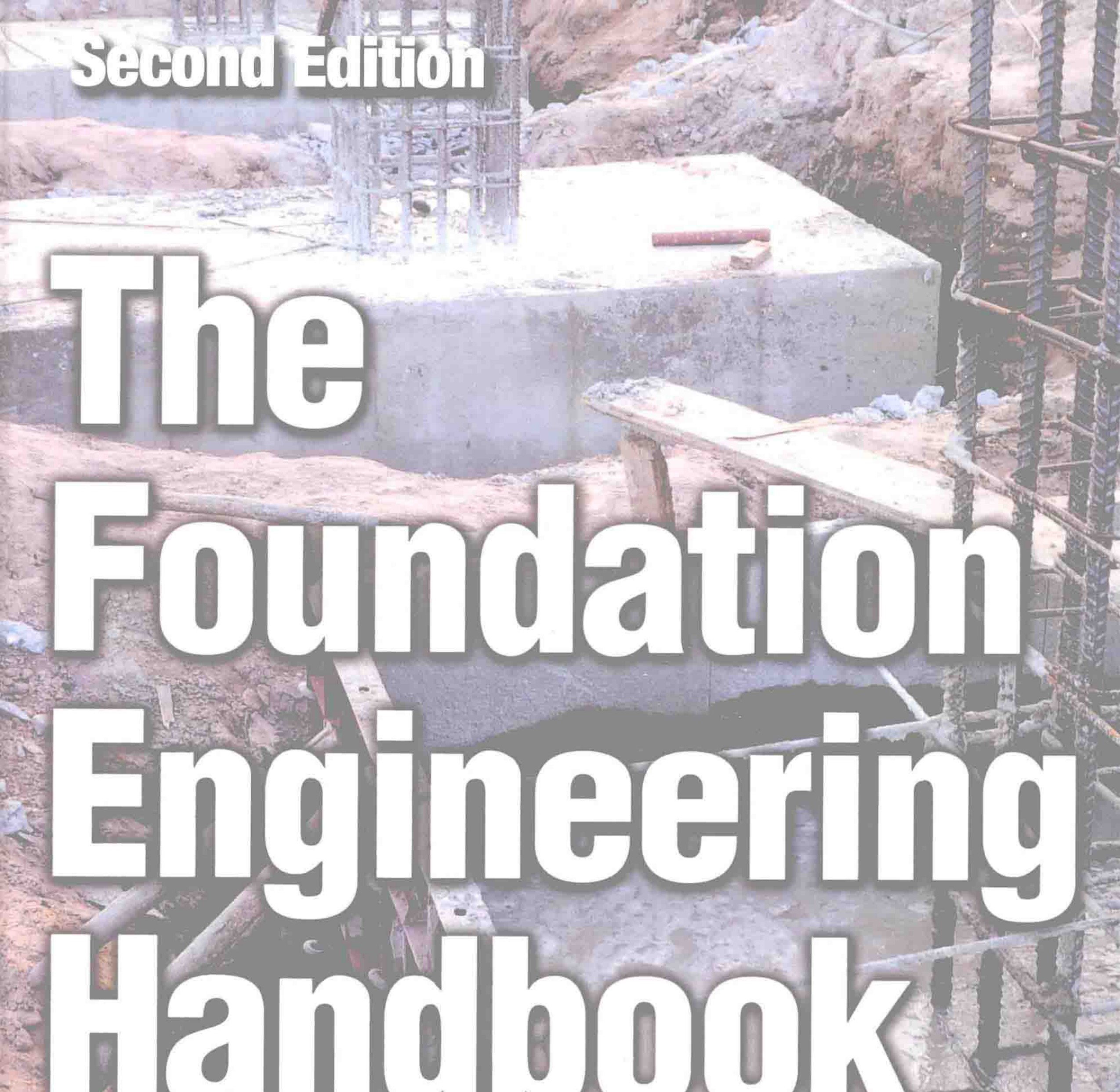

Second Edition

The Foundation Engineering Handbook

Edited by Manjriker Gunaratne

CRC Press
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Dedicated to My Parents

Preface

The first edition of the *Foundation Engineering Handbook* was well received by users. One major reason for this is its fulfillment of the need for both classical foundation design principles and the latest contributions made to the state of knowledge. Some of the unique areas covered in the first edition were innovative *in situ* testing and site improvement techniques, concepts of ground deformation modeling using the finite element method, reliability-based design concepts, and pile construction monitoring techniques that are in wide use today. In this new edition, the handbook includes additional applications in the state of the art such as unsaturated soil mechanics, analysis of transient flow through soils, deep foundation construction monitoring based on thermal integrity profiling, and updated ground remediation techniques. Furthermore, in the new edition, almost every chapter has been updated by adding alternative analytical techniques such as the force polygon method of analysis and a number of additional illustrative examples to complement the existing ones. Therefore, the applicability of this handbook as a supplementary textbook, at both undergraduate and graduate levels, has been vastly elevated.

It is indeed my pleasure to have worked with a distinguished set of contributors who once again performed their tasks in an outstanding manner amid their professional demands. Especially, my thanks are conveyed to Dr. Gray Mullins and James Hussin. My appreciation is conveyed to University of South Florida civil engineering graduate students Mohammed Naim, Alex Mraz, Ivan Sokolic, Mathiyaparanam and Kalyani Jeyisankar, Duminda Randeniya, John Metz, Justin Callahan, and Yordanka Goodwin for their contributions and to Ingrid Hall for help in preparing the manuscript. The support of my children, Ruwan and Aruni, and my wife, Prabha, during the arduous task of making this project a reality is also gratefully acknowledged. I wish to extend my special thanks to Joe Clements and Josie Banks-Kyle and other members of the staff at Taylor & Francis Group for their support in publishing the second edition of this handbook. Thanks are also due to the publishers who permitted the use of material from other references.

I acknowledge the mentorship of late Professor Alagiah Thurairajah, former dean of the Faculty of Engineering, University of Peradeniya, Sri Lanka, and a prominent member of the Cambridge University's Cam Clay group. Finally, I dedicate this second version of the handbook as well to my mother, Jeanette Gunaratne, and my late father, Raymond Gunaratne.

Editor

Manjriker Gunaratne, PhD, is professor and chairman of civil and environmental engineering at the University of South Florida, Tampa, Florida. He completed his secondary and high school education at Ananda College, Colombo, Sri Lanka, receiving the S.A. Wijetileke award for the highest ranking student at the GCE (advanced level) examination. Thereafter, he earned a BS in engineering from the Faculty of Engineering, University of Peradeniya, Sri Lanka, where he was awarded the Professor E.O.E. Pereira prize for the highest ranking student at the final (part II) examination in the overall engineering class. Subsequently, he pursued postgraduate education, earning the MASc and PhD degrees in civil engineering from the University of British Columbia, Vancouver, Canada, and Purdue University, West Lafayette, Indiana, USA, respectively.

During 28 years of service as an engineering educator, he has authored or coauthored over 40 research papers that have been published in a number of peer-reviewed international journals such as the *American Society of Civil Engineers* (geotechnical, transportation, civil engineering materials, and infrastructure systems), *International Journal of Numerical and Analytical Methods in Geomechanics, Civil and Environmental Engineering Systems, Computers and Geotechnics, Transportation Research, Transportation Research Record, IEEE Journal of Intelligent Transportation Systems,* and others. In addition, he has made a number of presentations at various national and international forums in geotechnical and highway engineering. He has supervised the master's theses of 20 students and the doctoral dissertations of 20 more students. All of them hold responsible technical positions in public service, industry, and academia in many parts of the world.

Dr. Gunaratne has been involved in a number of research projects with agencies such as the Florida Department of Transportation (FDOT), US Department of the Air Force, and the National Aeronautics and Space Administration (NASA) amounting to over $4 million. He has also held fellowships at the US Air Force (Wright-Patterson Air Force Base) and NASA (Robert Goddard Space Flight Center) and a consultant's position with the United Nations Development Program (UNDP) in Sri Lanka. He has also served as a panelist for the National Science Foundation (NSF), USA, and as a member of the task force for investigation of dam failures in Florida, USA.

Contributors

Panchy Arumugasamy
Private Consultant
Columbus, Ohio

Alaa Ashmawy
American University of Dubai
Dubai, United Arab Emirates

James D. Hussin
Hayward-Baker Incorporated
Tampa, Florida

Austin Gray Mullins
University of South Florida
Tampa, Florida

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Manjriker Gunaratne

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1.1 Introduction

Geotechnical engineering is a branch of civil engineering in which technology is applied to the design and construction of structures involving geological materials. Earth's surface material consists of soil and rock. Of the several branches of geotechnical engineering, soil and rock mechanics are the fundamental studies of the properties and mechanics of soil and rock, respectively. Foundation engineering is the application of the principles of soil mechanics, rock mechanics, and structural engineering to the design of structures associated with earthen materials. On the other hand, rock engineering is the corresponding application of the above technologies to the design of structures associated with rock. It is generally observed that most foundation types supported by intact bedrock present no compressibility problems. Therefore, when designing common foundation types, the foundation engineer's primary concerns are the strength and compressibility of the subsurface soil and whenever applicable, the strength of bedrock.

1.1.1 Origin of Geomaterials

The earth's interior consists of a core, mantle, and outer crust. The core is made up of a solid inner part and a liquid outer part existing at extremely high temperatures and pressures. The mantle consists of harder material under relatively cooler temperatures.

The outer zone of the mantle and the inner zone of the outer crust are made up of a dense, semisolid or plastic rock layer known as the asthenosphere. The outer crust or the lithosphere (rock sphere) contains hard brittle rock topped at most locations by the soil overburden or oceans and soil overburden.

The lithosphere is not formed as one continuing crust but rather constitutes a number of tectonic plates that constantly move somewhat independently of each other. Plate divergence at the boundaries produces rifts that allow molten material from the asthenosphere to rise, cool, and create new lithosphere. These locations generally coincide with areas of volcanic activity. On the other hand, plate convergence at the boundaries causes constant stress buildup, creating conditions for possible earthquakes.

A foundation engineer needs to be informed of two aspects of the above discussion. The primary information relates to the formation of the soil overburden. Gradual weathering of the rock material in the lithosphere due to physical means (i.e., pressure and temperature related), chemical means, or man's action can create distinct stages of decomposition. Ideally, successive *in situ* staged decomposition of rock would result in boulders, gravel, sand silt, and clay. The most important information that a foundation engineer must have regarding the site selected for a given building is the classification of soil type (Section 1.2) and the condition of bedrock (decomposed or solid). The secondary information pertains to the seismicity of the general geographical area. If the area is known to be seismically active, then principles of soil dynamics must also be incorporated in foundation design (Sections 3.6 and 3.7).

1.2 Soil Classification

1.2.1 Mechanical Analysis

According to texture or the "feel," two different soil types can be identified. They are (1) coarse-grained soil (gravel and sand) and (2) fine-grained soil (silt and clay). Whereas the engineering properties (primarily strength and compressibility) of coarse-grained soils depend on the size of individual soil particles, the properties of fine-grained soils are mostly governed by the moisture content. Hence, it is important to identify the type of soil at a given construction site because the most effective construction procedures depend on the soil type. Geotechnical engineers use a universal format called the Unified Soil Classification System (USCS) to identify and label soil. This system is based on the results of common laboratory tests of mechanical analysis and Atterberg limits.

In classifying a soil sample retrieved from a given site, mechanical analysis is conducted in two stages: (1) sieve analysis for the coarse fraction (gravel and sand) and (2) hydrometer analysis for the fine fraction (silt and clay). Of these, sieve analysis is conducted according to ASTM (American Society for Testing and Materials) D421 and D422 procedures, using a set of U.S. standard sieves (Figure 1.1); the most commonly used sieves are U.S. Standard numbers 20, 40, 60, 80, 100, 140, and 200, which correspond to sieve openings of 0.85, 0.425, 0.25, 0.18, 0.15, 0.106, and 0.075 mm, respectively. During the test, the percentage (by weight) of the soil sample retained on each sieve is recorded, from which the percentage ($R\%$) passing (or finer than) a given sieve size (D) is determined.

On the other hand, if a substantial portion of the soil sample consists of fine-grained soils ($D < 0.075$ mm), then sieve analysis has to be followed by hydrometer analysis (Figure 1.2). The latter test is performed by first treating the "fine fraction" with a deflocculating agent such as sodium hexa-meta-phosphate (Calgon) or sodium silicate (water glass) for about half a day and then allowing the suspension to settle in a hydrometer jar maintained at a constant temperature. As the heavier particles settle, followed by the lighter ones, a calibrated ASTM 152H hydrometer is used to estimate the fraction (percentage, $R\%$) by weight still settling above the hydrometer bottom at any given stage. Furthermore, the particle size (D) that has settled past the hydrometer bottom at that stage in time can be estimated from the well-known Stokes' law for settling of objects in a liquid. It is realized that $R\%$ is the weight percentage of soil finer than D.

Further details of the above tests such as the correction to be applied to the hydrometer reading and determination of the effective length of the hydrometer are provided by Bowles (1986) and Das (2002). For soil samples that have significant coarse and fine fractions, both sieve and hydrometer analysis results ($R\%$ and D) can be logically combined to

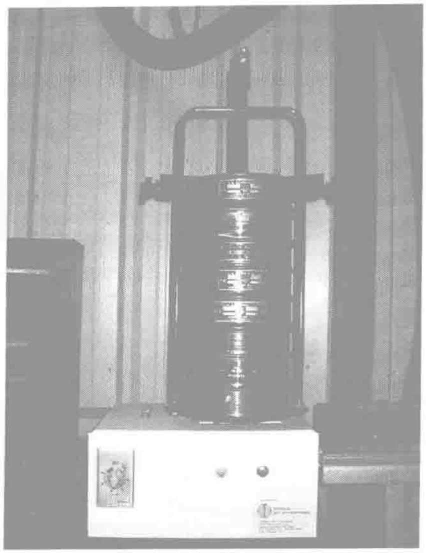


FIGURE 1.1
Equipment used for sieve analysis. (Courtesy of the University of South Florida.)

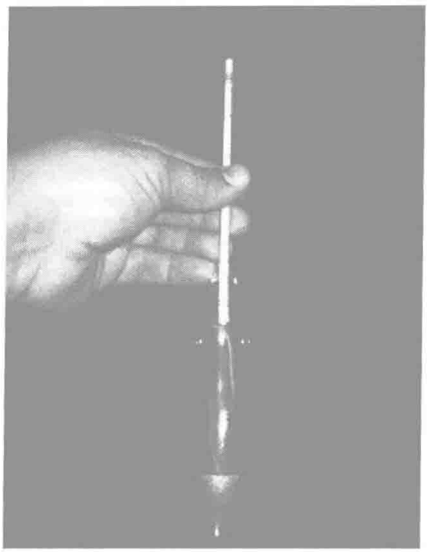


FIGURE 1.2
Equipment used for hydrometer analysis. (Courtesy of the University of South Florida.)

generate grain (particle) size distribution (PSD) curves such as those indicated in Figure 1.3. As an example, in Figure 1.3, it can be seen that 30% of soil type A is finer than 0.075 mm (U.S. No. 200 sieve), with $R\% = 30$ and $D = 0.075$ mm being the last pair of results obtained from sieve analysis. In combining sieve analysis data with hydrometer analysis data, one has to convert the $R\%$ (based on the fine fraction only) and D (size) obtained from hydrometer analysis to percent passing based on the weight of the entire sample, in order to ensure the

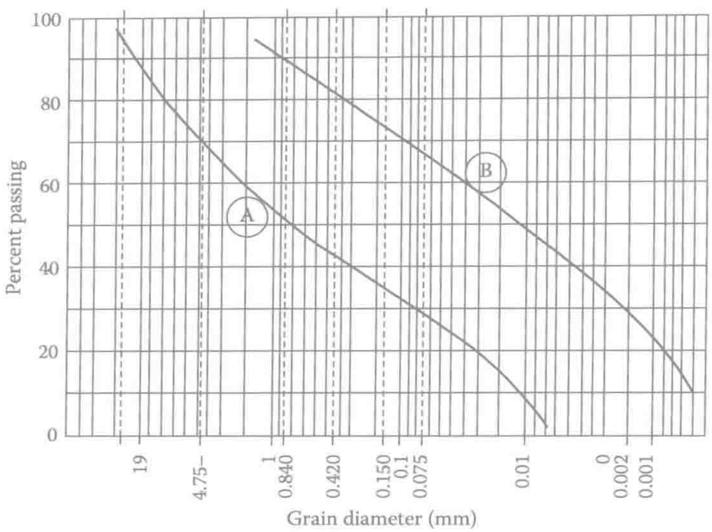


FIGURE 1.3
Grain (particle) size distribution curves. (From Edward Nawy (ed.), *Concrete Design Handbook*, Taylor & Francis, Boca Raton, FL, 1997.)

continuity of the PSD curve. As an example, let the results from one hydrometer reading of soil sample A be $R\% = 90$ and $D = 0.05$ mm. To plot the curve, one needs the percentage of the entire sample finer than 0.05 mm. Since what is finer than 0.05 mm is 90% of the fine fraction (30% of the entire sample) used for hydrometer analysis, the converted percent passing for the final plot can be obtained by multiplying 90% by the fine fraction of 30%. Hence, the converted data used to plot Figure 1.3 are percent passing = 27 and $D =$ 0.05 mm.

1.2.2 Atterberg Limits

As mentioned previously, the properties of fine-grained soils are governed by water. Hence, the effect of water must be the primary consideration in classification of fine-grained soils. This is achieved by using the Atterberg limits or consistency limits. The physical state of a fine-grained soil changes from brittle to liquid state with increasing water content, as shown in Figure 1.4.

Theoretically, the plastic limit (PL) of a soil is defined as the water content at which the soil changes from "semisolid" to "plastic" (Figure 1.4). For a given soil sample, this is an inherent property of the soil, which can be determined by rolling a plastic soil sample into

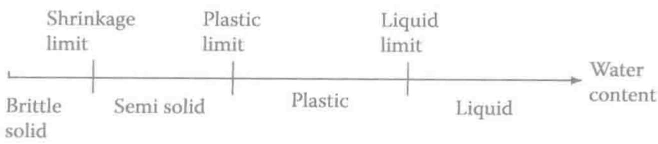


FIGURE 1.4
Variation of the fine-grained soil properties with the water content.

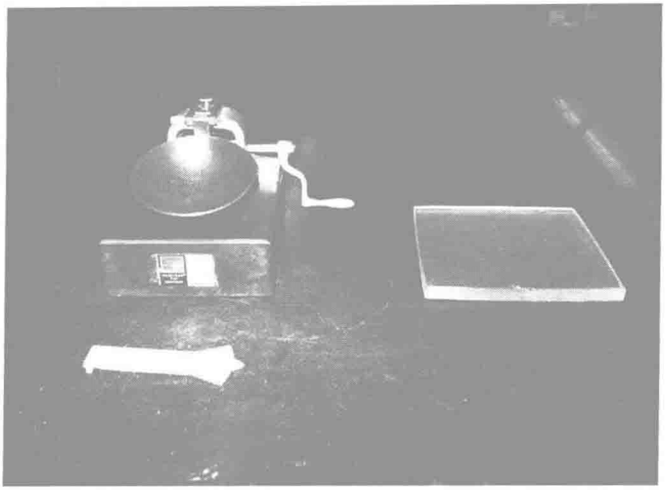


FIGURE 1.5
Equipment for the plastic limit–liquid limit tests. (Courtesy of the University of South Florida.)

a worm shape in order to gradually reduce its water content by exposing more and more of an area until the soil becomes semisolid in consistency. This change can be detected by cracks appearing on the sample. According to ASTM 4318, the PL is the water content at which cracks develop on a rolled soil sample at a diameter of 3 mm. Thus, the procedure to determine the PL is one of trial and error. While the apparatus (ground glass plate and moisture cans) used for the test is shown in Figure 1.5, the reader is referred to Bowles (1986) and Das (2002) for more details.

On the other hand, the liquid limit (LL), which is visualized as the water content at which the state of a soil changes from "plastic" to "liquid" with increasing water content, is determined in the laboratory using the Casagrande liquid limit device (Figure 1.5). This device is specially designed with a standard brass cup on which a standard-sized soil paste is applied during testing. In addition, the soil paste is grooved in the middle by a standard grooving tool thereby creating a "gap" with standard dimensions. When the brass cup is made to drop through a distance of 1 cm on a hard rubber base, the number of drops (blows) required for the parted soil paste to come back into contact through a distance of 1/2 in is counted. Details of the test procedure can be found in the work of Bowles (1986) and Das (2002). ASTM 4318 specifies LL as the water content at which the standard-sized gap is closed in 25 drops of the cup. Therefore, one has to repeat the experiment for different trial water contents, each time recording the number of blows required to fulfill the closing condition of the soil gap. Finally, the water content corresponding to 25 blows (or the LL) can be interpolated from the data obtained from all trials. The plasticity index (PI), which is a widely used parameter for the classification of fine-grained soils, is evaluated as follows:

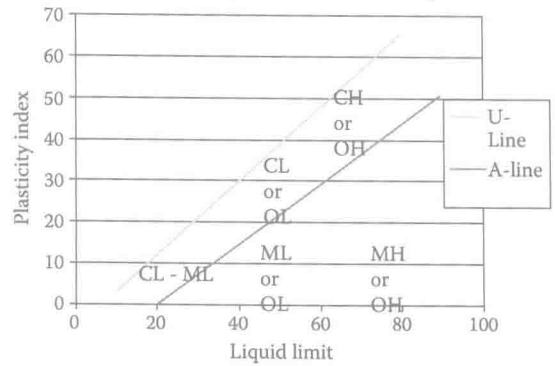
$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL} \tag{1.1}$$

1.2.3 Unified Soil Classification System

In the commonly adopted USCS shown in Table 1.1, the aforementioned soil properties are used effectively to classify soils. Example 1.1 illustrates the classification of the two soil

TABLE 1.1

Unified Soil Classification System

Division		Description	Group Symbol	Identification	Laboratory Classification Criteria
More than 50% soil retained in U.S. 200 sieve (0.075 mm)	More than 50% retained in U.S. No. 4 (4.75 mm)	Clean gravels	GW	Well-graded gravels	$C_u > 4, 1 < C_c < 3$
			GP	Poorly graded gravels	Not meeting GW criteria
		Gravel with fines	GM	Silty gravel	Falls below A line in the plasticity chart, or PI less than 4
			GC	Clayey gravel	Falls above A line in the plasticity chart, or PI greater than 7
	More than 50% passing U.S. No. 4 (4.75 mm)	Clean sand	SW	Well graded sand	$C_u > 4, 1 < C_c < 3$
			SP	Poorly graded sand	Not meeting SW criteria
		Sand with fines	SM	Silty sand	Falls below A line in the plasticity chart, or PI less than 4
			SC	Clayey sand	Falls above A line in the plasticity chart, or PI greater than 7
More than 50% soil passing U.S. 200 sieve (0.075 mm)	Fine-grained soils (LL < 50)		ML	Inorganic silts with low plasticity	
			CL	Inorganic clays with low plasticity	
			OL	Organic clays/silts with low plasticity	
	Fine-grained soils (LL > 50)		MH	Inorganic silts with high plasticity	
			CH	Inorganic clays with high plasticity	
			OH	Organic clays/silts with low plasticity	Use the Casagrande plasticity chart shown above
Highly organic soils			Pt		

Source: R.D. Holtz and W.D. Kovacs, *An Introduction to Geotechnical Engineering*, Prentice Hall, Inc., Engelwood Cliffs, NJ, 1981, with permission.

samples A and B represented by the PSD curves shown in Figure 1.3. Definition of the following two curve parameters is necessary to accomplish the classification:

Coefficient of uniformity (C_u) = D_{60}/D_{10}
Coefficient of curvature (C_c) = $D_{30}^2/D_{60}D_{10}$

where D_i is the diameter corresponding to the ith percent passing on the PSD.

Example 1.1

Classify soils A and B with PSD curves shown in Figure 1.3.

Solution

Soil A. The percentage of coarse-grained soil is approximately equal to 70% (=100% – 29%). It must be noted that 29% is the percent passing corresponding to 0.075 mm size designated as the U.S. No. 200 sieve size and the lower threshold size of coarse-grained soils. Therefore, A is a coarse-grained soil. The percentage of sand in the coarse-fraction is equal to (70 – 29)/70 × 100 = 57%. It must be noted that 70% is the percent passing corresponding to 4.75 mm size designated as the U.S. No. 4 sieve size and the upper threshold size of sands. Thus, according to the USCS (Table 1.1), Soil A is sand. If one assumes a clean sand, then

$C_c = (0.075)^2/(2 \times 0.013) = 0.21$, does not meet the criterion for SW
$C_u = (2)/(0.013) = 153.85$, meets criterion for SW

Hence, soil A can be classified as a poorly graded sand designated as SP.

Soil B. The percentage of coarse-grained soil is equal to 32% (=100% – 68%). Hence, B is a fine-grained soil. Assuming that LL and PL are equal to 45 and 35, respectively (which results in a PI value of 10 from Equation 1.1), using *Casagrande's plasticity chart* (Table 1.1) soil B can be classified as silty sand with clay (ML).

1.3 Water in Soils

1.3.1 Clay Minerals

Mechanical weathering described in Section 1.1.1 tends to produce coarse-grained soils such as boulders, cobbles, gravels, and sands, whereas chemical weathering produces clay minerals. The engineering behavior, which is primarily described by the strength and compressibility characteristics, of coarse-grained soils is mainly dependent on the grain-size distribution and the degree of packing. On the other hand, in clay minerals that are electrochemically active, the water content has a significant bearing on the engineering behavior.

Clay minerals are hydrous aluminum silicates that contain metallic ions such as Si^{2+}, Al^{2+}, Mg^{2+}, or Fe^{2+}. X-ray diffraction studies (Holtz and Kovacs, 1981) have revealed that the crystals of the above minerals consist of many crystal sheets having a repeating atomic structure. The two fundamental crystal sheets are tetrahedral silica and octahedral alumina. As shown in Figure 1.6a, the silica tetrahedral unit consists of four oxygen atoms at the corners surrounding a silicon atom. Similarly, in the octahedral alumina unit, six oxygen atoms or hydroxyls (OH) surround a metallic atom such as Al or Mg (Figure 1.6b).

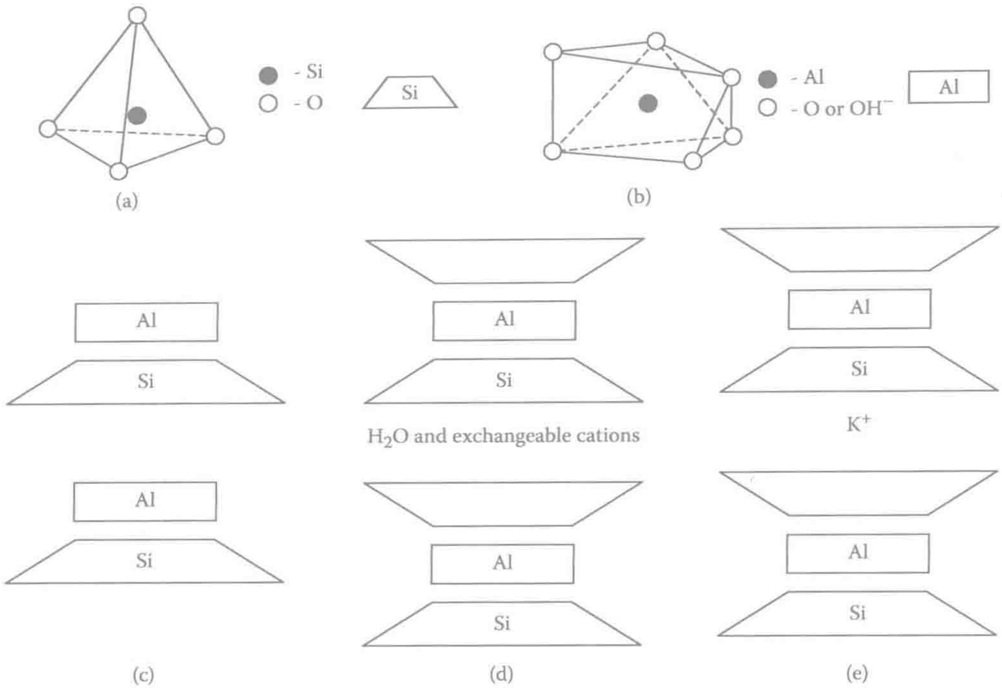


FIGURE 1.6
(a) Tetrahedral silica. (b) Octahedral alumina. (c) Basic kaolinite crystal structure. (d) Basic montmorillonite crystal structure. (e) Basic illite crystal structure.

An example of a 1:1 clay mineral is kaolinite with the basic crystal structure shown in Figure 1.6c. The tetrahedral and octahedral units share common oxygen atoms, whereas hydrogen bonding holds the successive layers together. The absence of interchangeable cations in between the basic layers limits the influence of water on the engineering behavior of kaolinite.

Montmorillonite (Figure 1.6d) and illite (Figure 1.6e) are common examples of 2:1 clay minerals. In the montmorillonite crystal structure, the bonding between the silica sheets is relatively weak compared to the bonding between slica and alumina in kaolinite. Hence, polarized water molecules and exchangeable cations can easily enter the space between the two layers in large quantities and separate them, thus imposing a significant effect on the behavior of such clays. Consequently, subsurface soils with a significant content of montmorillonite clay mineral can induce damaging swelling pressures on superstructures and roads. The activity of montmorillonite clay minerals can be reduced by lime stabilization whereby the addition of Ca^{2+} into the interlayer space can reduce the water affinity of those minerals.

In illite (Figure 1.6e), on the other hand, the individual layers are tightly bonded with potassium ions K^+, thus disabling any water molecules intruding into the interlayer space. Hence, illite clay minerals do not exhibit swelling activity.

1.3.2 Effective Stress Concept

Voids (or pores) within the soil skeleton contain fluids such as air, water, or other contaminants. Hence, any load applied on a soil is partly carried by such pore fluids in addition to