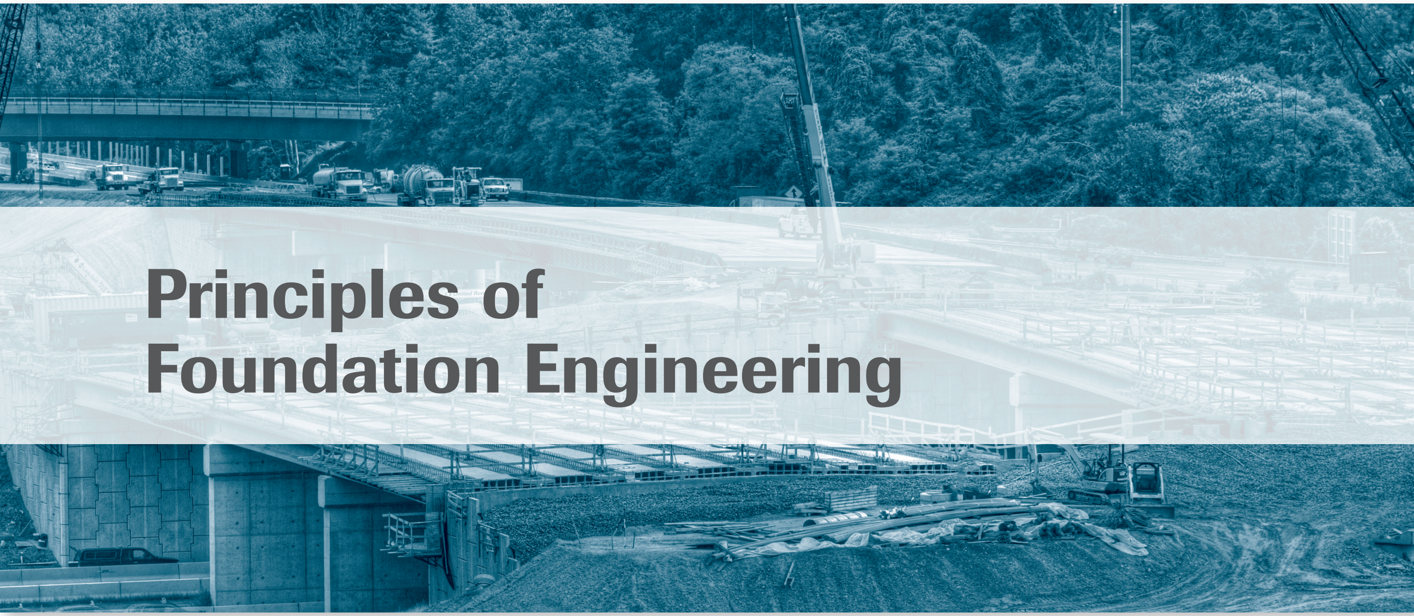
Principles of

FOUNDATION ENGINEERING

Eighth Edition

Braja M. Das



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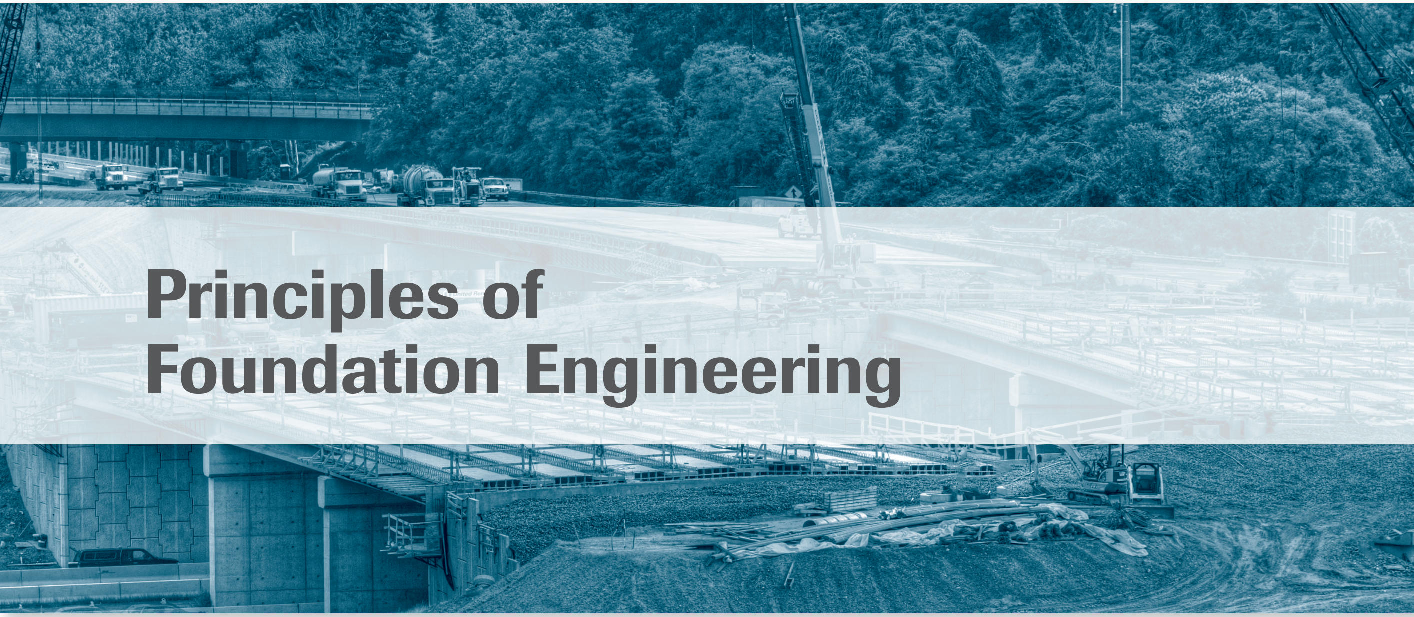

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Braja M. Das

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In the memory of my mother and
to Janice, Joe, Valerie, and Elizabeth

Contents

Preface

Soil mechanics and foundation engineering have developed rapidly during the last fifty plus years. Intensive research and observation in both the field and the laboratory have refined and improved the science of foundation design. Originally published in the fall of 1983 with a 1984 copyright, this text on the principles of foundation engineering is now in the eighth edition. It is intended primarily for use by undergraduate civil engineering students. The use of this text throughout the world has increased greatly over the years. It has also been translated into several languages. New and improved materials that have been published in various geotechnical engineering journals and conference proceedings that are consistent with the level of understanding of the intended users have been incorporated into each edition of the text.

Based on the useful comments received from the reviewers for preparation of this edition, changes have been made from the seventh edition. The text now has sixteen chapters compared to fourteen in the seventh edition. There is a small introductory chapter (Chapter 1) at the beginning. The chapter on allowable bearing capacity of shallow foundations has been divided into two chapters—one on estimation of vertical stress due to superimposed loading and the other on elastic and consolidation settlement of shallow foundations. The text has been divided into four major parts for consistency and continuity, and the chapters have been reorganized.

Part I—Geotechnical Properties and Exploration of Soil (Chapters 2 and 3)
Part II—Foundation Analysis (Chapters 4 through 11)
Part III—Lateral Earth Pressure and Earth-Retaining Structures (Chapters 12 through 15)
Part IV—Soil Improvement (Chapter 16)

A number of new/modified example problems have been added for clarity and better understanding of the material by the readers, as recommended by the reviewers. Listed here are some of the signification additions/modifications to each chapter.

- In Chapter 2 on Geotechnical Properties of Soil, empirical relationships between maximum (e_{max}) and minimum (e_{min}) void ratios for sandy and silty soils have been added. Also included are empirical correlations between e_{max} and e_{min} with the median grain size of soil. The variations of the residual friction angle of some clayey soils along with their clay-size fractions are also included.

- In Chapter 3 on Natural Soil Deposits and Subsoil Exploration, additional approximate correlations between standard penetration resistance and overconsolidation ratio and preconsolidation pressure of the cohesive soil deposits have been introduced. Calculation of the undrained shear strength from the vane shear test results for rectangular and tapered vanes have been updated based on recent ASTM test designations. Iowa borehole shear tests and K_o stepped-blade test procedures have been added.
- In Chapter 4 on Shallow Foundations: Ultimate Bearing Capacity, the laboratory test results of DeBeer (1967) have been incorporated in a nondimensional form in order to provide a general idea of the magnitude of settlement at ultimate load in granular soils for foundations. The general concepts of the development of Terzaghi's bearing capacity equation have been further expanded. A brief review of the bearing capacity factor N_γ obtained by various researchers over the years has been presented and compared. Results from the most recent publications relating to "reduction factors" for estimating the ultimate bearing capacity of continuous shallow foundations supported by granular soil subjected to eccentric and eccentrically inclined load are discussed.
- Chapter 5 on Ultimate Bearing Capacity of Shallow Foundations: Special Cases has an extended discussion on foundations on layered clay by incorporation of the works of Reddy and Srinivasan (1967) and Vesic (1975). The topic of evaluating the ultimate bearing capacity of continuous foundation on weak clay with a granular trench has been added. Also added to this chapter are the estimation of seismic bearing capacity and settlement of shallow foundation in granular soil.
- The procedure to estimate the stress increase in a soil mass both due to a line load and a strip load using Boussinesq's solution has been added to Chapter 6 on Vertical Stress Increase in Soil. A solution for estimation of average stress increase below the center of a flexible circularly loaded area is now provided in this chapter.
- Chapter 7 on Settlement of Shallow Foundations has solutions for the elastic settlement calculation of foundations on granular soil using the strain influence factor, as proposed by Terzaghi, Peck, and Mesri (1996) in addition to that given by Schmertmann et al. (1978). The effect of the rise of a water table on the elastic settlement of shallow foundations on granular soil is discussed.
- The example for structural design of mat foundation in Chapter 8 is now consistent with the most recent ACI code (ACI 318-11).
- Discussions have been added on continuous flight auger piles and wave equations analysis in Chapter 9 on Pile Foundations.
- The procedure for estimating the ultimate bearing capacity of drilled shafts extending into hard rock as proposed by Reese and O'Neill (1988, 1989) has been added to Chapter 10 on Drilled-Shaft Foundations.
- In Chapter 12 on Lateral Earth Pressure, results of recent studies related to the determination of active earth pressure for earthquake conditions for a vertical back face of wall with $c'-\phi'$ backfill has been added. Also included is the Caquot and Kerisel solution using the passive earth-pressure coefficient for retaining walls with granular backfill.

- In Chapter 15 on Braced Cuts, principles of general wedge theory have been added to explain the estimation of active thrust on braced cuts before the introduction of pressure envelopes in various types of soils.
- Chapter 16 on Ground Improvement and Modification now includes some recently developed empirical relationships for the compaction of granular and cohesive soils in the laboratory. New publications (2013) related to the load-bearing capacity of foundations in stone columns have been referred to. A brief introduction on deep mixing has also been added.
- A new Appendix A has been added to illustrate reinforced concrete design principles for shallow foundations using ACI-318-11 code (ultimate strength design method).

Natural soil deposits, in many cases, are nonhomogeneous. Their behavior as related to foundation engineering deviates somewhat from those obtained from the idealized theoretical studies. In order to illustrate this, several field case studies have been included in this edition similar to the past editions of the text.

- Foundation failure of a concrete silo and a load test on small foundations in soft Bangkok clay (Chapter 4)
- Settlement observation for mat foundations (Chapter 8)
- Performance of a cantilever retaining wall (Chapter 13)
- Field observations for anchored sheet-pile walls at Long Beach Harbor and Toledo, Ohio (Chapter 14)
- Subway extension of the Massachusetts Bay Transportation Authority (MBTA), construction of National Plaza (south half) in Chicago, and the bottom heave of braced cuts in clay (selected cases from Bjerrum and Eide, 1963) (Chapter 15)
- Installation of PVDs combined with preloading to improve strength of soft soil at Nong Ngu Hao, Thailand (Chapter 16)

Instructor Resource Materials

A detailed *Instructor's Solutions Manual* and PowerPoint slides of both figures and examples from the book are available for instructors through a password-protected Web site at www.cengagebrain.com.

MindTap Online Course and Reader

In addition to the print version, this textbook will also be available online through MindTap, which is a personalized learning program. Students who purchase the MindTap version will have access to the book's MindTap Reader and will be able to complete homework and assessment material online by using their desktop, laptop, or iPad. If your class is using a Learning Management System (such as Blackboard, Moodle, or Angel) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course. In MindTap, instructors can use the following features.

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- Promote student engagement through interactivity and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes, highlight content for easy reference, and check their understanding of the material.

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It is also fitting to thank Rose P. Kernan of RPK Editorial Services. She has been instrumental in shaping the style and overseeing the production of this edition of *Principles of Foundation Engineering* as well as several previous editions.

For the past thirty-five years, my primary source of inspiration has been the immeasurable energy of my wife, Janice. I am grateful for her continual help in the development of the original text and its seven subsequent revisions.

Braja M. Das

1 Introduction

1.1 Geotechnical Engineering

In the general sense of engineering, *soil* is defined as the uncemented aggregate of mineral grains and decayed organic matter (solid particles) along with the liquid and gas that occupy the empty spaces between the solid particles. Soil is used as a construction material in various civil engineering projects, and it supports structural foundations. Thus, civil engineers must study the properties of soil, such as its origin, grain-size distribution, ability to drain water, compressibility, shear strength, load-bearing capacity, and so on. *Soil mechanics* is the branch of science that deals with the study of the physical properties of soil and the behavior of soil masses subjected to various types of forces.

Rock mechanics is a branch of science that deals with the study of the properties of rocks. It includes the effect of the network of fissures and pores on the nonlinear stress-strain behavior of rocks as strength anisotropy. Rock mechanics (as we know now) slowly grew out of soil mechanics. So, collectively, soil mechanics and rock mechanics are generaly referred to as *geotechnical engineering.*

1.2 Foundation Engineering

Foundation engineering is the application and practice of the fundamental principles of soil mechanics and rock mechanics (i.e., geotechnical engineering) in the design of foundations of various structures. These foundations include those of columns and walls of buildings, bridge abutments, embankments, and others. It also involves the analysis and design of earth-retaining structures such as retaining walls, sheet-pile walls, and braced cuts. This text is prepared, in general, to elaborate upon the foundation engineering aspects of these structures.

1.3 General Format of the Text

This text is divided into four major parts.

- Part I—Geotechnical Properties and Exploration of Soil (Chapters 2 and 3)
- Part II—Foundation Analysis (Chapters 4 through 11).

Foundation analysis, in general, can be divided into two categories: shallow foundations and deep foundations. Spread footings and mat (or raft) foundations are referred to as shallow foundations. A *spread footing* is simply an enlargement of a load-bearing wall or column that makes it possible to spread the load of the structure over a larger area of the soil. In soil with low load-bearing capacity, the size of the spread footings is impracticably large. In that case, it is more economical to construct the entire structure over a concrete pad. This is called a *mat foundation*. Piles and drilled shafts are deep foundations. They are structural members used for heavier structures when the depth requirement for supporting the load is large. They transmit the load of the superstructure to the lower layers of the soil.

- Part III—Lateral Earth Pressure and Earth-Retaining Structures (Chapters 12 through 15)

This part includes discussion of the general principles of lateral earth pressure on vertical or near-vertical walls based on wall movement and analyses of retaining walls, sheet pile walls, and braced cuts.

- Part IV—Soil Improvement (Chapter 16)

This part discusses mechanical and chemical stabilization processes used to improve the quality of soil for building foundations. The mechanical stabilization processes include compaction, vibroflotation, blasting, precompression, sand and prefabricated vertical drains. Similarly, the chemical stabilization processes include ground modification using additives such as lime, cement, and fly ash.

1.4 Design Methods

The *allowable stress design* (ASD) has been used for over a century in foundation design and is also used in this edition of the text. The ASD is a deterministic design method which is based on the concept of applying a factor of safety (FS) to an ultimate load Q_u (which is an ultimate limit state). Thus, the allowable load Q_{all} can be expressed as

$$Q_{\text{all}} = \frac{Q_u}{\text{FS}} \tag{1.1}$$

According to ASD,

$$Q_{\text{design}} \leq Q_{\text{all}} \tag{1.2}$$

where Q_{design} is the design (working) load.

Over the last several years, *reliability based design methods* are slowly being incorporated into civil engineering design. This is also called the *load and resistance factor* design method (LRFD). It is also known as the ultimate strength design (USD). The LRFD was initially brought into practice by the American Concrete Institute (ACI) in the 1960s. Several codes in North America now provide parameters for LRFD.

- American Association of State Highway and Transportation Officials (AASHTO) (1994, 1998)
- American Petroleum Institute (API) (1993)
- American Concrete Institute (ACI) (2002)

According to LRFD, the *factored nominal load* Q_u is calculated as

$$Q_u = (LF)_1 Q_{u(1)} + (LF)_2 Q_{u(2)} + \ \ldots \tag{1.3}$$

where

Q_u = factored nominal load
$(LF)_i$ $(i = 1, 2, \ldots)$ is the load factor for nominal load $Q_{u(i)}$ $(i = 1, 2, \ldots)$

Most of the load factors are greater than one. As an example, according to AASHTO (1998), the load factors are

Load	LF
Dead load	1.25 to 1.95
Live load	1.35 to 1.75
Wind load	1.4
Seismic	1.0

The basic design inequality then can be given as

$$Q_u \leq \phi Q_n \tag{1.4}$$

where

Q_n = nominal load capacity
ϕ = resistance factor (<1)

As an example of Eq. (1.4), let us consider a shallow foundation—a column footing measuring $B \times B$. Based on the dead load, live load, and wind load of the column and the load factors recommended in the code, the value of Q_u can be obtained. The nominal load capacity,

$$Q_n = q_u(A) = q_u B^2 \tag{1.5}$$

where

q_u = ultimate bearing capacity (Chapter 4)
A = area of the column footing = B^2

The resistance factor ϕ can be obtained from the code. Thus,

$$Q_u \leq \phi q_u B^2 \tag{1.6}$$

Equation (1.6) now can be used to obtain the size of the footing B.

LRFD is rather slow to be accepted and adopted in the geotechnical community now. However, this is the future of design method.

In Appendix A of this text (Reinforced Concrete Design of Shallow Foundations), the ultimate strength design method has been used based on ACI 381-11 (American Concrete Institute, 2011).

1.5 Numerical Methods in Geotechnical Engineering

Very often, the boundary conditions in geotechnical engineering design can be so complex that it is not possible to carry out the traditional analysis using the simplified theories, equations, and design charts covered in textbooks. This situation is even made more complex by the soil variability. Under these circumstances, numerical modeling can be very useful. *Numerical modeling* is becoming more and more popular in the designs of foundations, retaining walls, dams, and other earth-supported structures. They are often used in large projects. They can model the soil–structure interaction very effectively.

Finite element analysis and finite difference analysis are two different numerical modeling techniques. Here, the problem domain is divided into a mesh, consisting of thousands of elements and nodes. Boundary conditions and appropriate constitutive models (e.g., linear elastic and Mohr-Coulomb) are applied, and equations are developed for all of the nodes. By solving thousands of equations, the variables at the nodes are determined.

There are people who write their own finite-element program to solve a geotechnical problem. For novices, there are off-the shelf programs that can be used for such purposes. *PLAXIS* (http://www.plaxis.nl) is a very popular finite-element program that is widely used by professional engineers. *FLAC* (http://www.itasca.com) is a powerful finite-difference program used in geotechnical and mining engineering. There are also other numerical modeling software available, such as those developed by GEO-SLOPE International Ltd. (http://www.geo-slope.com), SoilVision Systems Ltd. (http://www.soilvision.com), and GGU-Software (http://www.ggu-software.com). In addition, some of the more powerful and versatile software packages developed for structural, materials, and concrete engineering also have the ability to model geotechnical problems. *Abaqus* and *Ansys*® are two finite-element packages that are used in the universities for teaching and research. They are quite effective in modeling geotechnical problems too.

To simplify the analysis, it generally is assumed that the soil behaves as a linear elastic or rigid plastic continuum. In reality, this is not the case, and it may be necessary to adopt more sophisticated constitutive models that would model the soil behavior more realistically. No matter how good the model is, the output only can be as good as the input. It is necessary to have good input parameters to arrive at sensible solutions.

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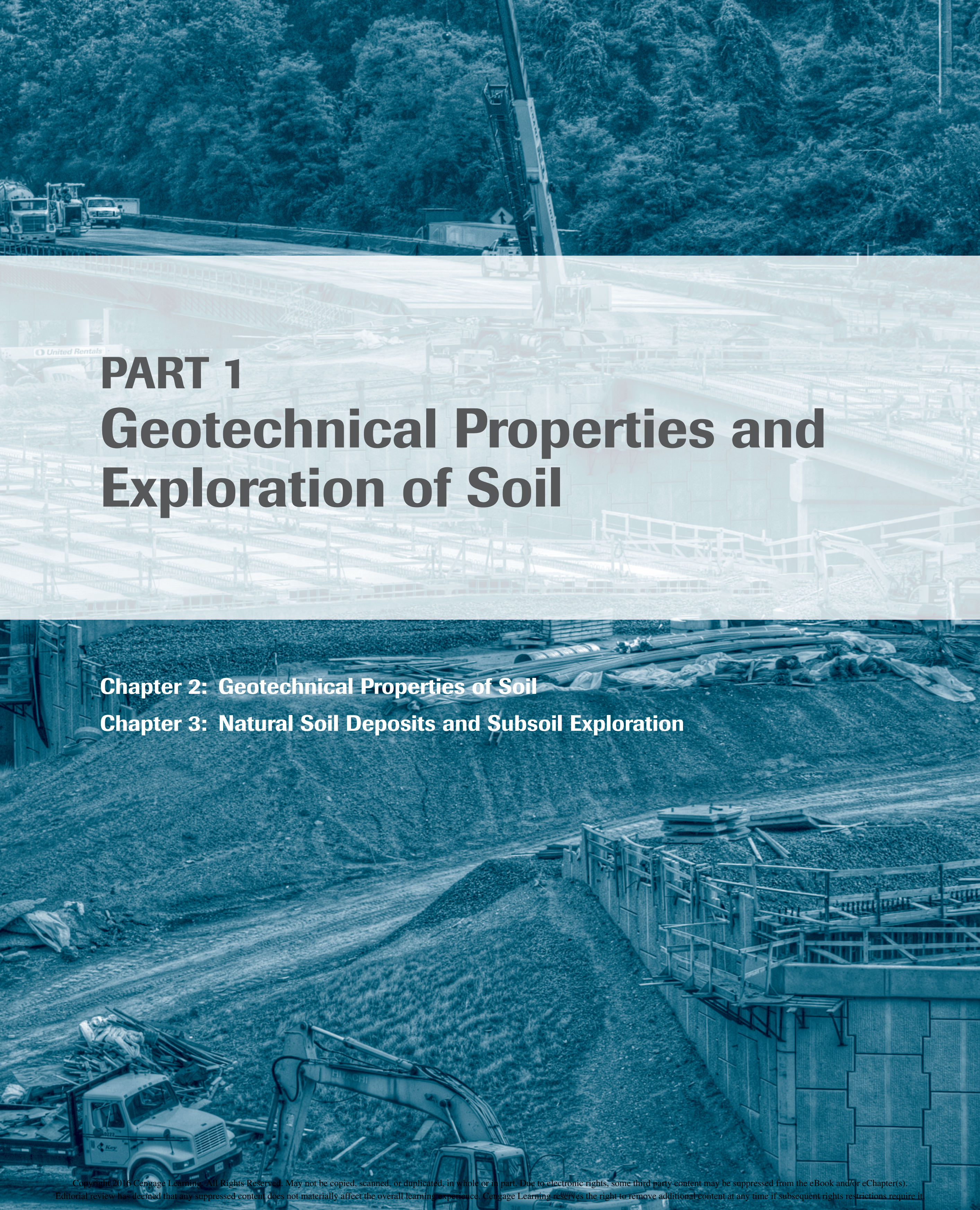

PART 1
Geotechnical Properties and Exploration of Soil

2 Geotechnical Properties of Soil

2.1 Introduction

The design of foundations of structures such as buildings, bridges, and dams generally requires a knowledge of such factors as (a) the load that will be transmitted by the superstructure to the foundation system, (b) the requirements of the local building code, (c) the behavior and stress-related deformability of soils that will support the foundation system, and (d) the geological conditions of the soil under consideration. To a foundation engineer, the last two factors are extremely important because they concern soil mechanics.

The geotechnical properties of a soil—such as its grain-size distribution, plasticity, compressibility, and shear strength—can be assessed by proper laboratory testing. In addition, recently emphasis has been placed on the *in situ* determination of strength and deformation properties of soil, because this process avoids disturbing samples during field exploration. However, under certain circumstances, not all of the needed parameters can be or are determined, because of economic or other reasons. In such cases, the engineer must make certain assumptions regarding the properties of the soil. To assess the accuracy of soil parameters—whether they were determined in the laboratory and the field or whether they were assumed—the engineer must have a good grasp of the basic principles of soil mechanics. At the same time, he or she must realize that the natural soil deposits on which foundations are constructed are not homogeneous in most cases. Thus, the engineer must have a thorough understanding of the geology of the area—that is, the origin and nature of soil stratification and also the groundwater conditions. Foundation engineering is a clever combination of soil mechanics, engineering geology, and proper judgment derived from past experience. To a certain extent, it may be called an art.

This chapter serves primarily as a review of the basic geotechnical properties of soils. It includes topics such as grain-size distribution, plasticity, soil classification, hydraulic conductivity, effective stress, consolidation, and shear strength parameters. It is based on the assumption that you have already been exposed to these concepts in a basic soil mechanics course.

2.2 Grain-Size Distribution

In any soil mass, the sizes of the grains vary greatly. To classify a soil properly, you must know its *grain-size distribution.* The grain-size distribution of *coarse-grained* soil is generally determined by means of *sieve analysis.* For a *fine-grained* soil, the grain-size distribution can be obtained by means of *hydrometer analysis.* The fundamental features of these analyses are presented in this section. For detailed descriptions, see any soil mechanics laboratory manual (e.g., Das, 2013).

Sieve Analysis

A sieve analysis is conducted by taking a measured amount of dry, well-pulverized soil and passing it through a stack of progressively finer sieves with a pan at the bottom. The amount of soil retained on each sieve is measured, and the cumulative percentage of soil passing through each is determined. This percentage is generally referred to as *percent finer.* Table 2.1 contains a list of U.S. sieve numbers and the corresponding size of their openings. These sieves are commonly used for the analysis of soil for classification purposes.

The percent finer for each sieve, determined by a sieve analysis, is plotted on *semilogarithmic graph paper,* as shown in Figure 2.1. Note that the grain diameter, D, is plotted on the *logarithmic scale* and the percent finer is plotted on the *arithmetic scale.*

Two parameters can be determined from the grain-size distribution curves of coarse-grained soils: (1) the *uniformity coefficient* (C_u) and (2) the *coefficient of gradation,* or *coefficient of curvature* (C_c). These coefficients are

$$C_u = \frac{D_{60}}{D_{10}} \tag{2.1}$$

Table 2.1 U.S. Standard Sieve Sizes

Sieve No.	Opening (mm)
4	4.750
6	3.350
8	2.360
10	2.000
16	1.180
20	0.850
30	0.600
40	0.425
50	0.300
60	0.250
80	0.180
100	0.150
140	0.106
170	0.088
200	0.075
270	0.053

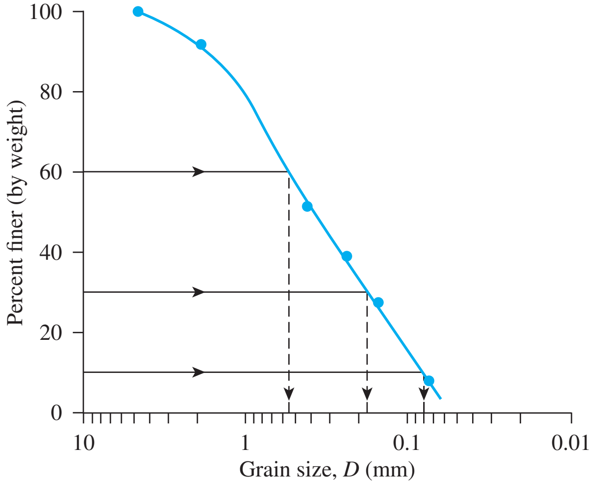

Figure 2.1 Grain-size distribution curve of a coarse-grained soil obtained from sieve analysis

and

$$C_c = \frac{D_{30}^2}{(D_{60})(D_{10})} \tag{2.2}$$

where D_{10}, D_{30}, and D_{60} are the diameters corresponding to percents finer than 10, 30, and 60%, respectively.

For the grain-size distribution curve shown in Figure 2.1, $D_{10} = 0.08$ mm, $D_{30} = 0.17$ mm, and $D_{60} = 0.57$ mm. Thus, the values of C_u and C_c are

$$C_u = \frac{0.57}{0.08} = 7.13$$

and

$$C_c = \frac{0.17^2}{(0.57)(0.08)} = 0.63$$

Parameters C_u and C_c are used in the *Unified Soil Classification System,* which is described later in the chapter.

Hydrometer Analysis

Hydrometer analysis is based on the principle of sedimentation of soil particles in water. This test involves the use of 50 grams of dry, pulverized soil. A *deflocculating agent* is always added to the soil. The most common deflocculating agent used for hydrometer analysis is 125 cc of 4% solution of sodium hexametaphosphate. The soil is allowed to soak for at least 16 hours in the deflocculating agent. After the soaking period, distilled water is added, and the soil–deflocculating agent mixture is thoroughly agitated. The